A CYCLOCONVERTER-EXCITED, DOUBLY-FED MACHINE

AS A WIND POWER CONVERTER

by

N.A. El Sonbaty
B.Sc., M.Phil. Leicester 1977

A thesis submitted to the University of Leicester
for the degree of Doctor of Philosophy

MAY
1983
To:

Mayi and Medo
my parents
my husband
and
my brothers
Memorandum

The accompanying thesis "A CYCLO CONVERTER-EXCITED, DOUBLY-FED MACHINE AS A WIND POWER CONVERTER" is based on work conducted by the author in the Department of Engineering at the University of Leicester between July 1981 and May 1983.

All work and ideas recorded in this thesis are original unless otherwise acknowledged in the text or by references. None of the work has been submitted for another degree in this or any other university.

I hereby declare that the statements in this memorandum are true in all particulars.

signed N.A. Elsonbaty
Department of Engineering
University of Leicester
May 1983
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<td>VSCF</td>
<td>Variable speed constant frequency</td>
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<td>WGS</td>
<td>Wind driven generators</td>
<td></td>
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<tr>
<td>HVDC</td>
<td>High voltage d.c. transmission</td>
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</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity of the turbine shaft</td>
<td>rad/s</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Optimum angular velocity of the turbine shaft</td>
<td>rad/s</td>
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<tr>
<td>$\lambda$</td>
<td>gear ratio</td>
<td></td>
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<td>$\lambda_0$</td>
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<td>$C_p$</td>
<td>Power coefficient of the turbine</td>
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<td>$C_{p_{max}}$</td>
<td>Maximum power coefficient of the wind turbine</td>
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<tr>
<td>$\mu$</td>
<td>Tip speed ratio</td>
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<tr>
<td>$\mu_{max}$</td>
<td>Maximum tip speed ratio</td>
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<td>$V_c$</td>
<td>Cut-in wind velocity</td>
<td>m/s, m.p.h.</td>
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<tr>
<td>$V_r$</td>
<td>Rated wind velocity</td>
<td>m/s, m.p.h.</td>
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<td>$R$</td>
<td>Blade radius</td>
<td>m</td>
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<td>$C_Q$</td>
<td>Torque coefficient</td>
<td></td>
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<td>VGVAVT</td>
<td>Variable geometry-vertical axis</td>
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<td>ADA</td>
<td>AC-DC-AC conversion</td>
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(ii) The Generator System

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<td>Doubly-fed generator</td>
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<td>Unit</td>
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<td>(\omega_1)</td>
<td>Angular frequency of primary supply</td>
<td>rad/s</td>
</tr>
<tr>
<td>(\omega_2)</td>
<td>Angular frequency of secondary supply</td>
<td>rad/s</td>
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<tr>
<td>(f_1)</td>
<td>Primary frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>(f_2)</td>
<td>Secondary frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>(P)</td>
<td>Number of pole pairs</td>
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<tr>
<td>(n)</td>
<td>Electrical speed of the machine</td>
<td>rev/min</td>
</tr>
<tr>
<td>(\omega)</td>
<td>Angular frequency of the system</td>
<td>rad/s</td>
</tr>
<tr>
<td>(\omega_g)</td>
<td>Angular velocity of the machine</td>
<td>rad/s</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Angular displacement between primary and secondary flux vectors</td>
<td>deg.</td>
</tr>
<tr>
<td>(v_1)</td>
<td>Primary voltage</td>
<td>v</td>
</tr>
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<td>(v_2)</td>
<td>Cycloconverter voltage output</td>
<td>v</td>
</tr>
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<td>(v_s)</td>
<td>Effective secondary voltage</td>
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</tr>
<tr>
<td>(s)</td>
<td>Slip</td>
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<td>(\theta)</td>
<td>Angular displacement between primary and secondary voltage</td>
<td>deg.</td>
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<tr>
<td>(\delta_1)</td>
<td>Angular position in primary fed system</td>
<td>deg.</td>
</tr>
<tr>
<td>(\delta_2)</td>
<td>Angular position in secondary fed system</td>
<td>deg.</td>
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<tr>
<td>(\delta_{22})</td>
<td>Phase shift in secondary fed system</td>
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<td>(r_1)</td>
<td>Total primary resistance</td>
<td>(\Omega)</td>
</tr>
<tr>
<td>(r_2)</td>
<td>Total secondary resistance</td>
<td>(\Omega)</td>
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<td>(L_1)</td>
<td>Total cyclic primary inductance</td>
<td>H</td>
</tr>
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<td>(L_2)</td>
<td>Total cyclic secondary inductance</td>
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<tr>
<td>(M)</td>
<td>Mutual inductance primary/secondary or secondary/primary</td>
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<td>(d,q)</td>
<td>Co-ordinate axes</td>
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<td>(I)</td>
<td>Complexor current</td>
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<tr>
<td>(I_1)</td>
<td>Total primary current in doubly-fed system</td>
<td>A</td>
</tr>
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<td>$I_2$</td>
<td>Total secondary current in doubly-fed system</td>
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<td>$I_{22}$</td>
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</tr>
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<td>$T_{I2}$</td>
<td>Induction torque in secondary-fed system</td>
<td>Nm</td>
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<td>$T_s$</td>
<td>Synchronous torque in doubly-fed system</td>
<td>Nm</td>
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<td>$T$</td>
<td>Total torque in doubly-fed system</td>
<td>Nm</td>
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<td>$P_{I1}$</td>
<td>Induction power in primary-fed system</td>
<td>W</td>
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<td>$P_{\text{max}}$</td>
<td>Maximum electrical power</td>
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<td>$P_m$</td>
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<td>Load angle in current source excitation</td>
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<td>Reluctance</td>
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<td>$\beta$</td>
<td>Excitation ratio</td>
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<td>$N$</td>
<td>Turns ratio, transformation ratio</td>
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<td>$r$</td>
<td>Input to output cycloconverter</td>
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<td>$I_m$</td>
<td>Crest value of alternating current</td>
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<td>$\tau$</td>
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<tr>
<td>$G$</td>
<td>Gain</td>
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<tr>
<td>$t$</td>
<td>Time</td>
<td>s</td>
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<td>$J$</td>
<td>Rotational inertia</td>
<td>Kg-m$^2$</td>
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<td>$K_g$</td>
<td>Power coefficient of the generator</td>
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<td>$K_{g_0}$</td>
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<td>$I_f$</td>
<td>Field excitation current in conventional synchronous machine</td>
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<td>CMOS</td>
<td>Complementary metal oxide semiconductor</td>
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<td>D/A</td>
<td>Digital-to-analogue</td>
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<tr>
<td>d.c.</td>
<td>Direct current</td>
<td>A</td>
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<tr>
<td>E.P.R.O.M.</td>
<td>Erasable programmable read only memory</td>
<td>-</td>
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<tr>
<td>TTL</td>
<td>Transistor-Transistor logic</td>
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<tr>
<td>V/F</td>
<td>Voltage-to-frequency</td>
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### (iv) Mathematical Symbols

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<td>p</td>
<td>( \frac{d}{dt} ), Laplace operator</td>
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<td>RL</td>
<td>Real part of</td>
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<td>[A]</td>
<td>The matrix A</td>
</tr>
<tr>
<td>j</td>
<td>( \sqrt{-1} )</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>The angle between two components</td>
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<td>&quot; 1.4</td>
<td>Schemes to use wind energy as a supplementary energy force</td>
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<td>&quot; (b)</td>
<td>Current source inverter Scherbius system</td>
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<td>&quot; 1.6</td>
<td>Cycloconverter for DFM systems</td>
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<td>D.F.M. equivalent circuit/phase</td>
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<td>Schematic diagram of a D.F.M. with the primary winding on the rotor</td>
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<td>&quot; 2.4(a)</td>
<td>The DFM with the same primary and secondary phase sequence, (a is +ve)</td>
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<tr>
<td>&quot; (b)</td>
<td>The DFM with the same primary and secondary phase sequence, (a is -ve)</td>
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<td>&quot; 2.5</td>
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Abstract

The thesis describes a wind-energy transducer system based on a doubly-fed, slip-ring machine and a cycloconverter operating with continuous circulating current. A theoretical analysis and experimental verification of the system have been carried out with a simulated wind turbine.

Points 1 to 8 list the points covered and work carried out:

The author has:

1) Surveyed existing wind energy transducers connected to the grid.

2) Developed an original theory of the doubly-fed machine operating as a generator.

3) Modified the doubly-fed generator theory to allow the generator to generate power proportional to the cube of its speed.

4) Computed a field voltage control function necessary to maintain cube-law generation at optimum power coefficient.

5) Further developed the generator theory to show that constant current excitation greatly reduces the induction power and permits the economic selection of electronic devices.

6) Designed and implemented digital and analogue electronic systems to satisfy the requirements of points (3) and (4) and to operate the system at optimum efficiency.

7) Successfully applied the cycloconverter, divided winding principle to the doubly-fed generator to provide a system able to withstand shock wind gusts over a wide-speed range.

8) Discussed the extrapolation of the system to large powers.
Introduction

Interest in wind energy utilization has been increasing recently. It is a consequence of the realization that easily accessible fossil fuel resources are indeed finite and that as the costs of the conventional fuels go up, it becomes increasingly worthwhile to explore the possibilities of tapping the unconventional and non-depleting energy of the sun in its various manifestations such as solar radiation, heat, winds, tides and ocean thermal gradients. Other than the miniscule amount of energy used to grow organic matter and a small amount of hydroelectric power generation, most of the incident solar energy goes unused as an energy resource in spite of the enormous amount of energy that reaches the earth every day from the sun.

This work is concerned with one manifestation of solar energy, namely wind. Wind energy utilization techniques can be divided into three broad categories.

A) Isolated continuous duty systems; to be used in conjunction with energy storage systems. At the present time, such applications are not economically attractive due to the expense of battery or pumped storage.

B) Direct wind to electricity conversion systems for use in conjunction with grid systems for the purpose of either (i) energy displacement or (ii) capacity displacement. In case (i), the total installed capacity of the power system is built up to an adequate level to handle the peak load expected on the system with suitable degree of reliability. Wind energy systems are then used only as a fuel (energy) supplement whenever the wind velocity is adequate. Therefore, the economic evaluation of wind energy systems used for this purpose must be based on comparing the output energy cost of
such systems with only the fuel cost of conventional fuel burning systems.

In the second case (ii), the wind energy system replaces part of the installed capacity, without affecting the reliability of the total system, in addition to supplementing the total energy generated by the system. The ability to displace capacity is affected by weather conditions, wind regimes, the amount of energy storage provided, and the number, size and location of such systems. By taking advantage of the statistical independence of wind velocities at different locations in the area served by the grid (utility), several smaller plants (of equivalent total size) can be installed instead of one large plant to decrease the duration of weather outages and thereby improve the ability to displace capacity. The output energy cost of wind energy systems used for capacity displacement can be directly compared with the total energy cost of the conventional systems.

C) Small rural systems for applications which are not critical (time-wise), can wait and use the energy in the wind when it is available.

It is obviously impossible to convert all the power of the wind into useful power. The portion that is usable is determined by aerodynamic and mechanical efficiencies. Maximum conversion efficiency occurs when the wind turbine is loaded (by the electrical generator) in such a way that its rotational speed is allowed to fluctuate in sympathy with wind-speed variations.

The modern windmill\(^2\) has an output characteristic in which the shaft power varies roughly in proportion to the cube of the wind speed if the direction and blade angle are optimised, and the ratio of rotor speed to wind speed is kept constant. A slip range of \(0.2 > s > -0.3\)
will for most wind regimes lead to an annual energy capture not far short of the one theoretically possible with a much wider rotor speed range. This occurs because the annual energy yield from winds both in the low speed range and the high speed range is relatively small, the latter because of the small number of high-wind hours per annum and because of the impossibility of maintaining optimum operation of any windmill in the highest winds. It is of course possible to operate with a much narrower range of rotor speeds than that suggested above and this is done in the majority of medium and large wind generators which use standard synchronous or induction machines connected directly to the three-phase mains. Annual energy yield is of course somewhat reduced, but the past absence of frequency conversion equipment of sufficiently low cost meant that such fixed speed or near fixed speed operation were virtually obligatory in order for grid connected schemes to be viable. The situation is now changing as a result of the tremendous improvements in solid state conversion technology but the cost of a 'full power' frequency converter is still high enough to constitute something of a disincentive to its use in wind power schemes. Two different approaches of variable speed-constant frequency operation have been carried out. The one (ref.1) being pursued at Oklahoma State University (10 kW prototype) allows the aeroturbine speed to vary with wind velocity and employs a variable-speed, constant frequency (VSCF) system with a field modulated generator to generate constant frequency power to be pumped into existing grids. The second approach uses a converter synchronous generator system essentially comprising a synchronous generator with a static frequency converter. This system first converts the mechanical power taken from the wind turbine into electric power with a frequency which differs from the power system frequency, and subsequently supplies after further conversion the electric power to the network at power system frequency. In both systems, the main disadvantage is the high
power requirement of the solid state devices needed for whole power

demodulation (in the first system) and conversion (in the second system).

The great advantage of slip energy control schemes is that the
power rating of the converter is much reduced, since it is only the slip
power that is dealt with by the converter. This technique has been used
in a further approach planned by Siemens\(^4\), known as the "GROWIAN" of 3 MW
rating. A doubly-fed asynchronous generator with a slip ring rotor and
a variable-frequency converter in the rotor circuit was adopted.

The system requires two independent methods of controlling the speed
and power incorporating the need for blade angle adjustment. At low
wind speeds the controller acts mainly on the converter, whereas at higher
wind speeds it adjusts the blade angle. Voltage and power factor control
are used to control the reactive power of the doubly-fed asynchronous
machine. A switch over to asynchronous operation must also be initiated
by the speed and power controller as soon as the highest possible control
speed and maximum permissible converter power are exceeded.

At Leicester University two alternative systems of wind energy
recovery to the grid system have been applied. The first system described
by Smith and Nigim\(^5\) is based on power generation over a wide range of sub-
and super-synchronous speeds by use of a current-source inverter. The
system requires specialised electronics (an electronic secondary e.m.f.
signal generator) and has a forced commutated inverter in addition to the
naturally commutated converter of the Kramer system. Disadvantages are
large commutation capacitors, a large d.c. link choke and the possibility
of commutation failure isolating the system from the grid. A near const-
ant driving torque over the whole speed range is produced.

The second alternative approach is described by the present author.
It consists of a doubly-fed machine excited by a half-wave cycloconver-
ter. Inverted operation of the doubly-fed generator with the slip ring
rotor connected to the 50 Hz supply (as the primary) and the cycloconverter
exciting the stator (as the secondary) avoids the need for high-current thyristors and six slip-rings.

The use of a divided-winding secondary\(^6\) extends the exciting frequency range to 25\(\text{Hz}\) with an acceptable harmonic content giving a system operating range of synchronous speed \(\pm 50\%\). Forced commutation components i.e. capacitors or chokes are not required. Line to line cycloconverter short circuits are prevented by the electrically isolated, magnetically coupled secondary windings. Continuous circulating current operation is obtained without the conventional cycloconverter inter-group reactors. This approach reduces the possibility of breakdown due to spurious firing with considerable economic advantage.

The doubly-fed machine is considered as an a.c. excited synchronous machine, and basically it behaves as a conventional d.c. excited synchronous motor when \(f_2\) (of the cycloconverter) is equal to zero. The doubly-fed generator operates synchronously at a speed of either the sum or the difference of the two supplies dependent on the relative phase rotation. Most of the power generated is load-angle dependent synchronous power, but some induction power is also produced. The ratio of synchronous power to induction power is maximised by appropriate control of the low-frequency exciting voltage. The cycloconverter is a self-commutating converter and synchronism is automatically restored after a momentary 'outage' providing the generator speed is within the operating range when the supply is restored. Although the thesis concentrates on the scheme's application to wind power systems, it could of course be considered for other generating systems where it is desirable for the prime mover to be able to operate over a speed range. The scheme could also form the basis of a variable speed drive with an ability for self starting. This eliminates the need for a 'pony' motor when starting the wind-turbine from standstill. The well known stability problems of a doubly-fed motor are not present in a doubly-fed generator due to the high mechanical source impedance.
Two types of converter, a voltage source- and a current source-
converter are used for secondary excitation. Generated power propor-
tional to the cube of the speed is obtained by

(i) Induction power control achieved by power electronic control
of the secondary current form factor and electrical control
of the secondary ampere turns, and

(ii) Control of generated synchronous power by load angle control as
a function of the excitation voltage.

With this approach, since a constant rotational speed is no longer
required by the use of the VSCF technique, aeroturbines can be designed to
maximise their power producing capability and minimize their cost.

At a given wind speed there is an optimum rotor speed at which
maximum power will be generated. This maximum power increases roughly
as the cube of wind speed. The design task is to ensure that throughout
the required operating range the windmill is loaded by the doubly-fed
machine and the grid just enough to enable it to run at the optimum rota-
tional speed (i.e. the speed at which the power that is extracted from
the wind, at its current velocity, is a maximum).

Briefly, this usually means that the load torque drag on the wind-
mill varies as the square of the shaft rotational speed, and that stable
operating points are obtained where the generator-load torque and wind
turbine torque equate. This has been achieved by a special control
function of excitation voltage which controls the load angle of the machine,
giving a simple and reliable optimising system.

A "naturally" matched wind generator system at the Rutherford
Laboratories, Abingdon, has a similar rating to the Leicester experimental
machine. It incorporates a fixed-pitch, variable-geometry, vertical
axis windmill with a fixed maximum tip-speed ratio.
Examples of naturally-matched wind generator systems are found in the literature. Perhaps the most successful large windmill system built so far, the Gedser windmill, employed a certain degree of natural matching with a fixed pitch windmill and a simple induction generator connected to the mains.

Operational problems of the complete system have been considered. The frequency of the cycloconverter is controlled by the speed of the turbine (represented by a variable-speed d.c. motor in the present experimental work). The amplitude of the cycloconverter output is determined by a speed and load related function, while the cycloconverter frequency is controlled by velocity feedback.

An important and desirable property for wind energy generators is their ability to cope with gusts. In the scheme reported in reference 4, a doubly-fed machine with variable frequency rotor excitation has been used in a 250 kW installation. Here the practical limitation is the inability of the converter to conduct the large rotor current surges occurring during gusting. Exciting capacitors and a swamp resistance are used to dump the excess energy by self-excited induction generation until the gust is over. In the system described in this work, the positive and negative thyristor group circuits of the cycloconverter are kept electrically separate by a divided winding stator arrangement. The possibility of transient line to line short-circuits through the converter is eliminated and the system is able to withstand severe input surges.

The experimental system described in the thesis is a 5 kW generator test facility, and the experimental results given were obtained with a separately excited d.c. motor as the prime mover. This motor was supplied through an electronic d.c. current source programmed to supply a current proportional to the square of the motor speed. In this way a source of power proportional to the cube of the speed corresponding to a wind turbine characteristic was provided. A test programme based on
wind spectra, including gusting, was carried out. The author believes that the principle established is applicable to 250 kW or larger installations.
Chapter 1

Wind Generator Systems

Wind power has been used for many centuries to meet the human needs, either to drive windmills, or when transformed into mechanical power to propel ships. The present work is concerned with transforming this wind power into electrical power, the easiest form of power to use. Work has been carried out during the last three decades to apply this transformation industrially, that is, to provide electrical power to a distribution network.

The basic factors to be considered in discussing the electrical technology associated with converting wind energy to electrical energy are listed below (they are illustrated in Fig.1.1).

(i) **Type of output**
   a) d.c.
   b) variable frequency a.c., or
   c) constant frequency a.c.

(ii) **Aeroturbine rotational speed**
   a) constant speed, or
   b) nearly constant speed, or
   c) variable speed.

(iii) **Utilization of the electrical energy output**
   a) battery storage, or
   b) other forms of storage (see Fig.1.1), or
   c) direct connection to the a.c. grid.

Direct d.c. generation is practical only on a small scale at present, limited to about 10 or 20 kW. Aeroturbine speeds can
be varied and usually battery storage is employed. Small scale power requirements in remote places can be satisfied adequately by such systems.

Storing wind energy in thermal form for subsequent use in space heating can be effectively achieved using a variable frequency a.c. (or d.c.) system in conjunction with heating coil-thermal storage. Again, the aeroturbine speeds need not be constant. It is also possible to use a rectifier system to obtain d.c., for battery storage or to be inverted into a constant-frequency a.c. supply. Large-scale wind generation of electrical energy should be in constant frequency a.c. forms, to be fed into an existing electricity grid.

Five direct grid connections (as given in ref.2) of wind turbine generators were considered:

(i) integration with hydroelectric facilities,
(ii) operation with pumped hydrofacilities,
(iii) supplemental power without storage,
(iv) operation with short term storage using batteries, and
(v) operation by nongenerating grids.

The first four applications are given in order of increasing cost of energy production.

In the first application (i), wind turbines are connected to a network which is also served by a hydroelectric power station. When the wind turbines produce power, the drawdown rate of water powered generation is reduced by an equivalent power level. The water thus conserved is used to produce peak power above the level which can be produced without the conserved water. Additional hydroelectric turbines are installed to accommodate the higher drawdown rates and these units add to the peaking capacity of the grid. Hydroelectric plants can accommodate changes in the load or wind power generation quickly.
1.3

Operation with pumped storage facilities (ii) means that wind generation is used to pump up the hydrosystem, except during peaking hours. During peaking hours, the wind generation is used directly and water in the high reservoir is conserved. It is assumed that wind generation will save base plant fossil fuel and that nuclear base plants will not be used for pumping.

In supplemental power without storage application (iii), a rapid increase or decrease in wind generation will disrupt the stability of the network due to the limited inertia and kinetic energy of the primary generating equipment. Surges or momentary disconnections from the supply (outages), which amount to a significant fraction of the demand may cause voltage or phase instability, trip the overload breakers that protect generators and transformers, and produce a blackout. Wind generation without storage must be limited to 15-20 per cent of the network power.

Operation with short-term storage (iv) may overcome stability limitations by adding storage capability to the network. This capability provides time for the primary generating plants to match the demand when the wind power falls off. The non-storage application is expected to precede operation with short-term battery storage because storage will not be required until wind power generation approaches the stability limit when the energy generated from wind power approaches 15% to 20% of the total power.

Operation by non-generating grid (v) is applicable in small local, mainly agricultural installations (refer to Fig.1.4).
1.4

1.0. Wind generators serving networks

1.1. Constant and near constant speed generators as direct transducers

Traditionally, synchronous- and induction-generators are used to convert wind energy into constant frequency a.c. electrical power. In both cases the aeroturbine has to run at a constant (or nearly constant) speed. The final choice between the induction and the synchronous generator determines the dynamic behaviour of the wind turbine generator (WTG).

The synchronous generator has substantial data base\textsuperscript{11} for operation in large or small networks. The main advantage is versatile power factor control by variation of the excitation and simple automatic voltage regulation. Severe stability problems due to the effect of wind speed fluctuation can occur if the wind system generates over 20\%\textsuperscript{12} of the network power. A sudden doubling of wind speed increase the blade torque by a factor of 4 and the machine may be thrown out of synchronism if the automatic blade pitch control mechanism fails to operate in time.

The use of synchronous machines with fixed pitch aerogenerators can present starting problems\textsuperscript{13}. The generator must be coupled to a pony motor or started as an induction motor and synchronised when the operating speed is reached. In either case the acceleration due to the wind near synchronous speed would require a fast response from the synchronising equipment and the field supply if pole slipping is to be avoided.

The most obvious suggestion is to run two synchronous generators of WTG in parallel with the grid power systems. Assuming that the grid system is large compared to WGS, the machine will be in synchronism for a varying energy input. The disadvantages are that the machine will draw power from the mains when motoring, and that during gusts, the tendency is to run out of synchronism is very great. Bringing the machine back to synchronism and connecting to the system is tedious.
An induction machine operates with slight speed variation as the drive torque changes. If it is driven above synchronism it acts as a generator. So long as the machine is stiff and running above synchronous speed the induction generator supplies energy back to the system at the system frequency.

The energy associated with rapid changes in incident wind speed can be absorbed through the torsional inertia of the turbine as additional kinetic energy. The cage induction generator is one of the simplest, cheapest and most reliable types of electrical machines, and is available in ratings from 5 kW up to 250 kW. Induction machines connected direct on-line to the supply system have a starting current of 5-6 times full load current and an almost completely reactive impedance. The line current falls to a low level near to synchronous speed and the induction machine is the preferred starter for a fixed-pitch-turbine.

The main points to be considered when starting a large group of induction machines are that they should reach operating speed in a reasonable time without over heating and without causing excessive dips in the supply voltage. It has the following three disadvantages:

1) It generates less energy from a given wind regime than the synchronous machine,

2) It operates at a low power factor due to heavy magnetisation currents which are nearly in quadrature with voltage; and

3) If wound rotor induction generators are used, the installation is more expensive than the synchronous generator, but this is offset by less stringent speed control mechanism.
It can be seen that the rotational dynamic behaviour of these two contrasting constant shaft speed wind-turbine-generators (induction and synchronous generators) is very different, and their respective advantages are best used in different applications. In a large integrated supply network, where the WTG capacity represents a modest proportion (say, less than 20%) of the total system generating capacity, the advantages of the induction generator (with a fixed-pitch-turbine) can be exploited. In low capacity high impedance networks, independent voltage and speed control can be effected by a synchronous generator driven by a variable pitch turbine. Much of the design work\textsuperscript{13,14} on large WTGs in the U.K. has focused so far on the induction generator type.

The first large wind turbine to be built was the Smith-Putnam unit installed on Grandpa's Knob near Rutland, Vermont, in 1941. The rated maximum output capacity of this unit was 1250 kW in winds of 30 miles per hour or higher. Recent work\textsuperscript{15} has been concentrated on the development of wind-driven generators of medium size with minimum costs. Other modern developments have been carried out as stated in the following table.
<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Site</th>
<th>Constructor/Operator</th>
<th>Rated Power (kW)</th>
<th>Rated Wind Speed (m/s)</th>
<th>Turbine Diameter (m)</th>
<th>Number of Blades</th>
<th>Rotational Speed (rev/min)</th>
<th>Pitch Control System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1931</td>
<td>USSR</td>
<td>Yalta</td>
<td>(TSVEI Central Institute of Wind Power Engineering)</td>
<td>100</td>
<td>10.5</td>
<td>30.0</td>
<td>3</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>1941</td>
<td>USA</td>
<td>Grandpa’s Knob, Vermont</td>
<td>S. Morgan-Smith Co. (Constructor and operator)</td>
<td>1250</td>
<td>13.5</td>
<td>55.3</td>
<td>2</td>
<td>26</td>
<td>V</td>
</tr>
<tr>
<td>1954</td>
<td>UK</td>
<td>Costa Hill, Orkney</td>
<td>John Brown &amp; Co. Ltd. (UK National Wind Power Committee)</td>
<td>100</td>
<td>15.25</td>
<td>15.3</td>
<td>3</td>
<td>130</td>
<td>V</td>
</tr>
<tr>
<td>1955</td>
<td>UK</td>
<td>St. Albans &amp; Grand Vent, (Algeria)</td>
<td>Enfield Gables Ltd. (UK National Wind Power Committee) (Electricité et Gaz d’Algérie)</td>
<td>100</td>
<td>13.5</td>
<td>24.4</td>
<td>2</td>
<td>variable ≤ 95.4</td>
<td>V</td>
</tr>
<tr>
<td>1957</td>
<td>Denmark</td>
<td>Gedser</td>
<td>SEAS/DEF- Association of Danish Electricity Undertakings (DEF Wind Power Committee)</td>
<td>200</td>
<td>15.0</td>
<td>24.0</td>
<td>3</td>
<td>30</td>
<td>P</td>
</tr>
<tr>
<td>1957</td>
<td>Germany</td>
<td>Stotten</td>
<td>(Deutsche Studiengesellschaft Windkraft eV)</td>
<td>100</td>
<td>8.0</td>
<td>34.0</td>
<td>2</td>
<td>42</td>
<td>V</td>
</tr>
<tr>
<td>1958</td>
<td>France</td>
<td>St. Rémy-des-Landes, (Manche)</td>
<td>Ets-Neyrpic (EdF)</td>
<td>132</td>
<td>12.5</td>
<td>21.2</td>
<td>3</td>
<td>56</td>
<td>V</td>
</tr>
<tr>
<td>1958</td>
<td>France</td>
<td>Nogent-le Roi, (Eure et Loir)</td>
<td>BEST-Romani (EdF)</td>
<td>800</td>
<td>16.7</td>
<td>30.2</td>
<td>3</td>
<td>75</td>
<td>F</td>
</tr>
<tr>
<td>1959</td>
<td>UK</td>
<td>Isle of Man</td>
<td>R. Smith (Horley) Ltd. (ERA/ Ministry of Power) Ets-Neyrpic (EdF)</td>
<td>100</td>
<td>18.5</td>
<td>15.2</td>
<td>3</td>
<td>75</td>
<td>P</td>
</tr>
<tr>
<td>1963</td>
<td>France</td>
<td>St. Rémy-des-Landes, (Manche)</td>
<td>(EdF)</td>
<td>1000</td>
<td>17.0</td>
<td>35.0</td>
<td>3</td>
<td>P(V above 650 kW)</td>
<td>I</td>
</tr>
<tr>
<td>1975</td>
<td>USA</td>
<td>Sedbury, Ohio</td>
<td>NASA Lewis Research Center</td>
<td>100</td>
<td>8.05</td>
<td>30.5</td>
<td>2</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>1977</td>
<td>USA</td>
<td>Clayton, New Mexico</td>
<td>NASA Lewis Research Center</td>
<td>200</td>
<td>8.05</td>
<td>38</td>
<td>2</td>
<td>4</td>
<td>V</td>
</tr>
<tr>
<td>1978</td>
<td>USA</td>
<td>Block Island, Rhode Island</td>
<td>NASA Lewis Research Center</td>
<td>2000</td>
<td>11.4</td>
<td>61</td>
<td>2</td>
<td>34.7</td>
<td>S</td>
</tr>
<tr>
<td>1980</td>
<td>Denmark</td>
<td>Nibe</td>
<td>DEFU/DOE</td>
<td>630</td>
<td>13</td>
<td>40</td>
<td>3</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>Under investigation</td>
<td>UK</td>
<td>Coast Hill of Scotland</td>
<td>British Aerospace Dynamic</td>
<td>3.9</td>
<td>22</td>
<td>60</td>
<td>2</td>
<td>34.1</td>
<td>P</td>
</tr>
</tbody>
</table>
Table I shows the use of synchronous and induction wind driven generators rated over 100 kW in different wind power plants (1931-1982) in constant and near constant speed operation respectively. Some kind of hydraulic pitch control is used to maintain a constant or near constant blade speed, and in turn (through the gear box), a constant or near constant generator speed to generate fixed frequency power to be fed into the network supply. Constant and near constant speed aeroturbines, in general, extract much less energy from a given wind regime (details are given in Chapter 3) at poor efficiency due to the mismatching between the turbine and the generator characteristics. Fig. 1.2 shows that this mismatch will increase with increased negative slips.

1.2. Generation with variable speed input and constant frequency output

Methods used or proposed to obtain constant frequency output from a variable speed shaft fall into two broad categories

A)

Mechanical techniques for constant speed and employing synchronous generators;

a) variable ratio gears

b) planetary gear systems

c) hydraulic pump-motor arrangements

Electrical techniques to obtain constant frequency use a frequency make-up generator (differential action by feeding slip frequency power to rotor).
Fig 1.2 Wind turbine and induction machine torque/speed characteristics
B) Non-differential methods

(i) static frequency changers

AC-DC-AC link\(^{20}\) (ADA) conversion

(ii) Rotary devices

a) AC commutator generators\(^{21}\)

b) field modulation and demodulation techniques\(^{22}\)

1) high frequency switching

2) low frequency switching

(field modulated generator system being
developed at Oklahoma State University)

c) amplitude modulated frequency changers

(square wave modulation; ac-ac converter)

d) cycloconverters and frequency changers\(^{23}\)

Figures (1.3) and (1.4) illustrate schemes to harness wind energy with and without the aid of a conventional utility grid. Non-differential methods are of major interest in the present work.

The concept in ADA conversion is to generate variable frequency a.c. from an alternator, convert to d.c., and then invert to constant frequency a.c. to tie with the utility system. Percy Thomas\(^{24}\) has suggested a variation to this approach using a d.c. generator coupled to a rotary converter.

In a brief summary of large WGS in the U.S., J.M. Savino\(^{25}\) has concluded that d.c. generators are limited in size and rotary converters are inefficient.

D.K. Reitan (ref.20) of the University of Wisconsin briefly described two asynchronous AC/DC/AC systems. The first system can use a
Fig. 1.3 Schemes to harness wind energy without the aid of a conventional utility grid

Fig. 1.4 Schemes to use wind energy as a supplementary energy force
variable or constant frequency alternator drive provided by wind power. The system generates variable frequency a.c., rectifies this with a frequency independent three-phase, two-way, six pulse bridge-rectifier operating with constant current control, using the constant current to drive a d.c. pumped storage system and a high-capacity 60 Hz bridge inverter.

The second system employs a similar rectification from a 60 Hz alternator. This system has no 60 Hz inverter linked to a power grid and it is thus meant to be a self-contained electrical supply.

The converter in the first system is expensive* and it has to be connected to a power grid as a supplementary system, while the second system has the option of mainly d.c. output with some sinusoidal 60 Hz and a small high frequency harmonic content 60 Hz from an 800 watt inverter.

Of the different schemes that have been summarised the only one of direct interest in the present work is the field modulated frequency down conversion system. In this system, an a.c. generator is excited by 60 Hz a.c. The output modulated sine wave is rectified, filtered and inverted to yield the necessary 60 Hz output. It is an interesting concept, but as a system it is complicated and costly. The need for a.c. excitation requires the machine to be completely laminated. The whole power output of the machine has to be demodulated by solid state techniques. Thus, the number of high power solid state devices used in a rectifier-inverter system (ADA) and in this system are comparable. This technique lacks the cost advantage of ADA which is also used in the HVDC transmission. Also, to keep a small modulating ratio, which is important, the frequency and hence the speed of operation is high.

A.R. Stocken with GEC Industrial Controls Ltd.\(^{26}\) has driven a

* by the Community of Wind Power Conversion Workshop\(^{18}\)
synchronous machine at high efficiency over a wide speed range with a
d.c. link of naturally commutated thyristors. The drive has undoubted
merit as a brushless system for applications not requiring rapid response.
The link system is reversible enabling motoring or regenerative operation
to be achieved. This drive was adopted as a starter to run the machine
up prior to synchronism. For wind energy transducers, the ability to
regenerate over a wide speed range and to self-start makes the system worth
considering in a wind power plant with a fixed pitch turbine which is not
self-starting. However, there are some disadvantages implicit as follows:

1) The generated power has to pass through the thyristors,
necessitating very high power devices,

2) Although the efficiency of the drive is high, the overall
system efficiency will be low due to the mismatching between the
constant torque/(speed) generator characteristics and the
wind turbine torque/(speed)^2 characteristics,

3) The complexity of the regulating system.

Kant and Perno\textsuperscript{27} have studied low- and medium-power devices in
wind energy conversion systems with an electromagnetic stabiliser.
This system requires storage batteries, but it will drive domestic
appliances. In reference 3, Schweickardt and Suchanek explain the basic
concept and the design of the use of converter-synchronous generator
systems for windmills. In their Swiqs system, the synchronous generator
runs at variable speed by means of field excitation control through a
brushless exciter with rotating diodes, a back-to-back thyristor a.c.
control element and an excitation transformer. The variable frequency
output is converted to the system frequency using a forced-commutating
d.c. link converter with a large choke and a further choke-capacitor
filter as a smoothing circuit. The system necessitates a power factor controller to enable satisfactory commutation to take place in the inverter. A microprocessor was adopted in the control structure given for a special wind power plant. Again, it can be seen that the system requires full power frequency conversion which is enough to constitute something of a disincentive. The use of bulky commutating chokes will add considerable cost and introduce long time constants to the system, possibly leading to stability problems.

An asynchronous generator, whose rotor is energized with alternating current via slip rings, permits operation at variable speeds. This basic, doubly-fed generator is described in reference 4 and was applied on the North German Plain. In this system, the frequency and the static voltage are held constant when the wind turbine is connected to the supply network. The speed of rotation and power output are regulated by controlling the blade pitch and a mechanical governor under extreme gust conditions, the generator deviates elastically in the sub-synchronous or hyper-synchronous modes of operation during fluctuations in the rotor speed until synchronous operation is re-established by an overriding speed regulator. The generator speed range is limited to the fundamental synchronous speed \( \pm 13.3\% \) by the harmonic content of the exciter which increases with slip. The practical limitation of the system is the inability of the converter to conduct the large rotor current surges occurring during gusting. This necessitates operating with a variable pitch turbine system to regulate the rotational speed and the power output in addition to the need for exciting capacitors and a swamp resistance to dump the excess energy by self-excited induction generation. The use of integral cycle blanking makes the cycloconverter operate with a discontinuous circulating current which makes the harmonic content of its output dependent on the output phase angle. The acceptable harmonic
content of the exciter output limits the output speed range, which is greatly reduced when compared with the link-inverter system.

At Leicester University two solutions have been suggested for large wind power generation at constant frequency from a variable shaft using low- and medium-power devices. These are both directly coupled to the grid using a similar slip-ring induction machine operating in the following ways:

1) variable-speed slip-energy recovery generator, and
2) a variable speed doubly-fed machine excited by a cycloconverter, operating as a generator.

The slip-energy recovery system is adapted from the Kramer or Scherbius drive with the main slip-ring machine operating as a generator. The a.c. commutator frequency converter has been replaced by a solid-state d.c. link inverter. An alternative to the d.c. link inverter is a cycloconverter for a 3-phase frequency conversion where the frequency ratio $> 3$.

Smith (ref.29) has shown that the cycloconverter slip power recovery scheme as a rotating drive can be attractive for pumping and ventilating applications where considerable mass-flow change can be achieved with a limited speed range above and below synchronous speed.

The d.c. link inverter technique of controlling the speed of a slip-ring induction machine has been described and analysed in many papers. However the conventional d.c. link inverter is quite complex requiring sophisticated commutation circuitry which can result in catastrophic failure in the event of a momentary supply failure.

An alternative much simpler and more reliable inverter is the current source inverter (Fig.1.5a) which can be used as a variable frequency source to the slip-ring induction motor.
Fig. 1.5a Current source inverter

3 phase supply

Windmill

Gearbox

Slip-ring induction generator

Secondary EMF signal generator

Inverter sequence control

Current-fed inverter of Fig. 1.5a

Fully controlled converter

Fig. 1.5b Current source inverter Scherbius system

supply

Cycloconverter for control system

Control signal

Secondary EMF signal generator

Windmill

Slip-ring induction generator

Fig. 1.6 Cycloconverter for DFM system
Wind energy recovery using a current source inverter-slip-ring induction generator is currently under investigation by Smith and Nigim (ref.32). Variable-speed operation using a doubly-fed generator excited by a cycloconverter\(^33\) rather than an inverter has been adopted for the following reasons:

(i) The current source inverter Scherbius system (Fig.1.5b) requires forced commutation dependent on the slip frequency. A rapid acceleration demand due to a sudden gust may cause commutation failure and shut down. The start-up procedure must be repeated when the wind gust is over. The cycloconverter in the DFM system (Fig.1.6) is naturally commutated and it will conduct only when the reference signal is applied. It can remain permanently connected to the supply. Under wind gust conditions, zero reference voltage may be applied and a mechanical brake used to stop the system.

(ii) Line to line short circuit failure is impossible in the present cycloconverter system because the thyristor groups of opposite polarity are electrically separate.

(iii) The current source inverter is more complicated and expensive than a cycloconverter due to the large commutation capacitors and costly d.c. link choke, which introduces a large d.c. link time constant to the system with consequent instability if sudden large speed increases are demanded\(^34\).

(iv) The rectangular current-waveform of the current source Scherbius needs to be filtered to remove higher frequency harmonics. For large powers the filter is both bulky and costly. It has, however, a virtually unlimited output frequency range.
If the control frequency range can be limited to about a third of the grid frequency, the ideal controller is the cycloconverter, having the following advantages:

(i) In its basic form the cycloconverter will conduct power from or to the source at leading or lagging phase angles through the same set of thyristors.

(ii) Ease of control. The cycloconverter requires only one control signal, which is called the modulating signal. The output amplitude and frequency may be controlled directly and independently by the amplitude and frequency of the modulating signal. Ideally, the cycloconverter acts as a high power amplifier.

(iii) Natural commutation. An external commutation supply is not required. Commutation losses are slight and conversion efficiency can be as high as 98%.

(iv) The envelope of the output waveform of the cycloconverter will be approximately sinusoidal. This obviates the use of filters and reduces the harmonic generation in the output.

For these reasons a doubly-fed machine excited by a cycloconverter has been employed in this work to act as a wind energy transducer.

1.3. Conclusion

A survey of existing experience and practice has been carried out. This has shown that variable-speed wind-turbine operation is possible with both synchronous and induction generators. The synchronous generator is essentially a constant speed machine when synchronised to the utility grid. This involves energy control by blade furling and excitation
control. It also requires external pony motor starting.

Viable variable-speed, grid coupled synchronous machine systems are possible if the generated power can be converted to mains frequency. This involves a d.c. link inverter interfaced between the grid and the generator. The solid state devices of the inverter must be rated at the power of the generator output. Forced commutation involving large capacitors is necessary. Any momentary disconnection from the grid will cause commutation failure with all the associated problems of re-synchronisation. Moreover, the link inverter, even if operating with pulse-width-modulation, essentially produces rectangular blocks of current. This inverter output requires considerable filtering and the associated chokes and capacitors slow down the response of the system. The d.c. link choke produces a dominant slow time response overriding the mechanical time constants. A field modulating system can solve the problems of time constant. This is achieved by generating power in a multi-polar generator at 960 Hz and feeding this to the grid through a link inverter. The other inherent disadvantages are still present.

Induction generator systems solve the problem of self-starting and generator power directly into the grid. They are, however, essentially small negative-slip, near constant speed systems requiring blade furling control.

The preferred system will be a form of slip-energy recovery system or a doubly-fed, variable synchronous speed system. Slip energy recovery generators based on the Kramer and Scherbius principle are efficient and economic in the use of semiconductor devices. However, they still have the inherent disadvantage of the d.c. link inverter, with its associated large time-constant and filter requirements if the injection of unacceptable harmonics into the supply is to be avoided. Problems of re-synchronisation after disconnection are severe and may
require stopping the system and subsequent restarting.

Clearly, a cycloconverter excited, doubly-fed system is to be preferred to overcome the remaining problems. However, if a conventional circulating-current-free cycloconverter is used, wind surges may introduce line-to-line short-circuits in the converter. This necessitates isolating from the grid, power dumping into resistors by self-excited induction generation and resynchronisation after the gust. Also the acceptable harmonic content of the cycloconverter restricts the speed range and requires speed regulation by blade pitch control system.

The work described in this thesis is based on the use of a cycloconverter operating with continuous circulating current, maintained by a divided stator winding of the generator. Most of the operating problems previously described have been systematically overcome. The following chapters describe this in detail.
Chapter 2

The doubly fed machine as a wind energy transducer

2.0 Introduction to the theoretical analysis and the physical action

There are two accepted methods of analysing the doubly-fed machine, both based on motor operation. The first is a damping torque technique developed by Prescott and Raju\textsuperscript{35}.

The second uses generalised electrical machine theory and the tensor techniques of Kron\textsuperscript{36,37,38}. Tensor methods of analysis can be conveniently handled by conventional digital computer subroutines. They require limited algebra, and can be extended to yield stability data by means of eigenvalues and root locus techniques similar to those used by Rogers\textsuperscript{39}. A stability analysis using this technique has been produced\textsuperscript{40} for a doubly-fed motor. In the present work, the analysis is extended to steady state variable speed operation both as a motor and a generator. The doubly-fed machine in this work operates as a generator at sub- and super-synchronous speeds. Generator operation differs from motor operation in that the motor operates from an infinite grid which offers a low impedance to the machine, while the wind turbine and inertia are a finite, high impedance source. Second order instability problems associated with the motor do not affect the generator performance. The present work, to the author's knowledge, is the first complete attempt at doubly-fed generator analysis.

The doubly-fed generator operates both synchronously and inductively. Separate stator and rotor supplies, one of which may vary in frequency and amplitude produce rotating fields in the air gap. The two fields will be stationary in space relative to one another and their interaction will generate a power dependent on the relative displacement angle between
the two fields, known as the flux or load angle. A load angle dependent synchronous power component will be produced.

Although the two fields are stationary relative to each other, they are moving with respect to each winding. Two induction power components will be generated, one due to the primary supply and the other due to the secondary supply. If the frequencies and the sequence of the two supplies are the same the resultant field is stationary. If one of the supplies changes in frequency with either the same or a reversed sequence, the machine speed will follow the change. When the two frequencies are the same and of opposite sequence, double speed operation results.

2.1. Steady state performance of the doubly-fed machine operating as a generator

Variable-speed double-fed generation can be achieved with one variable frequency, \( f_2 \), of either positive or negative sequence and a fixed frequency \( f_1 \). These two separate three phase supplies combine magnetically to produce a field in the air gap, rotating at the sum or the difference of the two frequencies. The speed of the generator must be constrained to be

\[
n = \frac{60}{P} (f_1 + |f_2|) \text{ rev/min}
\]

where \( P \) is the number of pole pairs and the negative values of \( f_2 \) are regarded as a reversed phase sequence.

Fig.(2.1) illustrates the doubly-fed machine excited by a cycloconverter as used in the present system. The machine parameters and the cycloconverter details are given in Appendix A1. Divided secondary windings are used for harmonic elimination and fault prevention. The function of the divided winding is given in Chapter 6.
Fig. 2.1  Doubly-fed generator schematic
The following assumptions have been made in the analysis;

(i) There is no saturation and machine operation is in the linear range.

(ii) Accelerations are small and their effect upon currents and voltages in the machine are negligible. Therefore the machine is analysed at constant speed.

(iii) Hysteresis, eddy current and tooth pulsation losses\(^{41}\), i.e. all internal losses are neglected.

(iv) The machine is of round rotor construction with distributed phase windings and a uniform air gap. This means that the magnetizing currents are spatially independent and justifies the analysis.

(v) Harmonics of space and time are neglected.

Fig.(2.2) represents the equivalent circuit for one phase of the doubly-fed machine, where \( v_2 \) is the injected voltage always at a frequency equal to the slip frequency of \( v_1 \). The machine may be represented in quadrature \( d-q \) axes with the primary winding on the rotor as shown in Fig.(2.3). From Figs.(2.2) and (2.3), the equations describing a symmetrical induction machine in synchronous rotating reference axes are expressed thus;

\[
\begin{bmatrix}
    v_{d1} \\
    v_{q1} \\
    v_{d2} \\
    v_{q2}
\end{bmatrix} =
\begin{bmatrix}
    r_1 + L_1 P & -\omega_1 L_1 & M_p & -\omega_1 M \\
    \omega_1 L_1 & r_1 + L_1 P & \omega_1 M & M_p \\
    M_p & -s\omega_1 M & r_2 + L_2 P & -s\omega_1 L_2 \\
    s\omega_1 M & M_p & s\omega_1 L_2 & r_2 + L_2 P
\end{bmatrix}
\begin{bmatrix}
    i_{d1} \\
    i_{q1} \\
    i_{d2} \\
    i_{q2}
\end{bmatrix}
\]

(2.1)

where \( p \) is the derivative operator and \( s \) is the slip defined as
Fig. 2.2 D.F.M. Equivalent circuit/phase

Fig. 2.3 Schematic diagram of a doubly fed machine with the primary winding on the rotor

$L_p =$ Primary leakage inductance  
$L_s =$ Secondary leakage inductance
\[ s = \frac{\omega_1 - \omega_2}{\omega_1} \] (2.2)

L₁ and L₂ are the per phase total cyclic inductance of the primary and the secondary respectively. r₁ and r₂ are the per phase primary and secondary resistance and M is the mutual inductance between the primary and secondary windings. The primary frequency, \( \omega_1 \), is assumed constant at 100 rad/s, and the secondary excitation frequency, \( \omega_2 \) varies with slip.

To obtain the actual primary and secondary excitation terms, consider first that the secondary winding is initially displaced by leading or lagging phase shift, \( \alpha \), as shown in Figs.2.4a and 2.4b. The voltages on the three axes can then be expressed as

\[
\begin{align*}
V_{b1} &= \sqrt{2} \cos(\omega_1 t - \frac{2\pi}{3}) \\
V_{c1} &= \cos(\omega_1 t + \frac{2\pi}{3})
\end{align*}
\]

and

\[
\begin{align*}
V_{b2} &= \sqrt{2} \cos(\omega_2 t + \alpha - \frac{2\pi}{3}) \\
V_{c2} &= \cos(\omega_2 t + \alpha + \frac{2\pi}{3})
\end{align*}
\]

The suffixes 1 and 2 in the voltage terms correspond to the magnetic axis of the primary and the secondary, respectively.

The transformation co-ordinate system, defined in Appendix A2, results in the following expressions for the d and q voltages:

\[
\begin{align*}
V_{d1} &= \sqrt{3} \cos \alpha \\
V_{q1} &= -\sin \alpha
\end{align*}
\]

and

\[
\begin{align*}
V_{d2} &= \sqrt{3} \cos \alpha \\
V_{q2} &= -\sin \alpha
\end{align*}
\]
**Fig. 2.4a** The doubly fed machine with the same primary and secondary phase sequence (α is +ve).

**Fig. 2.4b** The doubly fed machine with the same primary and secondary phase sequence (α is -ve).
Equation (2.1) gives the quadrature current components (Appendix A2).

These are:

\[ i_{d1} = \frac{\sqrt{3}}{D(s)} (v_1 A_1 + v_2 (A_3 \cos \alpha - A_4 \sin \alpha)), \]  

(2.7)

and

\[ i_{q1} = -\frac{\sqrt{3}}{D(s)} (A_2 v_1 + v_2 (A_4 \cos \alpha + A_3 \sin \alpha)) \]  

(2.8)

The primary current \( i_1 \) is

\[ i_1 = i_{d1} + j i_{q1}, \]

and

\[ |i_1|^2 = \frac{\sqrt{3}}{D(s)} ((A_1^2 + A_2^2) v_1^2 + (A_3^2 + A_4^2) v_2^2 + 2v_1 v_2 [(A_1 A_3 + A_2 A_4) \cos \alpha + (A_2 A_3 - A_1 A_4) \sin \alpha])^{\frac{1}{2}} \]  

(2.9)

Similarly, the quadrature secondary current components are,

\[ i_{d2} = \frac{\sqrt{3}}{D(s)} (A_5 v_1 + v_2 (A_7 \cos \alpha - A_8 \sin \alpha)) \]  

(2.10)

and

\[ i_{q2} = -\frac{\sqrt{3}}{D(s)} (A_6 v_1 + v_2 (A_8 \cos \alpha + A_7 \sin \alpha)) \]  

(2.11)

The secondary current,

\[ i_2 = i_{d2} + j i_{q2}, \]

and

\[ |i_2|^2 = \frac{\sqrt{3}}{D(s)} ((A_5^2 + A_6^2) v_1^2 + (A_7^2 + A_8^2) v_2^2 + 2v_1 v_2 [(A_5 A_7 + A_6 A_8) \cos \alpha + (A_6 A_7 - A_5 A_8) \sin \alpha])^{\frac{1}{2}} \]  

(2.12)

where \( D(s), A_1, A_2, A_3, A_4, A_5, A_6, A_7 \), and \( A_8 \) are defined in Appendix A2.

By inverting (2.1), the steady state torque can be derived in terms of the actual terminal voltages as

\[ T_e = PM (i_{q1} i_{d2} - i_{d1}^2 + i_{q2}^2) \]  

(2.13)

where \( P \) = the number of pole pairs, and \( M \) is the mutual inductance.

Substituting in Equation (2.13) from (2.7), (2.8), (2.10) and (2.11)

yields to,

\[ T_e = K(s)[s^2 r_2 \nu_1^2 - r_1 \nu_2^2 + \nu_1 \nu_2 \left\{ [(r_1 r_2 + s x_1 x_2 - x_m^2)] \sin \alpha - (s x_2 r_1 - r_2 x_1) \cos \alpha \right\}] \]

(2.14)
\[ D(s) = \left( r_1 r_2 - s(x_1 x_2 - x_m^2) \right)^2 + \left( r_2 x_1 + s r_1 x_2 \right)^2, \]

and
\[ K(s) = \frac{3P_x}{\omega_1 D(s)}, \quad x_1 = \omega_1 L_1, \quad x_2 = \omega_1 L_2 \text{ and } x_m = \omega_1 M. \]

Equation (2.14) represents the total developed torque in the doubly-fed machine. This may be expressed in synchronous and induction torque components as,
\[ T_e = T_{I1} + T_{I2} + T_s \]

where \( T_{I1} \) and \( T_{I2} \) are induction torque components dependent on slip, but independent of load angle and \( T_s \) is the synchronous torque dependent on the load angle.

\[ T_{I1} = K(s)sr_1^2, \quad (2.15) \]
\[ T_{I2} = -K(s)r_1^2, \quad (2.16) \]

and
\[ T_s = \frac{K(s)}{x_m} v_1 v_2 \left( [r_1 r_2 + s(x_1 x_2 - x_m^2)] \sin \alpha - [sx_2 r_1 - r_2 x_1 \cos \alpha] \right) \quad (2.17) \]

The developed power is then,
\[ \omega T_e = \omega K(s)[sr_2 v_1^2 - r_1 v_2^2 - \frac{v_1 v_2}{x_m} (r_1 r_2 + s(x_1 x_2 - x_m^2)) \sin \alpha - \]
\[ [(sx_2 r_1 - r_2 x_1 \cos \alpha)]] \quad (2.18) \]
\[ = P_{I1} + P_{I2} + P_s, \quad \text{where } P_{I1} = \omega K(s)sr_2 v_1^2, \text{ and } P_{I2} = -\omega K(s)r_1 v_2^2, \]

are two induction power components, one due to the primary supply has a
positive slip when \( \omega_1 > \omega \) and a negative slip when \( \omega_1 < \omega \); while the other due to the secondary supply always has a negative slip and generates into the supply.

\[
P_g = \frac{\omega K(s)v_1v_2}{x_m} \left[ r_1r_2+s(x_1x_2-x^2) \sin \alpha - [(sx_2r_1-r_2x_1) \cos \alpha] \right]^{2}
\]

is the synchronous power which makes up the total generated power equal to the loading power.

2.2. The effect of the load angle on the machine characteristics

Equations (2.9), (2.12) and (2.18) show that the primary and secondary currents are load angle dependent as well as the total developed power. The operation of the machine is treated as the result of the superposition (ref.35) of two hypothetical conditions of operation, one with the primary supplied and the secondary short-circuited, the other with the secondary supplied and the primary short circuited. Each of the primary and the secondary currents is the sum of two components due to the two supplies. So if the load angle between the two magnetic axes is \( \alpha \), then the variable supply phase shift angle is \( \theta \) where \( \theta = -\alpha + \delta_1 - \delta_2 \) where \( \delta_2 \) is negative as shown in the phase diagram of Fig.(2.5).

To show the effect of the load angle on the total internal e.m.f. of the doubly-fed machine, the phasor diagram of Fig.(2.6) has been developed as follows;

\[ v_2 \] is the injected voltage lagging \( v_1 \) by \( \theta \)

The resultant primary and secondary current phase shift angles behind \( v_1 \) are \( \phi_1 \) and \( \phi_2 + \theta \) (taking \( v_1 \) as the reference). When synchronised the net magnetizing reactance is frequency corrected, and the magnetizing current \( I_\phi \) will be \( I_\phi = I_1 + I_2 \). The angles between the
magnetizing current $I_\phi$ and the primary current $I_1$, and the secondary current $I_2$, respectively are $\delta_1$ and $\delta_2$.

Fig. 2.6 shows the time phasor diagram. The analysis begins with the assumption of a value for the constant frequency supply voltage at a reference phase angle of zero degrees. A known space angle, $\alpha$, exists between the primary and secondary MMF's. Therefore the net air gap MMF in terms of an equivalent current, $I_\phi$, can be found by summing the time phasors of currents which correspond to primary and secondary MMF's. For the primary the appropriate phasor is $I_1[\phi_1]$. For the secondary, since the primary winding (phase a for example) MMF at $t = 0$ is $\alpha$ electrical degrees in space in advance of the secondary winding (the primary is driven by the turbine in this case), the correctly referred secondary current must lag the primary current by $\alpha$. Therefore the appropriate secondary phasor is $I_2[\alpha+\phi_1]$

The internally generated EMF time phasor is found by multiplying the net magnetizing current $I_\phi$ by the frequency corrected magnetizing reactance, including a time phase shift of $90^\circ$ (representing the ideal machine). Its magnitude will be the sum of the phasor of $E_1$ and $E_2$.

As an induction machine, the torque angles are $\delta_1$ and $\delta_2$ in a primary fed and secondary short circuited system, and in a secondary fed and primary short circuited system, respectively. Hence,

\[
\begin{align*}
E_1V_1 &= \delta_1 \\
E_2V_2 &= -\delta_2 \\
E_1E_2 &= \alpha
\end{align*}
\]

From the phasor diagram,

\[
\begin{align*}
E_2V_1 &= \delta_1 - \alpha \\
V_1V_2 &= \theta = \delta_1 - \delta_2 - \alpha
\end{align*}
\]

as shown in the phasor diagram, Fig. 2.5.

If the two supply voltages are in phase ($\theta = 0$), $\alpha = \delta_2 - \delta_1$ as given by...
Fig. 2.5 Phasor diagram

Fig. 2.6 Time phasor diagram of DFM
Phillips (ref. 22). In the case of a d.c. excited synchronous machine, there is no coupling of $E_2$ with the secondary as $\delta_2 = \frac{\pi}{2}$. In this case

$$a = \frac{\pi}{2} - \delta_1$$

It can be seen from equation (2.17) that the synchronous torque $T_s$ is slip dependent and it can be divided into two components; these are

$$T_{s1} = -\frac{K(s)}{x_m} v_1 v_2 (r_1 r_2 + s(x_1 x_2 - x_1^2)) \sin a,$$

and

$$T_{s2} = \frac{K(s)}{x_m} v_1 v_2 (s x_1 x_2 - r_2 x_2) \cos a.$$

When the machine operates as a doubly-fed machine with a retarded rotor (i.e. negative load angle), the resultant synchronous torque may be either a generating torque or a motoring torque depending on the load angle value, the machine parameters and the operating range defining the slip $s$. However in both cases of either generating or motoring torque, the dynamic behaviour of the machine will be inherently unstable. This is because the synchronous torque component $T_{s2}$ will always be a generating (negative) component, even in sub-synchronous operation because $r_2 x_1 > s x_2 r_1$. With the exception of the standstill condition, motoring operation can be achieved only at very large load angles where $\cos a = 0$. This is because, $T_{s2} > T_{s1}$ in large machines where the reactances are much higher than the resistances in ohmic values.

At very large load angle values (near to $-\frac{\pi}{2}$), the output synchronous torque may be motoring with a very large damping coefficient

$$(s x_2 r_1 - r_2 x_1)$$

in this case, is equal to $\frac{K(s)}{x_m} (r_1 r_2 + s(x_1 x_2 - x_1^2))$. This causes an inherent instability in motoring operation. At low negative load angle values (near to 0), the output synchronous torque is a generating torque with a damping coefficient of $\frac{K(s)}{x_m} (r_1 r_2 + s(x_1 x_2 - x_1^2))$. The specific value of the negative load angle defines the motoring and generating synchronous torque is,

$$\alpha_s = \tan^{-1} \left( \frac{s x_1 x_2 - r_2 x_2}{s(x_1 x_2 - x_1^2 - r_1 r_2)} \right).$$
when $\alpha < \alpha_s$, $T_s$ is a generating torque and when $\alpha > \alpha_s$, $T_s$ is a motoring torque. Operation at a load angle as near to $-\frac{\pi}{2}$ as possible in a motoring system will greatly increase the machine stability. However another large negative induction torque will be produced at negative slips due to the component, $T_{I_1}$ of equation 2.14.

Induction torques in doubly-fed machine operation can be minimised when constant current excitation is used instead of the voltage source. This is discussed later in the chapter.

Stabilised motoring operation under voltage source excitation can only be achieved when,

1. The load angle is controlled and constrained to be near to its peak value.
2. The damping coefficient $\frac{[sx_2 r_1 - r_2 x_1]}{[r_1 r_2 + s(x_1 x_2 - x_m^2)]}$ of the synchronizing torque is minimised.
3. The induction currents of the voltage excitation system are minimised.

When the rotor leads the stator, i.e. the load angle is positive, the two synchronous torque components $T_{S_1}$ and $T_{S_2}$ are unidirectional. This increases the generating torque and stabilises the machine. A full stability analysis of the doubly-fed machine in a wind power conversion system is assessed in Chapter 6.
A digital computer program (given in the computation appendix) has been developed to calculate the machine performance with a series of constant load angles and a constant excitation voltage. This shows how much the machine characteristics can be affected by load angle variation. Fig.(2.7) and Fig.(2.8) show typical computed curves of primary and secondary current against speed at different values of $\alpha$ in the four-pole DFM at constant voltages, $v_2 = 20$ V and $v_1 = 62$ V. It can be seen that in synchronous operation, the DFM has "V" curve characteristics similar to those of a synchronous machine with D.C. excitation. Fig.(2.9) shows that load angle control can force the machine to generate power over a slip range of $1 < s < -1$ with constant excitation; and that the total generated power increases with $\cos \alpha$ and decreases with $\alpha$.

Fig.(2.10) shows a comparison between experimental and computed powers for the four-pole experimental machine (see Al). The secondary current was adjusted to correspond to the computed current as shown in Fig.(2.11) at each speed and the load angle was kept constant at a value to give maximum synchronous power (pull out power) at each speed. The machine rating has been reached at 1875 rev/min. The generated power returned to the supply by the cycloconverter represents about 25% of the total generated power as shown in the experimental power flow chart of Fig.(2.12), which also indicates the power factor at which the power is generated in the primary and secondary.

2.3. The required output characteristics of the DFM as a wind power transducer

A wind energy transducer interfaced between a wind turbine and the grid must respond to the random variation of wind speed approximately over a 7 to 1 speed range. For maximum wind power extraction it must also be capable of feeding an electrical power proportional to the
Computed V curves of primary and secondary current at constant excitation voltage and series of constant load angle, $\alpha$. 

(Fig. 2.7) 

$\alpha = 0$ 

$\alpha = 90^\circ$ 

(Fig. 2.8) 

$I_1$, A 

$I_2$, A 

Speed rev/min 

Speed rev/min
Fig. 2.9 Computed power/speed at excitation voltage $V_2$ of 20V for a series of constant load angles, $\alpha$. 
Open-loop DFM characteristics at maximum pull out load angle and the secondary current of Fig. 2.11

Fig. 2.11  Secondary current/speed
The total power

Power to the mains through the slip rings

Power to the mains through the cycloconverter

The secondary power factor

The primary power factor

---

Fig. 2.12 Experimental power flow. (primary voltage = 62 volt)
cube of the wind speed into the grid. A mechanical gear box with a number of gear ratios is a conventional solution. Electrical switching to change the number of poles effectively makes the machine an "electrical" gear box. However, this is difficult to achieve in a slip-ring machine. If six slip rings are permitted, a Dahlander winding can be used, but it is hardly an economic solution. If the doubly-fed generator can be controlled to follow the optimum turbine operation (given in Chapter 3) an operating speed range limited by $0.2 > s > -0.3$ will be good enough to enable a fixed gear ratio to be used.

2.4. **A cycloconverter-excited cube law system**

The aim of this work is to produce an efficient wind power generator, directly coupled to the grid. A doubly-fed generator operating as a wind power transducer aims;

a) to generate constant frequency power from the variable speed wind turbine rotor (VSCF),

b) to control this power to match the turbine characteristics, transmitting power proportional to the cube of the wind speed into the grid,

c) to achieve power conversion at its maximum efficiency,

d) to produce an economic system eliminating the need to optimise the blade angle of the turbine, and
2.13

e) to improve safety and availability of the wind power plant.

The present system as shown in Fig.(2.1) consists of a doubly-fed machine excited by a half-wave cycloconverter. With twice as many devices, a full-wave cycloconverter may be used and thus the star delta transformer can be eliminated. The cycloconverter output frequency is controlled by velocity feedback to maintain the angular velocity relationship,

\[ \omega = \omega_1 - \omega_2 \]

The shape of the doubly-fed machine output characteristic is determined by the amplitude and frequency of the cycloconverter excitation. Control of the reference signal enables the cycloconverter output voltage and form-factor to be modified. Many commercial cycloconverters use integral cycle blanking to prevent the simultaneous conduction of positive and negative thyristor groups. This makes the harmonic content of the output dependent on the output phase angle. The output harmonic content of the cycloconverter can be greatly reduced if the cycloconverter can be maintained in continuous conduction (details are given in Chapter 4).

Three methods of obtaining efficient generation over a wide speed range are considered. In each case the secondary frequency is controlled by velocity feedback to maintain synchronism. A full analysis of each case with experimental verification follows. These methods are:
1) Artificial modification of the induction power by means of,
   (i) electronic modification of the variable-frequency exciting current form factor,
   (ii) electrical modification of the secondary ampere turns.

2) Control of synchronous power, by means of
   (i) load angle control, with constant exciting voltage,
   (ii) load angle control by a voltage-speed exciting function at unity secondary power factor, and

3) Near elimination of induction power by means of constant current excitation.

2.4.1 Induction power modification

(i) The electronic modification of the variable frequency exciting current form factor

It has been shown in Fig.(2.7) and (2.8) that, in synchronous operation, the doubly-fed machine has "V" curve characteristics similar to those of a synchronous machine with d.c. excitation. The excitation ratio of a synchronous machine may be defined as the ratio of primary e.m.f. to primary applied voltage. In a doubly-fed machine, this ratio must be modified to

\[ s = \frac{v_2}{v_1} \cdot \frac{\omega_1}{\omega_2} \cdot N \]  

(2.20)

where \( N \) is the transformation ratio of the primary and secondary windings.

Figs.(2.13) and (2.14) show the effect of varying the excitation ratio under no-load conditions. Two fixed-frequency cycloconverter output conditions are illustrated. The phase rotation is opposed giving super synchronous operation in each case. Economic operation of the cycloconverter requires a current servo demanding minimum cycloconverter
Fig. 2.13 Running light stator current "V" curves.

Fig. 2.14 Running light rotor current (curves).
(secondary) current which may be obtained by the control of the excitation ratio.

The primary current (50 Hz) can also be minimised by control of the excitation ratio, but the primary and secondary current minima occur at different excitation ratios. A preferred operating condition of minimum secondary current was adopted.

The measured results of Fig.(2.10) were obtained when the DFM was driven by a d.c. motor. For wind power conversion investigations, a prime mover simulating a windmill was necessary to drive the doubly-fed generator. This prime mover was a separately excited d.c. motor supplied through an electronic d.c. current source programmed to supply a current proportional to the square of the motor speed. In this way a source of power proportional to the cube of the speed corresponding to a wind turbine characteristic was provided.

Fig.(2.15) shows measured and computed results of the doubly-fed generator when driven by the simulated windmill. These results were obtained with no additional secondary resistance and an excitation ratio of unity. $T_s$, the synchronous torque, makes up the difference between the total induction torque and the applied torque. As shown in Fig.(2.15) the synchronous torque component changes from a generating torque to a motoring torque, and back again over the operating speed range. Motoring synchronous torque reduces efficiency and introduces instability. Clearly all synchronous torques should be generating torques and to achieve this the induction torque must be reduced.

If the secondary resistance is increased, the peak induction torque will occur at a higher slip. Fig.(2.16) shows the effect of doubling the secondary resistance. The synchronous torque is always generating but additional losses will occur in the added resistance. It is impractical to physically add secondary resistance, and in the experimental system the effect of adding rotor resistance was achieved by modifying the
Fig. 2.15 Doubly fed generator torques/speed at minimum secondary resistance
Fig. 2.16  Doubly-fed generator torques/speed at twice minimum secondary resistance.
cycloconverter reference signal, and hence the thyristor group voltage envelopes to the form shown in Fig.(2.17). The exciting voltage then approximates to a series of caps of sine waves of alternate polarity. The ratio of r.m.s. current to r.m.s. net driving e.m.f. (i.e. secondary induced e.m.f., $E_2$ minus secondary supply voltage) can be changed by control of the conducting angle $2\gamma$, and the r.m.s./mean current ratio in the secondary changed. The relationship between the r.m.s. secondary current and the peak secondary current with full conduction will be similar but only very approximately so since the actual current waveform is likely to differ considerably from that indicated in Fig.(2.17) due to secondary inductance etc. However, first order predictions can be made assuming identical waveforms. In this case, the r.m.s. value of the shaded portion shown in Fig.(2.17) in terms of $A$ and $\gamma$ as defined there is given by

$$ (I_{rms})^2 = \frac{A^2}{2\gamma} [\gamma - \frac{3}{2} \sin 2\gamma + 2\gamma \cos^2 \gamma]$$

(2.21)

A table of approximate secondary resistance values obtained using equation (2.21) is given also in Fig.(2.17).

Fig.(2.18) shows the peak of "pull-out" power generated over the speed range. Three operating conditions are shown. In condition A, the excitation ratio is increasing linearly from 1.0 p.u. just above 1500 rev/min. to 1.5 p.u. at 2000 rev/min. A further increase in generated output power related to speed may be produced by increasing the excitation ratio and the near required cube-law generated power/speed characteristic results.

This near required cube-law characteristic increases the secondary current through the cycloconverter due to the induction generating torques at high speeds. Fig.(2.19) shows the cycloconverter current rising to 2.0 p.u. at 2100 rev/min.
Fig 2.17 Thyristor group voltage envelopes.
A; Linear increase of excitation ratio (1.0 at 1520 rev/min to 1.5 at 2000 rev/min)
B; Constant unit excitation ratio
C; Secondary current clamped 1.0 p.u.

\[ R_2 = 4.0 \text{ p.u.} \]

---

**Fig. 2.18** Peak power/speed

**Fig. 2.19** Current for peak power/speed

1 P.U. = 5 A

\[ \text{Power} \quad \text{kw} \]

---

Wind power characteristic

---

Primary

Secondary
The secondary current may be reduced by maintaining the excitation ratio constant. Condition B in Fig.(2.18) shows that the maximum cycloconverter current is 1.5 p.u. at 2000 rev/min.

Condition C shows the range of operation with the cycloconverter output current electronically clamped to 1.0 p.u. This allows a range of operation up to 2100 rev/min. before the mechanical power exceeds the electrical generating capacity. In this mode of operation, the induction power is greatly reduced, and synchronous generation at the trough of the "V" characteristic is maintained.

Fig.(2.20) shows estimates of system efficiency based on calculated gross output power when calculated copper losses and measured iron and mechanical losses are subtracted. Copper losses have been computed at each operating condition, consisting of $|i_1|^2r_1 + |i_2|^2r_2$ due to the primary and secondary current respectively. Estimates of iron and mechanical losses were made by measuring the primary and secondary power when the measured torque is zero and the speed of rotation provided by the prime mover is $(\omega_1+\omega_2)/P$ rad/sec.

(ii) Ampere turn reduction by using $\frac{2}{3}$ of the secondary winding

Secondary form factor modification moves the primary induction power peak to a higher negative slip by means of reducing the r.m.s. of the secondary current (or effectively increasing the secondary resistance) as shown in equation (2.21). However, this movement of the induction power peak occurs at the expense of increased excitation harmonics, increased copper losses and consequently reduced efficiency.

A reduction of secondary ampere-turns can achieve the required peak shift while sinusoidal excitation is maintained. This ampere turn reduction has the same effect as the increase of effective secondary
Fig 2.20 Efficiency – Power generated kW

A; Linear increase of excitation ratio 1.0 at 1520 rev/min to 1.5 at 2000 rev/min
B; Constant unit excitation ratio
C; Secondary current clamped 1.0 p.u.
   \( R_2 = 4.0 \text{ p.u.} \)
2.18

resistance. Fig.(2.21(a)) and (b) show the magnetically-coupled primary and secondary phase coils $N_1,N_2$ and their equivalent circuit. Assuming the transformation ratio $N$ to be equal to the turns ratio of the two coupled coils, $N=N_1/N_2$. In a purpose built experimental machine each secondary phase may be designed to have a reduced number of conductors per pole per phase. However, in the laboratory experimental machine, there are three coils/pole/phase. The only practical reduction of turn numbers is the removal of one coil from the set, leaving two-thirds of the winding to form the secondary. This has the same effect as making the air gaps larger and allows higher synchronous power to be generated with less induction power at each speed.

Consequently the machine parameters and the primary induction power may be modified as follows.

The secondary resistance $r_2\left|_{2/3} = \frac{2}{3} r_2 \right.$, \hspace{1cm} (2.22)

where $r_2$ is the original value of the secondary resistance.

The inductance of the coil $N_2$ is

$$ L = \frac{N_2^2}{S} \text{ H} $$

where $N_2$ is the number of turns/coil and $S$ is the reluctance of the associated magnetic circuit. Hence

$$ L_2\left|_{2/3} = \left[\frac{2}{3} N_2 \right]^2 / \frac{2}{3} S = \frac{2}{3} L_2 \right.$$ \hspace{1cm} (2.23)

where $L_2$ is the original value of the secondary inductance.

The turns ratio is

$$ N = \frac{N_1}{N_2} $$

and so the new effective turns ratio,
\[ N_{2/3} = \frac{N_1}{\frac{2}{3} N_2} = \frac{3}{2} N \quad , \]

where \( N \) is the original turns ratio.

The flux \( \phi \) cutting each conductor will be the same as that of full winding, where

\[ \phi = \frac{Ni}{S} \]

and for the 2/3 winding,

\[ \phi_{2/3} = \left( \frac{2}{3} N_2 \right) / \left( \frac{2}{3} S \right) = \phi_{2} \quad \text{Wb} \quad (2.25) \]

The induced e.m.f.

\[ e_2 = N_2 \frac{d\phi}{dt} \]

and for the 2/3 winding,

\[ e_{2/3} = \frac{2}{3} N_2 \frac{d\phi}{dt} = \frac{2}{3} e_2 \quad (2.26) \]

The mutual flux \( \phi_m \) linking all turns of both primary and secondary winding is given by

\[ \phi_m = \frac{N_1 i_1}{S_m} + \frac{N_2 i_2}{S_m} = \phi_{m1} + \phi_{m2} \]

and

\[ \phi_{m_{2/3}} = \phi_{m1} + \frac{2}{3} \phi_{m2} \quad \text{Wb} \quad (2.27) \]

where \( S_m \) is the core reluctance and is constant.

The mutual inductances \( M_{12} \) and \( M_{21} \) may therefore be defined as follows

\[ M_{12} = \frac{N_1 \phi_{m2}}{\frac{2}{3} i_2} = \frac{N_1 (\frac{2}{3} \phi_{m2})}{\frac{2}{3} \phi_{m2}} = \frac{2}{3} \frac{N_1 \phi_{m2}}{\frac{2}{3} i_2} = \frac{2}{3} M_{12} \quad (2.28) \]

and

\[ M_{21} = \frac{N_2 \phi_{m1}}{\frac{2}{3} i_1} = \frac{\frac{2}{3} N_2 \phi_{m1}}{\frac{2}{3} \phi_{m1}} = \frac{2}{3} \frac{N_2 \phi_{m1}}{\frac{2}{3} i_1} = \frac{2}{3} M_{21} \]

Hence,

\[ M_{2/3} = M_{12} = M_{21} = \frac{2}{3} M \quad (2.29) \]
Fig 2.21  (a) Two magnetically coupled coils $N_1$ and $N_2$
(b) Equivalent circuit of $N_1$ and $N_2$ involving the transformation ratio $N$ coils
(c) Two magnetically coupled coils $N_1$ and $\frac{2}{3}N_2$
(d) Equivalent circuit of $N_1$ and $\frac{2}{3}N_2$ involving $N$
where $M$ is the original value of the mutual coupling. The two magnetically coupled coils $N_1$ and $\frac{2}{3} N_2$ are shown in Fig.(2.21).

Now Equation (2.27) shows that the peak flux $\phi_m$ linking the two windings has been decreased. Thus the voltage $e_1$ induced in coil 1 by the total flux in the core ($N_1 \frac{d\phi_m}{dt}$) is decreased. The voltage, $e_1$, appears across the mutual inductance $NM$ (referred to the primary as shown in Fig.(2.21)). The current in the inductance $NM$ (the magnetizing current) is reduced and the iron losses will also be reduced.

Fig.(2.21d) shows the equivalent circuit of the two magnetically coupled coils $N_1$ (as a primary) and $\frac{2}{3} N_2$ (as a secondary) referred to the primary. Although the secondary impedance is reduced, the effect of changing the turns ratio, when considering the equivalent circuit with parameters referred to the primary, appears as if an external impedance is added in the secondary side due to the change of the turns ratio. It must be borne in mind that the winding factor $K_{W}$ was reduced due to the reduction of the number of turns per phase per pole.

The effect of reducing the winding factor gave a very slight distortion of the generated sine wave as shown in Fig.(2.22a) when compared with the generated sine wave with the full winding secondary, as shown in Fig.(2.22b). (Traces are shown during a load change.) The traces were taken with the generator operating as an induction generator with the secondary short circuited and an input change of the prime mover. Experimental verifications are given in Figs.(2.23) to (2.25) in both cases of an induction generator and a doubly-fed generator. It can be seen that the induction power component is greatly reduced (roughly to $\frac{2}{3}$ of its original value) at each speed. Fig.(2.23) shows that the induction power generated is changed as if an additional resistance has been added. This has been achieved with a reduced copper loss and primary and secondary currents as shown in Figs.(2.24) and (2.25).
Fig. 2.22a  Rotor current waveform, 4 pole, $\frac{2}{3}$ winding induction generator

Fig. 2.22b  Rotor current waveform, 4 pole, full winding induction generator
Fig. 2.23  DFM power/speed compared with induction generator power/speed for full and \( \frac{2}{3} \) secondary winding.
Induction generator, full winding

Speed, rev/min

**Fig. 2.24 Primary current/speed**

---

Primary fed, secondary s.c.
Primary fed, secondary of \( \frac{2}{3} \) its winding s.c.

Induction generator, \( \frac{2}{3} \) secondary winding

**Fig. 2.25 Secondary current/speed**
Again, the reduced winding factor gives very slight distortion of the primary current with a doubly-fed generation system as shown in Figs.(2.26) and (2.27) which compare the $\frac{2}{3}$ secondary winding and the full secondary winding respectively. The required excitation voltage was approximately half the excitation voltage used for the full winding connection. The operation was stable all over the speed range. When the $\frac{2}{3}$ winding excitation voltage was applied to the full winding secondary, the maximum power obtained at 2100 rev/min with the $\frac{2}{3}$ winding was reached at 1850 rev/min in the full winding connection, beyond which (1850 rev/min.) the machine was unstable as shown in Fig.(2.23). It can be seen that the reduction of the secondary ampere turns, reduces the total induction power within the usable speed range and modifies the total generated power characteristic to a near power/(speed)$^3$ characteristic. More synchronous power is generated in this case (sec.2.4.1) to balance the energy between the load and the generator. A higher efficiency results due to the generated power being synchronous and the reduction of the secondary copper loss to $\frac{2}{3}$ of its original value.

2.4.2 Control of synchronous power for cube law output

It has been shown in sections (2.4(i)) and (2.4(ii)) that induction power control may be achieved by the secondary resistance variation or the secondary ampere turns limitation to shape the total developed power characteristic to match a wind power characteristic. For high efficiency the generated power should correspond with the wind power. This may be achieved by control of the synchronous power which may be controlled by load angle control or by excitation voltage control. Ideally, the total electrical power given by Equation (2.18) should equal the mechanical shaft power after the wind turbine has been geared up to the required generator speed.
Fig. 2.26  Rotor current waveform 4 pole DFM, full winding

Fig. 2.27  Rotor current waveform 4 pole DFM, $\frac{2}{3}$ winding
The electrical power generated may be,

\[ P_e = k_g \omega^3 \]

where \( k_g \) is the electrical power coefficient of the generator and \( \omega_g \) is the rotational speed of the generator shaft. If the optimum power locus of the wind turbine is known, \( k_g \) can be determined by matching the two characteristics within the operating bounds on the variable with numerical optimisation using NAG library routines. This means that if either the power coefficient \( c_p \) or the optimisation speed ratio \( \mu_{\text{max}} \) are known \( k_g \) may be determined. The matching function,

\[ F_c = (P_e - k_g \omega_g^3)^2, \]

where \( P_e \) is the power given by Equation (2.18), may be minimised to equal zero, when constrained by the lower and upper bounds of the variables (load angle, the excitation voltage or both).

(i) Load angle control at constant excitation voltage

The E^04JAF routine has been chosen to minimise \( F_c \) because it is easy to use a quasi-Newton algorithm for finding the required minimum value (zero). Minimisation has been achieved between the fixed upper bound of the load angle, \( \alpha = \frac{\pi}{2} \) and the lower bound \( \alpha = 0 \), independent of the constant excitation voltage of 20 V. Successful minimisation has been obtained and a power characteristic of the form \( k_g \omega_g^3 \) results as shown in Fig.(2.28). The full load induction power determines the minimum \( k_g \) for stable operation as shown in Fig.(2.28). The corresponding numerical optimisation computer program is given in the computation appendix.
Power, watt

-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000

Speed, rev/min
1000    1500    2000

Stable region

Unstable region

Total induction power

Minimum output power

\[ P_e = K \omega^3 \]

Fig. 2-28  Power-speed characteristic minimised by load angle control at constant excitation voltage = 20V
If the load angle can be measured, and expressed as a voltage, then the required cycloconverter secondary exciting voltage can be demanded to maintain the cube law. This is possible if the e.m.f. generated in an electrically isolated, co-linear, secondary coil \( (E_1) \) is compared with the cycloconverter output voltage \( (E_2) \). The phase difference between the two e.m.f's can be sensed and expressed as the width of a rectangular pulse. In the present experimental system, tooth ripple blurred the edges of the pulse and caused instability.

(ii) Load angle control by a voltage-speed exciting function at unity secondary power factor.

An expression for the generated power at unity power factor can be developed from the torque-speed relationships at unity power factor given by Alston and Holmes\(^47\). The condition for unity secondary power factor is obtained by equating the imaginary component \( (i_{q2}) \) of \( I_2 \) to zero.

So, from Equation (2.11)

\[
- \frac{\sqrt{3}}{D(s)} \{ A_6 v_1 + v_2 (A_8 \cos \alpha + A_7 \sin \alpha) \} = 0
\]

\[
\therefore - A_6 v_1 = v_2 (A_8 \cos \alpha + A_7 \sin \alpha)
\]

\[
\frac{v_1}{v_2} = - \frac{A_8 \cos \alpha + A_7 \sin \alpha}{A_6} \tag{2.31}
\]

where \( A_6, A_7 \) and \( A_8 \) (defined in Appendix A2) are machine speed dependent parameters.
Substituting $v_2$ in Equation (2.18), the developed power becomes a function of one variable ($\alpha$), constant $v_1$ and the speed dependent machine parameters. Cube law characteristics have been obtained at different values of load angle and different speeds by using the same lower and upper bounds of the load angle control. Substituting $\alpha$ in Equation (2.22) gives the secondary voltage as a non-linear function of the speed as shown in Fig.(2.29) at different values of the power coefficient $k$, through the stable range given in Fig.(2.28). This has been achieved in the experimental system by control of the cycloconverter excitation frequency, phase and amplitude as shown in Fig.(2.30). The cycloconverter frequency is synchronised to the shaft speed by velocity feedback. Analogue and digital shaping circuits control the output voltage as a function of speed. The design of the control circuit is given in Chapter 4. Figs.(2.31) to (2.33) show the experimental four pole DFM characteristics corresponding to power $= (\text{speed})^3$ obtained by the given excitation function. The experimental secondary current is greater than the computed values (Fig.2.33) at speeds near to synchronous speed because of the harmonic content of the cycloconverter output.

The cycloconverter can clamp currents at a preset maximum by means of r.m.s. secondary current signal feedback. This is why measured secondary current is smaller than the computed value at sub-synchronous speeds. Induced secondary currents caused by changes of primary current can increase the measured results. The control function of Fig.(2.30) has been considered as the cycloconverter voltage with a shifted angle $\theta$, while the primary is short-circuited, producing the induction power $P_{I_2}$. The doubly-fed machine currents and voltages are the superimposition of two quantities of induction operation (primary fed with the secondary short-circuited, and the secondary fed with the primary short-circuited), taking the shift position of the two geometrical axis of the primary and the
Fig 2.29 Excitation voltage-speed function for power-speed$^3$ at various power coefficients
**Converter**

Control voltage

Amplitude voltage control function

Frequency control function

Phase rotation (-ve)

Phase rotation (+ve)

1000 2000

**Fig. 2.30** Excitation control function of the cycloconverter

1000 1200 1400 1600 1800 2000

**Fig. 2.31** Power/speed characteristic for the control function of

**Fig. 2.30** at a power coefficient = 1.96 x 10^{-4}
Primary and secondary current for the control function of Fig. 2.30
secondary into account. Fig.(2.34) shows a breakdown of the secondary voltage components. The cycloconverter voltage $v_2$ is always injected into the supply, at sub-synchronous speed, the total voltage $v_s$ is the vectorial sum of $v_2$ and $s_1$ ($s_1$ produces the mechanical motoring power $P_{I_1}$). The power going through the cycloconverter to the supply is $P_{I_2}$. When the machine runs supersynchronously $s_1$ reverses its direction, returning the induction power $P_{I_1}$ into the supply through the slip rings. The secondary voltage $v_s$ is the difference between $s_1$ and $v_2$, taking the phase shift angle into account.

The power/(speed)$^3$ control technique has been applied with the use of two-thirds of the secondary winding for different values of $k_g$ as shown in Fig.(2.35). The generated powers at sub-synchronous speeds are higher than those obtained with the full winding with greater stability due to the reduction of the peak primary induction power achieved by the limitation of the secondary winding (refer back to Fig.2.15).

2.4.3 Synchronous power output with constant current excitation

In the three methods discussed, induction power is a significant part of the total power. Referring back to Fig.(2.15), the slope of the induction torque at the operating points contributes negative damping and instability may result if the system motors momentarily. As the torque depends on the secondary field and the specific electric loading of the primary (rotor), if the cycloconverter can be made to impress secondary current, this impressed secondary current results in an impressed induction torque which is independent of the speed. The reason for this behaviour is that, unlike the ordinary induction motor, the secondary current can be adjusted independently of the slip. Load changes occurring lead to synchronous speed variation and the mechanical power output changes.
Fig. 2/34 Breakdown of the doubly-fed machine secondary voltage.
Fig 2.35 Experimental power-(speed)$^3$ characteristics at various values of $K_g$ and $\frac{2}{3}$ secondary winding.
As, however, the secondary power is constant (the secondary current is held constant), the primary power can only be changed by changes in the primary current. Consequently the power to be handled in the secondary circuit is very small. This will greatly reduce the required component ratings of the secondary circuit. Current-source excitation at a fixed secondary current has been used in a doubly-fed motor system to obtain greater transient stability. A similar technique can be used to minimise induction generation in a doubly-fed generator.

The secondary dq currents are now given as

\[
\begin{bmatrix}
I_{d2} \\
I_{q2}
\end{bmatrix} = \sqrt{3} I_2 \begin{bmatrix}
\sin \alpha_v \\
-\cos \alpha_v
\end{bmatrix}
\]

(2.32)

where \( I_2 \) is the fundamental component of the secondary current and \( \alpha_v \) is the load angle. Using Equations (2.32) and (2.1), the primary dq currents are given as (as derived in Appendix A3)

\[
I_{d1} = \frac{\sqrt{3}(v_1(r_1+jx_1) - I_2x_1r_1(j \sin \alpha_v + \cos \alpha_v))}{x_1^2 + (r_1+jx_1)^2}
\]

(2.33)

\[
I_{q1} = \frac{\sqrt{3}(-v_1x_1 - I_2x_1r_1(\sin \alpha_v - j\cos \alpha_v))}{x_1^2 + (r_1+jx_1)^2}
\]

(2.34)

From equations (2.18), (2.32), (2.33) and (2.34), an expression for generated power as defined in A3 is,

\[
\omega T = -\frac{3P}{\omega} \left( \frac{x_m}{r_1^2+4x_1^2} \right) \{ v_1I_2(x_1 \sin \alpha_v - r_1 \cos \alpha_v) + I_2^2r_1x_1 \}
\]

(2.35)

Equation (2.35) simplifies to

\[
\omega T = -\omega \left\{ \frac{3P}{4x_1} \frac{M}{v_1} I_2 \sin \alpha_v \right\}
\]

(2.36)

when \( r_1 \ll x_1 \).
In Equation (2.35) the induction torque $T_{i2} = -i_2^2 r_1 x_m$ is also present, but it is very small and independent of slip. The generated power is mainly synchronous power as given in Equation (2.36).

Power/(speed)$^3$ with a constant current excited doubly-fed generator was achieved using the experimental cycloconverter shown in Fig.(2.8) with electrically separated thyristor groups (divided winding system). If generation all over the allowable speed range (limited by the cycloconverter frequency) is required, the constant current excitation system has a reduced maximum power output of about 75% of the generated power in the voltage source excitation system. Clearly the power coefficient will be lower. However operation at the optimum power coefficient is possible at the expense of a reduced operating speed range. In the present experimental system, if a 5 kW output power (for example) is to be generated at 2100 rev/min, which represents the maximum power locus, the maximum power coefficient in this case is $4.39 \times 10^{-4}$. This is possible in a voltage source excitation system. In a constant current excitation system, the system may follow this maximum power locus over a limited range at 1977 rev/min and at a maximum power of 3.9 kW.

2.5 The ideal system

When the system operates at negative slip, the total power is passed into the grid. At positive slip one of the induction powers is drawn from the supply. In a voltage source excitation (dependent on the load angle $\phi$) system, this requires the cycloconverter excitation voltage to peak near the fundamental synchronous speed (as shown in Fig.(2.30)) to match the cube law characteristic. The actual secondary voltage $v_s$ is the vectorial sum between the excitation voltage $v_2$ and the induced e.m.f. $se_l$ is shown in the upper graph of the experimental results given in Fig.(2.36). The lower voltage-slip function of Fig.(2.36) shows the
Fig. 2.36 Secondary voltage-slip characteristics in voltage excitation system and constant current excitation system.
much lower voltage needed for the current source excitation system following the power-(speed)^3 relationship. In this case the actual secondary voltage, \( V_s \), may be given as \( V_s = V_2 = I_2 Z_2 \). The induced e.m.f. (se) in this case is \( = 0 \) due to the controlling current being independent of the slip. Fig.(2.37) shows the experimental power-slip characteristic constrained to obey the cube law power-speed requirement in both systems.

Voltage-source excitation is shown with the full secondary winding and with two-thirds only used to improve efficiency. Fig.(2.38) gives a primary/secondary power breakdown between the voltage-source and current source excitation systems. The current-source system can be seen to require devices of only half the power of the voltage-fed system. However the maximum power output in the current source excitation system is restricted to about 75% of the maximum power given by the voltage source excitation system. The constant current excited doubly-fed machine has no restricted minimum power coefficient due to the elimination of the primary power. It is not limited by stability region over the operating range unless the load angle exceeds \( \pi \).

Two sets of efficiency/slip results are given. In Fig.(2.39) efficiencies are computed at "pull-out" power. Fig.(2.40) shows the system efficiency when the output power increases in proportion to the (speed)^3. The voltage-source-excitation system is most efficient with only two-thirds of the secondary winding. The use of form factor induction torque optimisation is at the expense of a loss in efficiency. For contrast the efficiency of the Smith and Nigim (ref.32) Scherbius system implemented on a similar machine but with constant torque output is included.
Power generated

1.0 p.u. = 5 kW

- Required power,
- 2/3 secondary winding, A
- Full secondary winding, $\gamma = \pi/2$, B
- Constant secondary current, $\gamma = \pi/2$, C

Fig 2.37 Power fed into grid / slip

Primary and secondary power / slip

- Full secondary winding, $\gamma = \pi/2$, B
- Constant secondary current, $\gamma = \pi/2$, C
- Secondary power through cycloconverter
- Primary power

Fig 2.38 Primary and secondary power / slip
Fig. 2-39 EFFICIENCY/SLIP (At "PULL OUT" power)

- 2/3 Secondary winding, A
- Full secondary winding $\gamma = \pi/2$, B
- Constant secondary current, $\gamma = \pi/2$, C
- Full secondary winding - optimised induction power by $\gamma$ control, D

Fig. 2-40 EFFICIENCY/SLIP when supplying power = $kW^3$
(Peak power at $s = -0.3$)
2.6. **Conclusions**

Full analysis of the steady state operation of the doubly fed machine as a generator at sub- and super-synchronous speeds have been derived and expressed in the form of generalised theory. The required characteristics needed in the doubly-fed generator if it is to operate as an efficient wind energy transducer have been considered, and matched to the wind turbine performance.

It has been shown that a doubly-fed machine excited by a cycloconverter can operate stably and efficiently as a generator feeding a power grid when driven by a mechanical prime mover having a cube-law power/speed characteristic. A means of electronically controlling the secondary form factor has been demonstrated by cycloconverter reference control. This extends the peak power generation capability at high negative slips by 50% at the expense of a 5% reduction in efficiency.

Reduction of the secondary ampere-turns to two-thirds of its original value gives sufficient excitation to extend the peak-power generation, with a reduction of primary induction and copper losses to two-thirds of its original value with an increase of efficiency. An approximate power/(speed)$^3$ characteristic has been obtained at different power coefficients with only a very slight current peak distortion due to winding factor reduction.

Load angle control can constrain the output to follow the power/(speed)$^3$ locus at constant excitation voltage. The load has been shown to be a function of the secondary e.m.f. and so there is no need to measure the shaft position or to use a synchro control. Estimates of load angle are possible if the e.m.f. generated in an electrically isolated co-linear secondary coil is compared with the cycloconverter output voltage. The phase difference between the two e.m.f's can be sensed and
expressed as the width of a rectangular pulse. In the present experimental system, tooth ripple blurred the edges of the pulse and caused instability in the control system. A non-linear excitation voltage/load angle function can control the power output at secondary unit power factor to obey the law $P_e = k g^3$. This has been achieved using both the analogue and digital electronic control system (described in Chapter 4). The power generated contains two induction powers which limit the operating region.

Constant current excitation has been shown to be a preferred system, effectively eliminating the primary induction power and giving up to a 10% increase in efficiency with a 50% reduction in solid state device rating at the expense of a reduced maximum power of 75% of the value obtained with voltage source excitation. The system is stable all over the speed range due to the effective elimination of the primary induction power. Clearly, the doubly-fed machine can be controlled to generate $P_e$ at any power coefficient with 25% full power device rating. To specify the power coefficient at which maximum power can be converted, a study of optimum power conversion is described in the following chapter.
3.1 The wind power plant

A wind power generator feeding into an electrical grid is an effective fuel saver. The characteristics of the wind turbine, the transducer and the grid should be matched together to maximise the efficiency of generation and transmission.

The wind power system has four main elements. These are:

(a) The wind turbine
(b) An electric generator
(c) The generator-grid interface, and
(d) The control network

(a) The turbine converts wind power into rotational shaft power. It can be of a horizontal or of a vertical axis type with usually two or three blades (Fig. 3.1a-g). The blades can be articulated from the hub or at any point along the span to provide pitch variation. Maximum power extraction from the wind will occur at the same tip speed ratio for all speeds, providing lift is maximised and drag is minimised. The tip speed ratio, $\mu$, is the ratio of the rotor speed to the wind speed, expressed as the dimensionless term.

$$\mu = \frac{\omega_\text{R}}{V_1}$$  \hspace{1cm} (3.1)

where $\omega_\text{R}$ is the rotational speed of the wind turbine rotor, and $V_1$ is the wind speed.

The system efficiency can be improved if the electric generator and the generator-grid interface can be combined into one machine. This has been achieved in previous work by an induction generator\textsuperscript{48} and a synchronous generator\textsuperscript{49}. In the former case, near-constant-speed and in the latter case, constant-speed operation is required. Both systems
PLATE XXIV. (Left). 100 kW (John Brown) wind-driven generator on Costa Hill, Orkney (HAWTG)

PLATE XXV. (Right). 45 kW (SEAS) wind-driven generator at Bogo, Denmark (VAWTG)
Fig. 3.1c  THE ALDBOROUGH 56ft. WIND GENERATOR
TYPE II
(HAWTG)
Fig. 31d (PLATE XXVII) 1250 kW aerogenerator at Grandpa's Knob, Rutland, Vermont. (From Power from the Wind by P. C. Putnam. Copyright 1948. D. Van Nostrand Company Inc.)

Fig. 31e (PLATE XXVI) Showing the 100 kW Enfield-Andreau wind-driven generator during its installation on St. Albans test site. (Enfield Cables Ltd.)
Fig. 3.1f  The 4.5 metre diameter prototype VGVAWT.

Fig. 3.1g  The P.I. 6 metre diameter VGVAWT for both electricity generation and water pumping.
require modifications by control of blade position relative to the wind velocity to keep the net rotational force component constant to match the generator characteristics. This is achieved by control of the angle of attack and the pitch angle shown in Fig.(3.2). Matching can be achieved but full exploitation of wind-power varying as the cube of the wind velocity is not possible (ref.7).

The system designed and implemented by the present author combines the electric generator and the generator-grid interface into a single doubly-fed generator capable of wide-range variable-speed operation to allow the aeroturbine speed to vary with wind velocity. This is a variable-speed, constant-frequency (VSCF) generating system pumping constant frequency power into the existing supply mains. This approach appears to show considerable promise both from the technological and from the economic viewpoint. In this approach, since the need for maintaining a constant rotational speed has been obviated by the use of electrical control of the excitation of the doubly-fed generator, aeroturbines can be designed to maximise their power producing capability (by maintaining constant tip speed ratio at its maximum value) and minimize their cost. Fig.(3.3) shows a typical wind-turbine characteristic with variation of shaft-torque against angular velocity for constant wind speeds. In each case the maximum torque point can be seen. However, maximum power occurs at higher rotational speed at each wind speed as shown in Fig.3.4. Stalling or "pull-out" resulting in dangerous overspeeding must be avoided.

The mechanical power equations of a wind-turbine are given by Golding (ref.7) as follows: A windmill of blade radius, R, operating in a wind stream of velocity, \( V_1 \), is given as

\[
P_\omega = \frac{1}{2} \rho \pi R^2 C_p V_1^3
\]

(3.2)

where \( \rho \) is the air density and \( C_p \) is the power coefficient.
Fig. 3.2 Wind turbine blade, angle of attack, pitch, lift and drag.

Fig. 3.3 Wind turbine torque rotational speed characteristics.
Fig. (3.4) shows a family of curves of rotor power against rotor velocity at fixed wind speeds. It should be noted that the peaks occur at the same tip-speed ratio as defined in Equation (3.1). One of the primary characteristics of a wind turbine rotor is the power coefficient against the tip speed ratio shown in Fig. (3.5). This Fig. tells us that for maximum power extraction, the maximum power coefficient $C_{\text{p max}}$ is achieved for only one value of the tip speed ratio $\frac{u}{u_{\text{max}}}$ irrespective of variation in wind speeds.

(b) The generator will rotate at a much greater speed than the wind turbine. A gear box will be required as a coupling. A choice must be made between a fixed and a variable ratio. Variable ratio systems are, in general, relatively costly, high in maintenance costs, and lower in reliability and efficiency than simple fixed ratio systems. The main fixed ratio options are direct-drive gears, chains, belts and hydraulic couplings. The optimum tip-speed ratio $0.50, 51$ (about 5 for a 2-bladed turbine) is largely independent of turbine size, with the rotational speed varying inversely with diameter.

Small systems may exploit the simplicity of a direct drive but large systems, e.g. a 60 m turbine operating at 35 rev/min, can only be directly coupled to a multi-polar generator, which may be unacceptable because of its high cost and weight. A compromise between the possibility of a low cost and design compromise between the transmission ratio and the number of poles of the generator. The limit of rotational speed from the wind turbine and the available speed range of the generator will be defined as the optimum gear ratio. A more detailed explanation is given later.

The electrical generator converting mechanical energy to electrical energy should be capable of operation over a wide speed range. It was shown in Chapter 1 that the principal choice is between a slip-ring induction machine operated as a slip-energy recovery system excited by
Fig. 3.4 Wind turbine powers-rotational speed characteristics

Fig. 3.5 Rotor power-coefficient/tip-speed-ratio characteristic
a current-source inverter, or as a doubly-fed generator with a variable synchronous speed obtained by cycloconverter excitation. The characteristics of the current-source system are described by Smith and Nigim in reference (32). It was shown in Chapter 2 that a doubly-fed generator with appropriate excitation can generate a power proportional to the cube of the generator speed corresponding to the wind turbine characteristic. Fig. (3.6) shows a family of computed power-speed characteristics for the experimental doubly-fed system for a range of power coefficients. A study must now be made to investigate how the system efficiency is affected by the choice of power coefficient, its optimum value and the corresponding gear ratio.

(c) The generator-grid interface. If the wind generator system is directly coupled to the grid, the generator output must be a constant sinusoidal voltage at grid frequency. In a large integrated supply network where the wind turbine generator capacity represents a small part (< 20%) of the total system capacity, the grid will dictate the system voltage and frequency and no control function at the WTG is necessary. However, in a low capacity, high impedance network such as a small island supply, independent voltage and frequency control is very important.

3.2. Wind power conversion and generation policies for optimum power production

For maximum energy extraction from a wind energy system, constant tip-speed ratio operation is desirable. Fig. (3.4) shows a typical family of wind power/rotational speed curves for different wind speeds showing that the peaks occur at the same tip speed ratio. With direct drive (or neglecting losses in the intermediate gearing) the power output from the rotor is identical to the power input to the generator. The power in the wind is proportional to the cube of the wind velocity and so the output of the rotor will be proportional to this cube if its efficiency remains
Fig. 3.6 Generated power/speed for various power coefficients.
constant. This implies that the power requirement of the generator driven by the rotor should be proportional to the cube of the speed. Clearly the rotor and generator characteristics must be matched to produce the best effect. Optimum power can be obtained if the power output given by the electric generator can be controlled to pass through the different peaks of the turbine characteristic as the wind speed varies. The optimum power $P_o$ is,

$$P_o = \frac{1}{2} \rho \pi R^2 C_{p_{\text{max}}} V_1^3,$$  \hspace{1cm} (3.3)

where $C_{p_{\text{max}}}$ is the maximum power coefficient. At $C_{p_{\text{max}}}$, the tip speed ratio $\mu$ has a unique value of $\mu_{\text{max}}$ (ref.49) irrespective of the wind speed $V_1$ and with respect to the rotational speed $\omega_o$, where

$$\mu_{\text{max}} = \frac{\omega_o R}{V_1},$$  \hspace{1cm} (3.4)

$\omega_o$ is the optimum rotational speed for $P_o$.

Combining (3.3) and (3.4) gives

$$P_o = \frac{1}{2} \rho \pi R^2 C_{p_{\text{max}}} \frac{\omega_o R^3}{\mu_{\text{max}}^3},$$  \hspace{1cm} (3.5)

and

$$P_o = K_o \omega_o^3,$$  \hspace{1cm} (3.6)

where

$$K_o = (\rho \pi C_{p_{\text{max}}} R^5/2\mu_{\text{max}}^3).$$  \hspace{1cm} (3.7)

Equation (3.6) is the broken line passing through the peaks of converted wind power shown in Fig.(3.7) at each peak power, the tip speed ratio, $\mu_{\text{max}}$ is constant.
Shaft power p.u.  $P_{\text{max}} = K_{\text{max}} \omega^3$  $P_0 = K_0 \omega^3$

$10,000 \, W = 1 \cdot 0$

$0.6$  $0.8$  $1.0$  $1.2$  $1.4$  $1.6$

$0.8$  $0.6$  $0.4$  $0.2$  $0.0$

$P_2 = K_2 \omega^3$

$P_3 = K_3 \omega^3$

Fig. 3.7  Power/rotational speed curves for different wind speeds showing the optimum power locus
3.6

In the present experimental system the exciting frequency is controlled to maintain synchronism. An independent excitation amplitude control enables the generated electrical power to be maintained proportional to $\omega^3$. Referring back to Fig.(3.6), the system output for a number of values of constant $K_g$ can be seen. The value of $K_g$ is restricted by the maximum available cycloconverter voltages to the value $6.12 \times 10^{-4}$ as shown in Fig.(2.29). If the cycloconverter can be modified to give an increased maximum voltage to frequency ratio, higher values of $K_g$ can be obtained.

Increasing the excitation until the system follows the curve

$$P_{\text{max}} = K_{\text{max}} \omega^3$$

as shown in Fig.(3.7) can greatly increase the power variation for large changes of wind speed in a relatively small speed range. However, a restriction in speed range is only obtained at the expense of a reduced efficiency in both of wind turbine (due to poor $C_p$) and generator (due to the corresponding excessive excitation voltage as shown in Chapter 2).

3.3. Wind turbine operation with doubly fed generator

A slip range of $0.2 > s > -0.3$ will for most wind regimes lead to annual energy capture not far short of the one theoretically possible with a much wider rotor speed range. This occurs because the annual energy yield from winds both in the low speed range and the high speed range is relatively small, the latter because of the small number of high-wind hours per annum and because of the impossibility of maintaining optimum operation of any windmill in the highest winds. From Equation (3.4), for known maximum tip speed ratio, the optimum rotational speed range can be defined as

$$\omega_{\text{max}} = \left(\frac{\mu_{\text{max}}}{R}\right)V_r$$

and
where \( V_r \) is the rated wind speed to give the maximum designed power output and \( V_c \) is the minimum wind speed at which the rotor can generate positive torque (cut in wind speed). This optimum speed range has been defined for a typical wind rotor characteristic to be 
\[ 0.25\omega < \omega_0 < 0.75\omega. \]
The optimum gear ratio, \( \lambda_o \), is then
\[ \lambda_o = \frac{\omega_g}{\omega_0} \]  
(3.10)

where \( \omega_g \) is the optimum rotational speed of the generator. Using Equation (3.10), the generator optimum power locus, \( K_{g_o} \) is
\[ K_{g_o} = \eta_m \frac{K_o}{\lambda_o^3} \]  
where \( \eta_m \) is the mechanical transmission and gearing efficiency.

In the ideal case when \( \eta_m = 100\% \),
\[ K_{g_o} = \frac{K_o}{\lambda_o^3} \]  
(3.11)
on substituting in Equation (2.30) on \( K_g = K_{g_o} \). The cycloconverter can now be commanded to give the necessary excitation voltage to maintain the output power, \( K_{g_o} \omega_g^3 = K_o \omega_o^3 \) providing the output avoids the stalling points.
Fig. 3.8: Rutherford Laboratory wind spectrum.
3.4. Relating the experimental system to real wind turbine characteristics
- the Rutherford Laboratory aerogenerator

For most of the experimental results described in this thesis, the prime-mover simulating a wind turbine is a separately excited d.c. motor. This motor was supplied through an electronic d.c. current source programmed to supply a current proportional to the square of the motor speed. In this way a source of power proportional to the cube of the speed corresponding to a wind turbine characteristic was provided.

To assess the capability of the system in a real situation, data supplied by the Rutherford Laboratory on their 6 kW wind turbine has been used. This system is compatible in size with the doubly-fed experimental machine. Fig.(3.8) shows a wind spectrum given by the Rutherford Laboratory for their 6 kW vertical axis variable geometry aerogenerator. The near 6 kW - RAL site 1980 curve has been used in conjunction with the combination of Equations (3.4), (3.6) and Fig.(3.8) to construct a family of power-speed characteristics at different wind speeds, as given in Table 1 of Appendix A4. The aerogenerator output is shown as a broken line in Fig.(3.9) and represents an optimum power locus, where the power coefficient $K_o$ is kept nearly constant between 7.4 and 8 (at constant tip speed ratio $\lambda_{max} = 5.14$) for a speed range of 2 m/sec to 5 m/sec. If the wind speed increases to 6 m/sec, $K_o$ falls to 5.3. The optimum rotational speed is found in the range 40 rev/min. to 81.74 rev/min. However, the rotor speed limits lie between 60 rev/min. and 120 rev/min.

To interface the 4-pole doubly-fed machine with the aerogenerator the gear ratio, $\lambda_o$, has been chosen to scale 81.74 rev/min to the highest speed possible within the cycloconverter frequency range (2100 rev/min.).

$$\lambda_o = \frac{2100}{81.74} = 25.69 = 26$$
Fig. 3.9 Rutherford aerogenerator characteristics matched to the Leicester system
Knowing $\omega_0$ and $K_g$, then

$$K_{g_o} = \frac{K_0}{\lambda_0} = \frac{7.732}{(26)^3} \quad \text{(mean value of } K_0) = 4.399 \times 10^{-4}$$

Assuming 100% gear ratio and transmission system efficiencies and substituting in Equation (2.30) of Chapter 2 the excitation voltage required to equate the DFM power output with $K_{g_o} \omega_0^3$ is given in Fig.(3.10).

It can be seen that the furling point (at which the extracted wind power falls and the wind rotor runs at excessive speeds) occurring at wind speed = 6 m/sec can be avoided by controlling the DFM to load the wind turbine with a load just sufficient for the optimum operating case.

3.5 The effect of the choice of gearing

The value of the gear ratio, $\lambda$, will determine the value of $K_g$ dependent of the rotational speed. A higher gear ratio will enable solid state devices of a reduced voltage rating to be used. If a fixed gear ratio is used, this value must be a compromise between the extremes of device rating. Considerable cost savings are achieved by a constant gear ratio. Gear ratio changing requires complex mechanisms. If the cycloconverter voltage is specified in amplitude and frequency to produce an electrical generated power characteristic of the form $P = K_g \omega_0^3$, this voltage function will peak at the same speed as given previously in Fig.(2.29), and its value increases with the increase of $K_g$.

It was shown in Chapter 2 that the power flow is excitation dependent (i.e. a function of $\frac{V_2}{V_1} N$). Taking this into account, the optimum gear ratio is then the ratio that gives the optimum rotational speed range for wind generation corresponding to the highest available operating range of the doubly-fed generator, i.e. Equation (3.10) becomes

$$\lambda_o = \frac{\omega_{g_{max}}}{\omega_{c_{max}}^3} = 3 \sqrt{\frac{K_0}{K_g}}$$

The aim of this is to achieve the required power generation at the smallest possible value of $K_g$. When this is achieved by the minimisation of secondary current, $v_2$ is minimised, optimum power achieved with about 25% of the
Fig. 3.10 The computed excitation voltage required to give the DFM output of Fig 3.9
generated power passing through the exciting source.

3.6. Conclusions

The energy extracted from the wind, converted to electricity and eventually supplied to the grid, is influenced by the three following characteristics:

(i) the rotor characteristic (wind turbine)
(ii) the generator characteristic, and
(iii) the grid characteristic.

So the overall efficiency of the wind turbine-generator-grid combination is maximised if those three characteristics are matched to produce the best effect.

At each wind speed, the wind turbine produces power increasing in a way which depends upon the rotational speed of the rotor, until peak value is reached, then the power decreases. So a family of power curves are produced at different wind speeds. Their peaks occur at the same tip-speed ratio, and maximum power coefficient. The operating points for optimum power generation can thus be specified.

The design task in the present work is to ensure that throughout the normal operating range the windmill is loaded by the doubly-fed generator and loaded just enough to enable it to run at optimum rotational speeds (i.e. the DFG power output curve is passing through the peaks of the family of curves given by the windmill). Stalling points are avoided and the overall system efficiency may be increased. Natural wind-turbine-generator-grid matching is given by using one of the Rutherford Laboratories wind turbine characteristics (a near rating of the experimental machine). The optimum gear ratio scales the optimum output power locus of the windmill to the highest available rotational speed of the
doubly-fed machine given by the cycloconverter to ensure lowest electric power coefficient, and hence the lowest excitation voltage requirement.
Chapter 4

The requirements for electronic excitation

Introduction

The variable frequency electronic control system (inverter or cycloconverter) connected between the secondary winding of the wind turbine generator and the a.c. mains supply should be designed to meet the following five basic requirements.

(i) Ideal-minimum harmonic injection into the supply.

(ii) Reversible energy flow-variable leading and lagging power factor operation.

(iii) Natural commutation (this eliminates the link inverter) with protection against line to line short-circuit, and a fast response to transient load changes.

(iv) An economic, simple control system.

(v) Amplitude and frequency must be controlled independently so that the generator can be excited by an excitation function varying with speed.

The power injected into the grid must have a minimum harmonic content based on a fundamental sinusoidal voltage. If armature reaction and tooth ripple effects are small and saturation is avoided in the generator, harmonics will mainly be generated by the electronic exciter. Winding distribution and chording can then minimise the exciter introduced harmonics in the air gap m.m.f. Bi-directional power flow is required in the exciter, together with the facility to work at widely-varying leading and lagging power-factors. A current-source inverter or a cycloconverter can meet the reversible energy flow requirements, while a cycloconverter with an input to output frequency ratio >2 will provide a much smaller harmonic content (ref.6).
In an ideal cycloconverter, a sinusoidally varying input control signal will produce an array of gate pulses which can produce a sinusoidally varying output voltage. This ideal condition can only be produced by an infinite number of commutations per output cycle. In a practical system, the harmonic content of the cycloconverter output voltage decreases as the number of input phases increases.

Section 3.3 defines a range of maximum wind power developed within the speed range of $|\omega_o|$. If sub and super synchronous operation is to be considered, a gear ratio must be chosen to fix the synchronous speed ($s = 0$) at $\omega = \frac{\omega_o}{2}$. Then the machine will generate over equal speed ranges above and below synchronous speed. The electronic frequency changer must be able to return energy to the supply at positive or negative slips.

Smith and Nigim (ref.32) have overcome the problem of returning energy to the supply by the use of a current source inverter acting as part of a slip-energy recovery system with reversible energy flow capabilities. For the reasons discussed in Chapter 1, the cycloconverter rather than the current source inverter (restricted to lagging power factor operation only in the secondary side) has been adopted to excite the wind turbine generator.

4.0. The cycloconverter

The cycloconverter as a direct frequency converter without a d.c. link is well known as a power amplifier\textsuperscript{52,53} employing phase-controlled thyristors. In an a.c. variable-speed drive, power flow is reversible and lagging or leading power factor operation is possible. Regenerative braking can thus be achieved.

The cycloconverter can operate in two distinct modes. These are:
(i) circulating current-free cycloconversion, and

(ii) cycloconversion with continuous circulating current.

The choice of the mode of operation must now be made based on the requirements previously specified.

4.1. **Harmonics in the cycloconverter output voltage.**

(i) **Circulating current free operation**

The basic cycloconverter element is shown in Fig. 4.1. Multiples of these elements can form polyphase frequency converters of which Fig. 4.2 shows a half-wave, 3-phase, converter. Further elements of three thyristor groups can be added to give full-wave or multi-phase operation. If the thyristor gate pulse positions are modulated and an inter-group reactor as shown in Fig. 4.1 is provided for inductive energy storage to ensure regenerative operation, the voltage and current profiles shown for unity load power-factor in Fig. 4.3a and 4.3b will be generated. Fig. 4.3 is based on the traditional cosine-crossing method of pulse timing with the constraint relating group firing angles of

\[ \theta_{1+} + \theta_{1-} = \pi \]  

(4.1)

where + and - refer to the positive and negative group firing angles respectively. This method of pulse timing gives the best approximation to a sine wave of output voltage obtainable by natural sampling, although the output profile can be improved considerably by the use of sampling techniques\(^5^4\).

If the voltage profiles of Figs. 4.3a and 4.3b are superimposed, an instantaneous voltage difference will be observed. This voltage difference must be limited by an inter-group reactor as shown in Fig. 4.1. Commercial cycloconverters dispense with the reactors by use of integral
Fig 4-1 THE BASIC 3-PHASE INPUT, 1-PHASE OUTPUT CYCLOCONVERTER UNIT

Fig 4-2 3-PHASE INPUT, 3-PHASE OUTPUT, HALF-WAVE CYCLOCONVERTER SYSTEM
POSITIVE THYRISTOR GROUP VOLTAGE AND CURRENT (Unity P.F. Load)

Fig. 4.3a

NEGATIVE THYRISTOR GROUP VOLTAGE AND CURRENT (Unity P.F. Load)

Fig. 4.3b

- instantaneous voltage
- mean voltage
- mean current

* thyristors A, B, C, D, E, F
cycle blanking. In this case the part of the output cycle over which conduction takes place varies with the fundamental displacement angle of the load current as shown in Fig.4.4. The harmonic content of the output voltage now depends on,

(a) the input to output frequency ratio,
(b) the ratio of the input voltage amplitude to the control reference signal amplitude, and
(c) the angle of displacement between the fundamental output voltage and current.

Conduction intervals for the positive and negative thyristor groups are $\phi_{22} \leq \omega_2 t \leq (\phi_{22} + \pi)$ and $(\phi_{22} + \pi) \leq \omega_2 t \leq (\phi_{22} + 2\pi)$ respectively.

If two unit functions, $f_p(\omega_2 t)$ and $f_N(\omega_2 t)$ are used to define the positive and negative conducting periods respectively, the cycloconverter output voltage will be

$$v_2 = v_p f_p(\omega_2 t) + v_N f_N(\omega_2 t) \quad (4.2)$$

The substitution of the group conduction limits and the unit function Fourier Series into equation 4.2 gives the following output expression, defined by Pelly in reference 53.

$$v_2 = \frac{3\sqrt{3}v_p}{2\pi} \left[ \sin f_1(\omega_2 t) + \frac{1}{2} \sin 3\omega_1 t \cos 2f_1(\omega_2 t) + \frac{1}{4} \sin 3\omega_1 t \cos 5f_1(\omega_2 t) + \frac{1}{7} \sin 6\omega_1 t \cos 7f_1(\omega_2 t) + \text{etc.} \right]$$

$$+ \frac{3\sqrt{3}v_N}{2\pi} \left[ \frac{1}{2} \cos 3\omega_1 t \sin 2f_1(\omega_2 t) + \frac{1}{4} \cos 3\omega_1 t \sin 4f_1(\omega_2 t) + \frac{1}{5} \sin 6\omega_1 t \cos 5f_1(\omega_2 t) + \frac{1}{7} \sin 6\omega_1 t \cos 7f_1(\omega_2 t) + \text{etc.} \right]$$

$$\times \frac{4}{\pi} \left[ \sin (\omega_2 t + \phi_{22}) + \frac{1}{3} \sin 3(\omega_2 t + \phi_{22}) + \frac{1}{5} \sin 5(\omega_2 t + \phi_{22}) + \frac{1}{7} \sin 7(\omega_2 t + \phi_{22}) + \text{etc.} \right] \quad (4.3)$$

$v_2$ should have the greatest possible fundamental to harmonic ratio.

The control voltage needed to implement this is

$$v_c = rv_c \sin \omega_2 t \quad (4.4)$$
Fig 4.4 THYRISTOR GROUP VOLTAGES IN CIRCULATING CURRENT FREE MODE OF OPERATION
(output fundamental displacement angle $= \frac{\pi}{6}$)
where \( \hat{v}_c \) is the peak value of the control voltage and \( r \) is a dimensionless scaling factor between 0 and 1 allowing for amplitude variation. In a physical system, \( r \) is the ratio between the peak control voltage and the peak timing voltage. The thyristor firing function is now

\[
f(\omega_2 t) = \sin^{-1} (r \sin \omega_2 t)
\]

(4.5)

which implies that the firing angle is moved from the \( \frac{\pi}{2} \) quiescent position by the angle \( \sin^{-1} (r \sin \omega_2 t) \). An inspection of equation 4.3 (as shown in Appendix A5) shows that the families of harmonics present in the output voltage can be expressed in frequency terms by the equations,

\[
\frac{f_H}{f_0} = 3 (2p_v - 1) \frac{f_1}{f_2} + 2n_v
\]

and

\[
\frac{f_H}{f_0} = 6p_v \frac{f_1}{f_2} + (2n_v + 1)
\]

(4.6)

(4.7)

where \( p_v \) is any positive integer and \( 0 < n_v < \infty \). \( f_1(\omega_2 t) \) is the control reference signal, usually defined as \( f_1(\omega_2 t) = \sin^{-1} (r \sin \omega_2 t) \), where \( r \) is the ratio of reference to timing signal amplitudes.

The harmonic amplitudes are phase angle dependent.

Fig.4.5 illustrates the complete harmonic families present in the output voltage. The thick sloping lines represent equation 4.6 plotted for the case where \( p_v = 1 \) and the thin sloping lines equation 4.7 when \( p_v = 1 \). All values of \( n_v \) are significant. Fig.4.5 indicates the output harmonic frequencies present at any value of \( f_1/f_2 \) by reading the frequency values of the intercepts drawn through a vertical line passing through the appropriate value of \( f_1/f_2 \). It can be noted that sub-harmonics will be present in the output voltage at all frequencies.
Fig 4.5 OUTPUT HARMONICS RELATED TO INPUT-OUTPUT FREQUENCY RATIO
(CIRCULATING CURRENT FREE CASE)
(ii) Continuous circulating current operation

If continuous circulating current operation is possible, the thyristor group output voltage profiles will be as shown in Fig. 4.3 and their superposition shows that considerable harmonic cancellation will take place where

\[ V_2 = \frac{V_p + V_N}{2} \]  

(4.8)

In this case, only the first bracketed term of Equation 4.3 remains and the harmonic frequencies present in the output voltage are now represented by Fig. 4.6. This indicates that if continuous circulating current operation can be maintained, the operation is independent of load power factor, and

(a) The harmonic frequencies present in the cycloconverter output voltage increase as a linear function of \( f_1/f_2 \). Thus operation at the highest possible input to output frequency ratio is desirable, and

(b) Sub-harmonics will not be produced if the input to output frequency ratio > 1.66. For a six-phase input or a three-phase full-wave system, this limit is reduced to 1.33.

The harmonic cancellation is shown in practice in Fig. 4.7. The cycloconverter has been driven into saturation to exaggerate the harmonic content of the output.

No general harmonic amplitude pattern can be derived. However, particular cases can be computed from Equation 4.3 as given in Appendix A5 with the aid of Fourier coefficients given in reference 53. Fig. 4.8 shows the harmonic amplitude variation caused by changing the control ratio, \( r \). It can be clearly seen that the optimum performance will be obtained when \( r = 1 \). Fig. 4.9 shows the correlation between computed and measured harmonic amplitudes with the cycloconverter driving into a static load.
OPERATING FREQUENCY LIMIT TO AVOID SUB-HARMONICS IN A 3-PHASE INPUT, HALF WAVE SYSTEM

Fig 4-6 OUTPUT HARMONICS RELATED TO INPUT-OUTPUT FREQUENCY RATIO
(CONTINUOUS CIRCULATING CURRENT)
Fig. 4.7 Operation with continuous circulating current

\[ \frac{f_1}{f_2} = 6 \quad r = 1.0 \]
FIG 4.8 AMPLITUDE OF HARMONICS RELATED TO OUTPUT RATIO $r$

3 Thyristors per group Cycloconverter operating with continuous Circulating Current
Fig 4.9 HARMONIC FREQUENCIES WITH CONTINUOUS CIRCULATING CURRENT
4.2. **Reversible energy flow-variable power factor operation**

(i) **Circulating current free operation**

Suppose the positive thyristor group receives a sinusoidally modulated train of gate pulses when $0 \leq \omega_2 t \leq \pi$ and no pulses when $\pi \leq \omega_2 t \leq 2\pi$ and the negative thyristor group receives gate pulses when $\pi \leq \omega_2 t \leq 2\pi$ and no pulses when $0 \leq \omega_2 t \leq \pi$ this will correspond to circulating current free operation under a resistive load condition. In the present work the cycloconverter is connected to an inductive load (DFM), typical voltage profiles are shown for a lagging power factor load in Fig.4.10a and for a leading power factor load in Fig.4.10b. The first thyristor group will cease to conduct at an angle $\theta_2^+$ shown in Fig.4.10a which is delayed beyond the extinction point in the resistive load case. Short-circuit breakdown occurs when the extinction point of the first thyristor group coincides with the beginning of conduction in the following group, i.e. $\theta_2^+ = \theta_1^-$ in Fig.4.10a.

The cycloconverter may be used to start the machine as an induction motor (see Chapter 5). The load current displacement angle $\phi_{22}$ will be confined within the normal range, $\frac{\pi}{2} > \phi_{22} > 0$. When the system is switched to synchronous operation, this gives a regenerative condition in the cycloconverter and the fundamental load current displacement angle can exceed $\frac{\pi}{2}$. The conversion and inversion gate pulses need to be interchanged to accommodate the antiphase voltage-current situation. An additional logic circuit capable of detecting the instant when $\phi_{22}$ just exceeds $\frac{\pi}{2}$ and then performing the pulse switchover is required. This logic circuit must also reverse the current zero detection sequence. Moreover, safe operation without line to line short circuit demands a gap of up to 6 ms duration between thyristor group currents.
Fig. 4.10a  LAGGING POWER FACTOR

Fig. 4.10b  LEADING POWER FACTOR

CONDUCTION CHANGEOVER BETWEEN THYRISTOR GROUPS IN CIRCULATING CURRENT-FREE CYCLOCONVERTER
The position of this gap on the voltage wave is load dependent as shown in Fig.4.11. This results in poor voltage regulation in low power factor operation.

(ii) Continuous circulating current operation

The continuous circulating current system has no gaps in its output waveform (see Fig.4.3). It can also naturally commutate at leading or antiphase displacement angles and permit regenerative braking with no need for zero current detection or a detecting logic circuit.

4.3. The ability to avoid line to line short-circuits, due to device misfiring.

(i) Circulating current free operation

A wind generator should be capable of rapid acceleration and retardation. It should be able to maintain a near constant speed anywhere within its speed range and it must be stable when subjected to step changes of the wind turbine input. Circulating-current-free systems have been implemented in 10,000 h.p. steel mill drives, but these are essentially constant torque drives unlikely to be subjected to step changes in speed or loading. The most common and potentially catastrophic fault condition is line to line short-circuiting. In this condition both the thyristor groups conduct simultaneously and a direct short-circuit exists between two supply lines. Such a fault may be due to any of the following causes;

a) Spurious firing due to transient voltage exceeding the thyristor forward breakover voltage.
FIG. 4.11 THE EFFECT OF THYRISTOR GROUP CHANGEOVER DELAY ON THE FUNDAMENTAL VOLTAGE AND CURRENT OF A CYCLOCONVERTER OPERATING WITHOUT CIRCULATING CURRENTS
b) Spurious firing due to excessive $\frac{dv}{dt}$ generated by sudden step or cut in wind speed.

c) Momentary induction generation during braking, and
d) The detection of false current zeros under high power factor load conditions.

Misfiring due to (a) and (b) can be overcome by careful transient suppression. (c) requires additional gate logic circuitry to avoid malfunctioning and the effect, (d) can be overcome by the use of a pulse counter linked to the input to output frequency ratio to ensure that changeover always occurs on the last pulse.

A fast electronic current clamp can prevent a catastrophic failure leading to device failure or fusion if sufficient line reactance is present to avoid a current build-up sufficient to cause device failure in a time up to half period of the input voltage. This is because the current clamp can only phase back the gate pulse in the conduction period following the one in which the fault is detected.

(ii) Continuous circulating current operation

Fig.4.12a shows a 3-pulse, half-wave cycloconverter element complete with inter-group reactor. If $\frac{\omega_1}{\omega_2}$ is large, the output harmonics will be small and the system may be represented by the equivalent circuit shown in Fig.4.12b. The two voltage generators each generate a voltage $\frac{V_2M}{2} \sin \omega_2 t$ and each thyristor group is represented by a diode. Assuming that the load current $i_{22} = I_{22M} \sin \omega_2 t$ starts to flow at $t = 0$ when the load is switched on as shown in Fig.4.13a. In the first quarter-cycle, $i_{22}$ comes from the positive converter (i_p in Fig.4.13b) while the negative converter is biased off (i_N in Fig.4.13c). The circulating current,
**Fig 4.12a** 3 PULSE HALF WAVE CYCLOCONVERTER ELEMENT

**Fig 4.12b** EQUIVALENT CIRCUIT OF CYCLOCONVERTER ELEMENT
\[ i_{22} = I_{22} \sin \omega_2 t \]

Fig. 4.13a OUTPUT LOAD CURRENT

\[ i_p = \frac{I_{22}}{2} (1 + \sin \omega_2 t) \quad t \geq \frac{\pi}{2\omega_2} \]

Fig. 4.13b POSITIVE THYRISTOR GROUP CURRENT

\[ i_n = \frac{I_{22}}{2} (-1 + \sin \omega_2 t) \quad t \geq \frac{\pi}{2\omega_2} \]

Fig. 4.13c NEGATIVE THYRISTOR GROUP CURRENT

\[ i_c = \frac{I_{22}}{2} (1 + \sin \omega_2 t) \]

\[ i_c = \frac{I_{22}}{2} (-1 + \sin \omega_2 t) \]

Fig. 4.13d CIRCULATING CURRENT

\[ v_L = \frac{\omega_2 L}{2} \cos \omega_2 t \]

Fig. 4.13e VOLTAGE ACROSS INTER-GROUP REACTOR
4.10

$i_c$ (Fig. 4.13d) will be zero during the first quarter-cycle, during which time the voltage across the inter-group reactor,

$$L \frac{di_{22}}{dt} = \frac{I_{22M} \omega_2 L}{2} \cos \omega_2 t$$

as shown in Fig. 4.13e. When $t = \frac{\pi}{2\omega_2}$,

$$\frac{di_{22}}{dt} < 0$$

and the voltage across the inter-group reactor will try to reverse, but it will be clamped by the negative thyristor group diode. This means that both diodes will conduct simultaneously and the voltage across the inter-group reactor (between A and B in Fig. 4.12b) will be clamped at zero. The inter-group reactor current will then remain constant at a value equal to its peak, which means that

$$\frac{i_p N_r}{2} + \frac{i_N N_r}{2} = \frac{I_{22M} N_r}{2}$$

and hence $i_p + i_N = I_{22M} \quad (4.9)$

where $N_r$ is the number of turns of the inter-group reactor.

The output current, $i_{22}$ will consist of the difference between the two thyristor group currents, $i_p$ and $i_N$ and so,

$$i_p - i_N = I_{22M} \sin \omega_2 t$$

$$\therefore \quad i_p = \frac{I_{22M}}{2} + \frac{I_{22M}}{2} \sin \omega_2 t \quad , \quad (4.10)$$

and

$$i_N = - \frac{I_{22M}}{2} + \frac{I_{22M}}{2} \sin \omega_2 t \quad . \quad (4.11)$$

Physically this means that the circulating current is set up by energy which oscillates between the two thyristor groups without passing through the load and line to line short circuit in this way is not possible. A small amount of energy will be dissipated in the inter-group reactor resistance and a high $Q (Q = \frac{\omega_2 L}{R_e})$ reactor is necessary to maintain the circulating current. However, the precise value of $Q$ is unimportant.
4.4. Using the machine stator as a reactor.

A static high Q centre-tapped reactor capable of handling both the energy oscillating between the thyristor groups due to circulating current and the output load current will be costly and bulky. If the machine windings can be made to perform this function, a considerable saving will be made. This can easily be achieved in a double-layer stator if the layers are electrically separate. In the experimental system an experimental induction machine was used with each layer of stator winding connected as a conventional four-pole winding. The upper layer, star-connected was connected between the positive thyristor groups and neutral, while the lower layer, identically wound was connected between the negative thyristor groups and neutral. In this way each phase of the system represents an electrically separate, magnetically coupled circuit as shown in Fig.4.14a. The winding acts as an impedance to circulating currents, while providing an alternating MMF as in a conventional machine.

Circulating current operation may be considered if one phase of the system is represented by the equivalent circuit of Fig.4.14b. Here each cycloconverter group is represented by a voltage generator in series with a diode. Continuous circulating current operation requires the simultaneous conduction of both diodes. The neutral point, N, is a zero-potential point and circulating current cannot be maintained by flux storage on the principle of the inter-group reactor alone. However, it can be maintained by induction from one load winding to the other. Suppose that the positive thyristor group voltage \( V_p \sin \omega_2 t > 0 \) and conduction takes place with \( i_p \) flowing through the left-hand winding (Fig.4.14b). An e.m.f. will be induced in the right-hand winding which can maintain \( i_N \) through the inversion half cycle if this mutually induced e.m.f. exceeds the negative group
Fig 4.14a  Cycloconverter with separate winding load

Fig 4.14b  Equivalent circuit of cycloconverter with separate winding load
generator voltage. This condition can be maintained in practice by constraining the inversion voltage envelope to exceed the conversion voltage envelope, a factor which is achieved by the use of the firing circuit described in Appendix A6. Even if 100% mutual coupling at a turns ratio of unity can be achieved, circulating-current-free operation will only be achieved if the inversion voltage envelope exceeds the conversion voltage envelope in each case. Line-to-line short-circuits are eliminated because there is no electrical connection between the two thyristor group circuits, while the m.m.f. and air gap flux alternate as in the conventional machine. Now that short-circuiting has been eliminated, the thyristors are only subjected to the currents demanded by the generator.

Electrical separation of thyristor group circuits reduces the utilisation of copper and increases the apparent stator resistance and leakage fluxes. However, an increased secondary resistive effect helps to maintain synchronous generation over a much greater speed range (as shown in Chapter 6) and gives increased stability. No special machine design is required, because large machines usually have double layer stator windings.
4.5. **Controller implementation**

The controller provides the reference signal for the cycloconverter gate circuits. This is essentially a 3-phase signal generator with provision for independent control of amplitude and frequency from a signal proportional to the generator shaft speed.

The frequency control loop commands a frequency to maintain synchronism at various shaft speeds as dictated by the wind velocity. This frequency demand will be zero (d.c.) at fundamental synchronous speed ($f_1/P$) and the reference signal must change phase-sequence when passing through fundamental synchronous speed.

Optimum power generation means power generation at optimum power coefficient and a generated power proportional to the cube of the shaft speed. This is achieved by reference signal amplitude control related to frequency by a non-linear control function to be specified later.

Fig.4.15 shows the outline of the experimental system.

(i) **Frequency control**

Fig.4.16 shows the tachometer output voltage (A) and the required voltage (B) needed to command the cycloconverter output frequency plotted against speed. This frequency compensates the difference between the system angular frequency and the angular velocity of the generator shaft. The required shaper system is shown schematically in Fig.4.17. This consists of a simple R-C filter, an operational amplifier shaper (B) which moves the tachometer voltage-speed axis (0,0) to give zero output at 1500 rev/min, and a two-stage absolute value rectifier (C). The absolute value rectifier inverts the shaper output at speeds below 1500 rev/min giving a linear rise of equal shape on either side of fundamental synchronous speed. Fig.4.18 shows the complete shaper, absolute value rectifier and
Fig. 4-15 3-Phase closed-loop doubly fed machine system
Fig. (4-16) Control function for cycloconverter frequency related to speed.
Fig. 4-17  Schematic diagram of velocity feedback and reference frequency demand
To the reference generator

**Fig. 4-18** Power supply and shaper circuits showing link to tachometer and filter and absolute value rectifier
stabilised power supply. The offset controller enables the zero output point to be set at fundamental synchronous speed.

(ii) Amplitude controller

The required relationship between the cycloconverter output amplitude and the speed was defined in section 2.4.2 and displayed in Fig.(2.29). This control function can be generated by a solid state 3-phase reference generator with independent voltage and frequency control with an appropriate programme burnt into an EPROM.

A simple and cheap alternative analogue control can be used if the amplitude control function of Fig.(2.29) is linearised into that of Fig.(4.19). The analogue controller shown in Fig.(4.20) was constructed to control the amplitude output of the reference generator. Four operational amplifiers are used. The amplifiers A1, A3 and A4 shape the tachometer voltage-speed output which is then scaled by operational amplifier A2. This enables power speed cube law characteristics with different values of power coefficients to be obtained. The potentiometers allow the shapes and break point A of the function to be changed (Fig.4.19).

4.6. Reference generator considerations

The reference generator must generate a 3-phase variable-frequency, sinusoidal signal to act as a control signal for the cycloconverter. The following requirements govern the generator output;

i) Variable frequency in the range 0 to 20 Hz
ii) Variable amplitude from 0 to 15 peak volts
iii) The phase sequence must be reversible.
Fig. (4-19) Linearised control function for cycloconverter amplitude related to speed.
Fig 4-20  Analogue amplitude controller
The control sine waves are then compared with 50 Hz sinusoidal timing waves from the supply and the points of intersection of each appropriate phase are used to determine the thyristor firing points. Then the cycloconverter acts as a 3-phase amplifier, amplifying the control signals from the reference generator and exciting the DFG. The amplitude of the generated waveform may be varied independently of the signal frequency. Fig. (4.21) shows the method of generating the timing signals in the present experimental cycloconverter through timing transformers connected to the input main. In this form the timing voltage amplitude will be constant and the amplitude of the output voltage will be varied by varying the amplitude of the input reference signal.

In the experimental system, two types of reference signal generators are used. The early work was carried out using an electromechanical Velodyne Magslip generator. Later this was replaced by a digital, solid-state generator.

4.6.1. Electromechanical reference generator

(a) Methods of control

(i) Frequency control

The electromechanical reference generator consists of a 32 V Velodyne servo-motor driving a 3-phase Magslip generator with a separately excited field. Control of the Velodyne speed and Magslip output frequency is achieved by controlling the Velodyne armature voltage. The analogue armature voltage controller was required to supply 1.5 A at all voltages. A Darlington pair transistor stage was added to the operational amplifier as shown in Fig. 4.22 to increase the gain to achieve this at low speeds. Mechanical
Fig 4.21. DIRECT COSINE CROSSING PULSE TIME SELECTION SYSTEM
stiction was a problem at low speeds. The reference generator must produce a frequency equal to the difference between the shaft angular velocity in electrical radians per second and the fundamental synchronous angular velocity \(2\pi \times \frac{1500}{60}\). A change in phase rotation is required at fundamental synchronous speed (1500 rev/min). This is achieved by differentiating the control function (B in Fig. 4.16). When the slope of the control function is positive, a positive voltage is fed through a diode to change over relay which interchanges two lines of the 3-phase reference generator output. A negative control function produces no signal to the relay.

(ii) Amplitude control

The amplitude of the reference generator output is varied by control of the "Magslip" field current using the amplitude controller previously described. This amplitude control is independent of the frequency control system. The control function demands voltages of significant amplitude at very low frequencies (and d.c. at 1500 rev/min). A rotating generator is unable to generate voltages at standstill and so an electromechanical reference system cannot be used alone for continuous operation through fundamental synchronous speed. Supersynchronous operation over a useful range was achieved by the Velodyne-Magslip system.
Fig. 4.22 Driving amplifier circuit for the electro mechanical reference generator
(b) Dynamics of the electromechanical system

The electromechanical reference generator used is a Velodyne motor driving a Magslip generator having two control circuits, for independent voltage amplitude and frequency control. Two constants are now introduced into the system, a mechanical time constant due to the inertia of the rotating armatures and an electrical field time-constant due to the generator field inductance and resistance. Changes in frequency of the reference signal depend upon the speed of the reference generator and the mechanical reciprocal time constant,

\[ \omega_2 = \frac{F}{J} + \frac{k^2}{R_a J} \]  

(4.13)

where \( F \) is the frictional drag, \( J \) is the polar moment of inertia of the two armatures, \( R_a \) is the motor armature resistance and \( k \) the back e.m.f. constant. The generator field reciprocal time constant introduced due to the changes of the reference voltage amplitude will be

\[ \omega_v = \frac{R_f}{L_f} \]  

(4.14)

where \( L_f \) is the field inductance and \( R_f \) the field resistance.

Equations 4.13 and 4.14 form the basis of the cycloconverter block diagram shown in Figure (4.23a), where \( k_v \) and \( k_{u2} \) represent the amplifier gain independently in terms of voltage and frequency, and \( p \) is the Laplace operator.

The effect of the cycloconverter current clamp is to reduce the excitation of the reference generator and hence the amplitude of the reference voltage when the r.m.s. cycloconverter output current reaches a predetermined limit. In effect, the current
**Fig. 4.23a** Cycloconverter block diagram using electromechanical reference generator

**Fig. 4.23b** Cycloconverter block diagram using electronic reference generator
clamp is a voltage limiting block and it is shown as such in Fig. 4.23a. Its operation may be defined as follows,

\[ f(I_c) = 1 \quad \text{when} \quad 0 < I_{22} < I_c \quad (4.15) \]

and

\[ f(I_c) = \frac{k I_c z(\omega_2, \omega_m)}{v_c} \quad \text{when} \quad I_{22} = I_c \quad (4.16) \]

where \( z(\omega_2, \omega_m) \) is the frequency and speed dependent load impedance, \( v_c \) is the reference voltage amplitude and \( k \) is a constant.

Operation at optimum power locus of wind speeds requires fast response and high accuracy of cycloconverter output for continuous synchronisation. If the electromechanical reference generator is replaced by an electronic reference generator, the mechanical time constant \( \frac{1}{\alpha_2} \) and the time constant \( \frac{1}{\alpha_v} \) are eliminated. The block diagram then reduces to that shown in Fig. (4.23b).

A solid state 3-phase reference generator with independent voltage and phase-sequence control is a preferred solution. The timing and phase-sequence can be controlled digitally and the control function burnt into an EPROM.

4.6.2. **Electronic reference generator**

The electronic reference generator is required to meet the reference generator considerations given in Section 4.6. This signal generator develops the reference sinusoidal signals demanded by the analogue frequency and amplitude controllers described in Section 4.5. Frequency demand of all the sine wave output signals was controlled using a digital pulse train (clock pulse). The amplitude of all of
the sine wave output signals was controlled by D/A conversion using an EPROM, and a digital signal from the counter controls the phase sequence of the sine wave output signals. A simplified block diagram of the system is shown in Fig.(4.24). This is divided into four stages:

(i) The clock;
(ii) The UP/DOWN counter;
(iii) Production of the binary coded amplitudes of a sine wave using an EPROM, and
(iv) Digital-to-analogue conversion.

(i) The Clock

The frequency command, which determines the output frequency, is a pulse train which is compatible with digital integrated circuits. The pulse train required is obtained from one variable frequency clock which consists of a single RS 307-070 V/F converter and associated external circuitry (see Fig.(4.25a)). By a choice of appropriate values of $R_{in}$, $C_{ref}$ and $C_{int}$ it is possible to obtain the desired range of output frequency which is linearly proportional to the analogue d.c. input voltage - Fig.(4.25b). The clock operates at a frequency 256 times that of the required output frequency, and the range 0 to 5 kHz was chosen for this system (20 Hz maximum).

(ii) The UP/DOWN counter

An 8-bit binary up/down counter was used (by cascading two 74193 packages). The design shown in Fig.(4.26) was used to achieve a 'count up' and 'count down' sequence at a specific command.
Fig. 4.24 Independent V and f reference generator block diagram
Fig. 4.25a  Circuit diagram of clock

$$f_o = \text{clock output frequency}$$

$$C_{\text{int}} = 600\,\text{pF}; \quad C_{\text{ref}} = 150\,\text{pF}$$

Fig. 4.25b  Graph of frequency vs. analogue input voltage for V/F converter
PL = Load
MR = Master reset or clear
UP = Count-up input
DN = Count-down input
TC = Terminal count or carry
B = Borrow
+TR = Leading edge trigger
Q = Inverting output

Fig. 4.26 Schematic circuit diagram of counter stage
An 'UP' count is effected by placing the 'phase sequence command' at a high level or logical '1'. This loads a series of zeros into the data inputs of the counter via a flip-flop, and feeds the clock pulses to the 'count-up' pin of the counter. The counter then counts up to 255 or binary 11111111 and is automatically reset by the monostable to continue counting up. A buffer/driver (7407) was used as the CMOS flip-flop was unable to drive more than 2-3 TTL gates. Similarly, a logical '0' at the 'phase sequence command' implements the 'count down' sequence by loading 1's into all the data inputs of the counter and feeding the clock pulses into the 'count down' pin. This then provides the required phase reversal for the system. The counter also acts as the sequential address to the next stage, an EPROM, which holds the binary coded amplitudes of the sine waves to be fed into the D/A converter.

(iii) Production of the binary coded amplitudes of a sine wave using an EPROM

To obtain the desired sine wave output, the appropriate binary codes must be fed into a D/A converter. The D/A converter then produces an output level which is unique to the given binary input. The source of these binary codes is an Erasable Programmable Read Only Memory - an EPROM. The memory format is organised into eight pages of 256 8-bit words, each page being independently addressable. Fig.(4.27a) shows the variation of the sine wave amplitudes with count for the three phases. The axis labelled 'Count' may be thought of as being analogous to a time axis. The data for each complete cycle of each phase is stored on a 'page'. Each 'page' in turn consists of 256 8-bit words. Each word - representing an amplitude - is stored in its respective 'sequential location' in
Fig 4.27a  Graphical representation of amplitude vs. count for the three phases.

Fig 4.27b  Pictorial representation of EPRM contents.
the range 0 - 255 inclusive. Fig.(4.27b) shows the contents of the EPROM, as the sine waves have been programmed into the device as positive half-cycles; the appropriate sign-change is implemented at the D/A stage. On page 001 - where the coded amplitudes of the first phase are stored - location 64 contains the coded amplitude for the sine of 90 degrees. Similarly, on page 010 - where the amplitudes of the second phase are stored - the sine of 90 degrees occurs in location 149.

The three pages where the coded amplitudes would be stored were selected so that they could be addressed from the master clock without the need for an additional addressing system, which would have posed problems in synchronisation with the main clock. Fig.(4.28a) shows the paging system. The outputs from the three monostables (CD 4098B types COS/MOS Dual Monostables) are shown in Fig.(4.28b). The first monostable is triggered by the positive-going edge of the clock pulse. The negative-going edge of the output from the first device then triggers the second monostable and the negative-going edge of the second output triggers the third device. In this way, one clock pulse generates 3 pulses which are used to address a page in the EPROM. The monostables each provide an output pulse of 1 microsecond which is very small compared with the period of the clock (approx. 156 microseconds). This value was chosen to ensure that the EPROM had sufficient time to make the data available at its outputs. These pulses also serve to 'enable' the latches which are discussed later.

Programming the EPROM was achieved by 'burning in' the various codes into their correct locations. This was done manually by typing in all the coded amplitudes on a 'SOFTY' mini-computer unit. The programme used to generate the binary coded amplitude for the first phase is shown in Fig.(4.29a); a listing of the codes is shown
Fig. 4.28a Schematic circuit of monostables forming PAGE address to E.P.R.O.M.

Fig. 4.28b Timing waveforms
PROGRAM EPROM(INPUT,OUTPUT,TAPE7=INPUT,TAPE2=OUTPUT)
C DIMENSIONING STORAGE SPACE FOR THE EIGHT BINARY BITS
DIMENSION J(128)
C PRINTING OF TITLE
WRITE(2,5)
5 FORMAT('BINARY CODED AMPLITUDES OF A SINE WAVE')
WRITE(2,6)
6 FORMAT('**********************************************')
WRITE(2,10)
10 FORMAT('COUNT',5X,'THETA',5X,'SINE(THETA)',3X,'SCALED_UP',
17X,'BINARY',9X,'HEX')
C SET THETA TO ZERO
C SET COUNT TO ZERO
THETA=0
KOUNT=0
C OBTAIN VALUE OF PI
PIE=ATAN(1.0)*4
DO 50 1=1,256
A=SIN(THETA)
C SCALING UP SIN(THETA) TO WITHIN THE RANGE 0 TO 255
SCALE=A*255
C OBTAIN MODULUS OF SCALING UP VALUE
AMOD=ABS(SCALE)
C TRUNCATING THE MODULUS TO AN INTEGER VALUE
AMOD=AMOD+0.5
IDEC=INT(AMOD)
C BECAUSE I WANT IDEC TO BE PRINTED OUT, I USE ANOTHER VARIABLE
C WHICH TAKES THE VALUE OF IDEC, BUT WHICH WILL ALSO CHANGE ITS
C VALUE IN THE FOLLOWING CALCULATIONS.
N=IDEC
C SET ALL THE BINARY BITS TO ZERO; THESE WILL REMAIN ZERO UNLESS
C SPECIFICALLY CHANGED
J(1)=0
J(2)=0
J(4)=0
J(8)=0
J(16)=0
J(32)=0
J(64)=0
J(128)=0
C USE A VARIABLE K IN THE FOLLOWING CALCULATIONS TO INDICATE
C THE CORRESPONDING BINARY BIT. THE VALUE OF THE MOST
C SIGNIFICANT BIT IS 128; SO SET K=128
K=128
IF(IDEC)60,200,11
C TO CONVERT FROM DENARY TO BINARY, THE VALUE OF N IS COMPARED WITH
C EACH BINARY BIT IN TURN, STARTING WITH THE MOST SIGNIFICANT BIT;
C IF N>= THAT BIT, THEN THAT BIT IS SET TO '1'. THE VALUE OF THIS
C BIT IS THEN SUBTRACTED
11 IF(N-K)25,15,20
15 J(K)=1
GOTO200
20 N=N-K
J(K)=1
25 K=K/2
GOTO11
200 WRITE(2,30)KOUNT,THETA,A,IDEC,J(128),J(64),J(32),J(16),
 1 J(8),J(4),J(2),J(1),IDE
30 FORMAT('COUNT',5X,'THETA',5X,'SINE(THETA)',3X,'SCALED_UP',
17X,'BINARY',9X,'HEX')
KOUNT=KOUNT+1
THETA=THETA+PIE/128
IF(THETA<PIE)50,60,60
50 CONTINUE
60 STOP
END

Fig. 4:29 a Binary coded amplitude
generation program, phase A
in Fig.(4.29b) (the column labelled 'HEX' provides the hexadecimal equivalent of the coded amplitudes to enable ease of programming on 'SOFTY' which possesses a HEX keyboard). Programs and listings for the other two phases may be found in Appendix A8. Briefly, the programme starts by setting the value of KOUNT to zero - this corresponds to the sequential location mentioned earlier. It also sets THETA to zero as an initial value. Then the program proceeds to find the sine of THETA. The value of sin (THETA) is then scaled up to within the range 0 - 255 to facilitate conversion to its binary equivalent. THETA is then incremented by $\frac{2\pi}{256}$ while KOUNT is incremented by 1. The program continues as before until the final value of THETA = $2\pi$ is reached (or KOUNT = 255). The coded amplitudes for the other two phases are obtained in a similar manner, but with the initial and final values of THETA being displaced by 120 degrees to either side of the first phase.

iv. Digital-to-analogue conversion

The device used for this purpose is the DAC-02. This is a 10-bit plus sign D/A converter. Because of its power requirements, a separate power supply of ±15V was needed for the three units used. The DAC-02 was chosen because it has an easily accessible sign-change facility built into the device. Hence, no additional circuitry or alteration to the input coding is necessary to implement a sign-change. Fig.(4.30a) shows the block diagram for the D/A stage while Fig.(4.30b) shows the logic used to effect the necessary sign-change.

Having successfully read from the contents of the EPROM, the next problem was to convey the coded amplitudes to the respective D/A converters. This was done using three Octal Latches
Fig. 4.30a  Block diagram of D/A stage
Fig. 4-30b  Sign changing logic for phase B and C
(54LS/74LS373) to hold the information before passing it on to the D/A converters. For every clock pulse, the monostables discussed previously provide 3 pulses which are displaced in time as depicted in Fig.(4.30b).

As already mentioned, the 3 monostables select the required page to be read from the EPROM and make the data available at the EPROM outputs. Each monostable output also serves as an 'enable' command to the respective latch so that data from the EPROM is allowed to enter the latch. Once the pulse to the 'Latch Enable' is completed, the inputs of the latch are impervious to any further data attempting to enter it. The latch then acts like a Read Only Memory, allowing the data to be read from its outputs. This data enters the appropriate D/A converter which gives an output proportional to the coded input. On the next clock pulse, a fresh sample of data enters the latch, the previous data being 'discarded', and the process is repeated as described above.

Each latch-D/A pair is uniquely associated with one phase so that only one main clock is required to produce all three phases, the only limitation being that the clock period be sufficiently long to enable 3 pages to be read from the EPROM.

Sign-changing for the first phase was a simple matter. From Fig.(4.27b) it can be seen that the output of the D/A converter must be negative from a count of 123 to 255. This was done by using the Most Significant Bit of the counter outputs, putting this through an inverter (54/7404), and then to the sign-change pin on the D/A converter - see Fig.(4.30a).

Sign-changing for the other two phases was achieved using the AND gates and flip-flops of Fig.(4.30b). Referring to Fig.(4.27b), for phase B, the requirement is that the output be negative for a
count from $0 - 85$, then it must become positive from $86 - 213$, after which it goes negative again. Similarly, for phase $C$, the output must change sign at points $43$ and $171$ in the count. It was therefore necessary to identify these changeover points in the count. At these points, a pulse was required to change the output of the trigger flip-flop which consequently changed the sign of the output of the D/A converter. Table 3 below summarises these requirements.

Table 3 - Changeover points for Sign-change

<table>
<thead>
<tr>
<th>PHASE</th>
<th>COUNT</th>
<th>BINARY</th>
<th>SIGN-CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>128</td>
<td>10000000</td>
<td>+ve to -ve</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>00000000</td>
<td>-ve to +ve</td>
</tr>
<tr>
<td>B</td>
<td>85</td>
<td>01010101</td>
<td>-ve to +ve</td>
</tr>
<tr>
<td></td>
<td>213</td>
<td>11010101</td>
<td>+ve to -ve</td>
</tr>
<tr>
<td>C</td>
<td>43</td>
<td>00101011</td>
<td>+ve to -ve</td>
</tr>
<tr>
<td></td>
<td>171</td>
<td>10101011</td>
<td>-ve to +ve</td>
</tr>
</tbody>
</table>

Sign-changing for phase $A$ has already been dealt with. For phases $B$ and $C$ however, a method had to be found to uniquely identify and isolate the 2 points where sign-changes were to occur. This was done by using the AND gates (54/7421) of Fig.(4.30b). By inverting all the 0's shown in Table 1, and then combining the 7 Least Significant Bits of the counter outputs with a logical '1' via a 2-input AND gate, the gate output was 'high' only at the 2 specific change-over points for each phase. The resulting pulses were then fed into a trigger flip-flop, thus changing the level at its output. This level change was in turn fed to the appropriate D/A converter to change the sign of its output.
The relationship between the amplitude of the three phase sine waves generated to their frequency has been shaped to meet the requirement of optimum power generation, via the D/A converter and V/F converter (see Fig.(4.24)). The amplitudes of all three phases of the reference generator must vary simultaneously and together follow the function of Fig.(4.24). Additional buffer stages were added to vary the output in proportion to the control signal from the absolute value rectifier of Fig.(4.20). The following figures show the results obtained with the system controlled to run synchronously above the fundamental synchronous speed (1500 rev/min) and delivering power $a(speed)^3$ using the electronic reference generator commanded by simple analogue frequency and amplitude controllers. Fig.(4.31) shows the variation of the amplitude control function for a range of output constants, $K_g$. The appropriate output powers are shown in Fig.(4.32), and a breakdown of output power into primary and secondary power is given in Fig.(4.33). It is significant that the power through the cycloconverter falls with increasing supersynchronous speed. Primary and secondary currents against speed are shown in Figs.(4.34) and (4.35).

4.7. Conclusions

The requirements of the electronic exciter, to control a doubly-fed generator driven by a wind-turbine connected and feeding power directly into the grid have been considered. A cycloconverter rather than an inverter has been adopted because of its natural commutation. (Commutating capacitors, d.c. chokes are dispensed with.) The cycloconverter allows power flow in either direction with no additional circuits.

It has been shown that the continuous circulating current operation produces a minimum output harmonic content independent of the
Fig. 4-31 Control function for frequency and amplitude command

Fig. 4-32 Power speed\(^3\) by control function of Fig. 4-31
Fig. 4.33 Power flow chart of mechanical power-speed of Fig. 4.32
Fig. 4.34 Primary current/speed for the control function of Fig. 4.31

Fig. 4.35 Secondary current/speed for the control function of Fig. 4.31
condition of loading. It can be operated with leading or lagging power factor.

The significant fault condition of line-to-line short circuits has been prevented by electrically-separate, magnetically coupled thyristor group circuits. This enables the machine to cope with the wind rotor under wind gust conditions.

The overall utility has been improved by eliminating the bulky and costly external inter-group reactors and using the machine stator to perform the function of the reactors. Integral cycle blanking required for circulating current free operation is unnecessary. The number of thyristors used in the cycloconverter are halved by using a neutral point star-connected transformer.

The frequency and amplitude of the cycloconverter has been controlled independently by the speed of the turbine to achieve the optimum operating condition. Two analogue controllers have been designed and constructed to control the frequency and the amplitude of the reference generator.

Two reference generators have been used, an electromechanical reference generator and an electronic digital reference generator. The digital system eliminates two time constants of the electromechanical system. In both systems the frequency and amplitude were shaped using the same analogue shaper.
Chapter 5

The Operation of the Complete System

Chapter 3 described the operating principles of a small experimental wind generator with optimum gear ratio interfaced with the supply grid through a doubly-fed generator. If such a system is to be considered in practice, the following operational problems have to be considered.

1) The procedure for starting and acceleration from standstill until the wind power can maintain rotation.

2) Synchronising the generator.

3) Resynchronising after a momentary interruption of the grid supply.

4) The events following a sudden overload pulling the generator out of synchronism.

5) Retaining synchronism through fundamental synchronous speed, and

6) The ability of the system to cope with wind gusts.

5.1. Start-up procedure

Self-starting by wind power can be achieved if a variable blade angle wind turbine is used. When an appropriate pitch is selected, the rotor will accelerate the turbine from standstill up to the minimum rotational speed at which the system can be synchronised. This speed is known as the cut-in wind velocity. The selection of an optimum gear ratio will match the cut-in speed to the cycloconverter frequency limit defined by \( \omega_1 - P \omega_0 \), where \( \omega_1 \) is the supply angular frequency, \( \omega_0 \) is the optimum angular velocity and \( P \) is the number of pole pairs.

The cycloconverter will only conduct when the reference signal is
applied. At zero reference voltage, the cycloconverter output impedance is very high, and so the 3-phase supply can be permanently connected to the cycloconverter and the slip-rings. If the system is asynchronised and the reference signal is removed, the generator is in effect an induction machine with open-circuited secondary, drawing only magnetising current. Then the turbine will, in effect, only be accelerating the inertia of the system. If the phase rotation of the generator and the grid are the same, the cycloconverter reference signal can be applied at the cut-in wind velocity and the generator will synchronise to the grid. The amplitude and frequency of the reference signal are demanded by the velocity feedback controlled shaper network described in Chapter 4.

Variable-pitch wind turbines are expensive and they require complex blade angle control systems. The doubly-fed machine can operate at speeds over a wide range, with output control related to the wind velocity. Consequently, a fixed blade turbine can be used and variable pitch operation dispensed with, providing the generator can self-start as an electric motor.

Fixed blade wind turbines are difficult to self-start and induction generators are often used so that they can run up to cut-in speed as induction motors. Pony motors are used to start synchronous generators. The doubly-fed machine can be used in a self-starting mode with a fixed blade turbine by isolating one supply and short-circuiting the machine secondary. The machine then accelerates to cut-in speed as an induction motor. Then the secondary short-circuit is removed and the secondary reconnected to the cycloconverter. The cycloconverter reference signal is applied at zero slip and synchronisation achieved with the minimum induction power transient through the cycloconverter.

The high induction starting current incurred in direct-on-line starting at 50 Hz (5-6 times of full load) may be reduced if the
cycloconverter can accelerate the machine at a lower frequency with the primary short-circuited until the cut-in speed is reached. Then the primary can be reconnected to the supply and the cycloconverter reference voltage applied at the appropriate frequency demanded by a velocity feedback signal. This will then synchronise the machine to the supply. The optimum gear ratio is selected as a design feature to increase the cut-in speed to the lower speed limit dictated by the cycloconverter frequency limit. The starting up procedure given above has been developed on the assumption that the machine will operate at both sub- and super-synchronous speeds.

The experimental system has been designed to be compatible with the Rutherford Laboratory aerogenerator which operates on a variable geometry axis, using its aerodynamic characteristics to operate on the optimum power locus (maintaining the maximum tip speed ratio constant at $\mu_{\text{max}} = 5.14$). Referring back to Fig. 3.9, we can see that if operation is to be maintained on the optimum power locus, the minimum operating speed is 60 rev/min. Cut-in must occur at 60 rev/min and the upper limit is 82 rev/min. With a suitable choice of gear ratio, the doubly fed machine can effectively operate within this rotational speed range, operating entirely above fundamental synchronous speed. This would eliminate the phase rotation reversal network.

Super-synchronous speed operation has a higher efficiency than sub-synchronous speed operation because the three power components of the output (two induction and one synchronous) all represent power generation. Sub-synchronous operation is less efficient because the 50 Hz induction torque is a motoring torque drawing power from the supply. The complexity of designing a system to pass through, the fundamental speed (see Section 5.5) can be avoided. The gear ratio is chosen so that the cut-in speed is above synchronous speed, while the ability to accelerate from standstill is maintained.
5.2. **Methods of Synchronising**

The synchronizing process in a conventional synchronous generator depends on the generator speed, the phase rotation and the generated voltage amplitude which is a function of the d.c. field current. In the doubly-fed machine, generation occurs at a leading load angle, where the load angle is dependent on a non-linear exciting-voltage speed control function as shown in Equation 2.31. The conditions to be satisfied for the synchronizing process are:

(i) The angular speed of the machine to be connected to live bus-bars must be such that its frequency is nearly the same as the angular frequency of the busbars supply, i.e. \( \omega_1 = P\omega_0 + \omega_2 \), where \( \omega_1 \) is the supply angular frequency, \( \omega_0 \), the optimum angular velocity and \( \omega_2 \) the cycloconverter angular frequency.

(ii) The two induced e.m.f's in the primary and secondary windings should be co-phasal.

The rotational speed will depend on the wind speed. Hence, \( \omega_2 \) must vary in phase and amplitude as a function of speed. This has been achieved by feeding a tachometer output into the cycloconverter control system. Excessive current through the cycloconverter is prevented by electronic current clamping commanded by a current transformer signal when the specified current is reached. Thus any "overshooting" of cut-in speed does not cause catastrophic failure.

5.3. **Disconnection from the Grid**

Any interruption of supply from the grid removes the torque opposing the wind turbine and rapid acceleration to a dangerous speed results. A mechanical brake incorporating a slipping clutch which
5.5

5.4. **Overload and System Shutdown**

An advantage of using a doubly fed machine excited by a cycloconverter is that the loading to the turbine can be easily adjusted by controlling the excitation voltage. Changing the load torque of the machine in response to the control system means that better matching can be achieved between the turbine and the load. It was shown in Chapter 3 Fig.(3.7), that the doubly-fed machine can be controlled to follow the maximum power line of a wind turbine. If the wind turbine can extract power at rotational speeds related to wind speeds by the optimum tip speed ratio \( \left( u_{\text{max}} = \frac{\omega_0 R}{V} \right) \), the machine will load the turbine sufficiently to maintain the optimum operating condition until rated wind speed is reached (at which maximum power for the plants occurs). Operation beyond this rated wind speed will be explained later. When operating at less than optimum conditions, the wind turbine may extract the power for the same wind speed but at a higher tip speed ratio. Then the rotational speed will increase and its dependent excitation control function automatically decreases. If a steady state condition follows, matching is achieved and the system operates at a lower power coefficient. When the turbine ceases to recover by extracting higher power at the given wind speed, the rotor adjusts its rotational speed to the optimum value and the required new excitation automatically takes place. If this adjustment of excitation takes too long, an overload may cause the load angle \( \alpha \) to exceed \( \frac{\pi}{2} \) and pull the machine out of synchronism. The machine will
then operate as a doubly-fed induction machine at high negative slip. The synchronous power will be zero and output power is now two induction powers $P_{I1} + P_{I2}$. The range of slips at which regenerative braking will occur is approximately defined by the ratio of the slip dependent resistance to the slip independent resistance. In the slip range $0 > s > -\frac{r_d}{r_1}$, where $r_d$ is the slip dependent resistance and $r_1$ is the slip independent resistance, the braking at a fixed frequency will be regenerative and energy will be returned to the supply. Beyond this range when $s < -\frac{r_d}{r_1}$, braking torques will be produced but the kinetic energy of the system will be dissipated in the machine. With the secondary fed and the primary assumed to be short circuited, the braking is always regenerative, where the system slip $s_1$ is a high negative slip $\gg \frac{r_d}{r_1}$ and defined by $s_1 = \frac{\omega_2 - \omega_1}{\omega_2}$. In the primary fed system with the secondary assumed to be short circuited the ratio $\frac{r_d}{r_1} = -\frac{r_2}{r_1}$ must be less than $s$. In the experimental system $\frac{r_2}{r_1} = 4.55$ and the braking was always regenerative.

As shown in Chapter 2, the constant current excitation increases the efficiency and decreases the required rating of solid state devices at the expense of a reduced maximum power output limited by the load angle $\alpha$. To match the maximum power locus from cut-in to rated wind speed, constant current excitation will have a reduced range of operation than when compared with voltage excitation. Constant current excitation reduces the induction power to a very low level which makes the induction braking effect ineffective.

If runaway after pull-out occurs, dynamic braking must be applied immediately. In the present experimental system braking is achieved by switching to voltage excitation and introducing effective external secondary resistance by means of the current form factor control described in Chapter 2. The lower speed limit for induction braking is fundamental.
synchronous speed. When the speed is back within the synchronous range, the system is resynchronised.

Short time operation beyond the rated wind speed range depends upon the aerogenerator characteristics. The two different types of wind turbine characteristics are shown in Figs.(5.1) and (5.2). Fig.(5.1) shows the first type of WTG characteristics and compares the output characteristics of the Rutherford wind turbine and the laboratory experimental system in terms of wind velocities in m/sec. Any increase in wind velocity beyond the rated wind speed will cause a decrease in the optimum tip speed ratio. The maximum power coefficient will fall and low efficiency power extraction results. Using the Rutherford wind turbine characteristics, the maximum power locus is defined between a cut-in wind speed of 3.5 m/sec and a rated wind speed of 5 m/sec. Any increase beyond 5 m/sec will drop the maximum power coefficient (see Appendix A4, Table 1).

The second type of wind turbine characteristic is the NASA-NSF 150 kW system shown in Fig.(5.2). It has a cut-in wind speed of 8 miles/hour and a rated wind speed of 18 miles/hour. It can extract maximum power during very strong gusts between 18 and 60 miles/hour. Normally a doubly-fed generator will operate, allowing for a suitable gear ratio, within the wind velocity range of 8 to 18 miles/hour. The generated power must not exceed a maximum value of 150 kW as shown in Fig.(5.2). If a short strong wind gust occurs it causes the wind turbine to accelerate beyond the maximum rotational speed limit of the maximum cycloconverter output frequency. The cycloconverter must then be replaced by a variable resistance bank and the machine will operate as a constant power induction generator until the gust is over, when resynchronisation can take place. This NASA generator requires the disconnection of the cycloconverter, but the present author's experimental
Fig. 5.1 Comparison of the Rutherford turbine and the Leicester DFM characteristics.
Fig. 5:2 Nasa wind turbine characteristics

- Wind turbine power
- D.F.G. power
- Induction generator power
system can achieve the effect of added resistance by secondary form factor control as shown in the 8 pole experimental results of Fig.(5.3). Here the maximum speed limit defined by the experimental cycloconverter excitation is 1050 rev/min., where the current form factor has been changed in the range of 1050 to 1200 rev/min. to match the cube law. The principle should be applicable to large systems. Power generation will be required to match the NASA characteristics beyond this range, constant.

If the wind gust lasts longer than five minutes, the system will automatically shut down. The blades will be feathered at a fixed rate reducing the input torque to the generator to zero. When the doubly-fed generator power output is zero, the feedback circuit to the reference generator may be opened and the shaft brake engaged.

5.5. **Operation through Synchronous Speed**

If the doubly-fed generator is to be operated at speeds above and below fundamental synchronous speed and to pass smoothly through fundamental synchronism, the control amplitude function will have a profile of the form shown in Fig.(2.29). This function peaks at fundamental synchronous speed to allow the cycloconverter to increase excitation and the synchronous power component when the generated induction power falls to zero. This control function amplitude maintains the power generated in the relationship with speed, $P_g = k \omega^3$. However, a severe problem of continuous operation through fundamental synchronous speed is the necessity of changing phase rotation. A positive phase rotation when $s > 0$ must be changed to a negative rotation when $s < 0$. The selection of the correct instant for the reversal of phase rotation while stability is maintained is difficult. If an error in selecting the switching point occurs, the generator may oscillate.
Pole switching can provide a range of fundamental synchronous speeds which allow the generator to operate super-synchronously throughout the wind speed range. To achieve this effectively, close-ratio, pole-amplitude modulation with, say, 6, 8, 10 poles is necessary. This in a doubly-fed machine means pole switching the rotor as well as the stator, with the uneconomic disadvantage of multiple slip-rings.

Pole changing with a 2-1 ratio using a Dahlander winding is simpler to achieve, but the range of cycloconverter exciting frequency required to switch from one pole number to the other is too large to maintain an acceptable harmonic level. However, if a full-wave cycloconverter with double the number of devices is used a 2-1 pole changing system may be possible.

Fig.(5.3) shows the results of the experimental system operating in 4- and 8-pole modes. The rotor in the experimental machine is tapped for a Dahlander connection and brought out to 6 slip rings. Pole-switching is possible but the gap between the two characteristics is so wide that an exciting frequency range of 0 to 50 Hz is necessary, clearly an impossibility with a cycloconverter.

5.6. Problems due to Gusting

P.A. Sheppard has discussed the changes of speed which occur in natural winds with reference to different time scales and has shown that, whether the units on the time scale be seconds, minutes, hours, days or even years, the graph of wind speed can always be represented as a curve fluctuating relatively slowly with a more rapid fluctuation superimposed on it. From the point of view of wind power, the slower variations are of interest in so far as they affect the turbine energy output; rapid changes (gusty wind condition), occurring in steps of one second or less, are particularly important for calculations of blade stress (for blade
Fig. 5.3  Speed range to be bridged by pole amplitude modulation if super-synchronous operation is required over a wide speed range.
design consideration) and for the wind driven electronically controlled
generators dependent on wind speeds and synchronised to the grid.

Information on the actual behaviour\textsuperscript{59} of the wind under gusty
conditions yields to three important types of input power to the wind
driven electrical generator which must be considered. The three forms
are:

1) an impulse input;
2) a step input; and
3) an oscillatory input.

Variable speed, constant frequency in a modern wind driven generator
requires an electronic control system if a rapid response is to be
achieved. This impulse, step, oscillating input will cause surges of
power and current which can induce incorrect firing of the thyristors due
to the excessive rate of rise of current.

In a conventional winding system of the doubly-fed generator, the
cycloconverter must detect current zero points and change operation from
the positive to the negative thyristor groups, a very precise and expensive
integral cycle blanking circuit to prevent simultaneous conduction of the
thyristor groups is necessary.

In the scheme reported in reference 4, a doubly-fed machine with
variable frequency rotor excitation has been used in a 250 kW installation.
Here the practical limitation is the inability of the converter to conduct
the large rotor current surges occurring during gusting. Exciting capaci-
tors and a swamp resistance are used to dump the excess energy by self-
excited induction generation until the gust is over.

In the system described in this thesis, the positive and negative
thyristor group circuits of the cycloconverter are kept electrically
separate by a divided winding stator arrangement. The possibility of
transient line to line short-circuits through the converter is eliminated
and the system is able to withstand severe input surges.

Fig.(5.4) contrasts circulating current free operation with a conventional winding with the performance of the same machine with a divided winding and continuous circulating current. These traces were taken with a fixed cycloconverter frequency (no feedback) to illustrate "pull-out". It shows the system behaviour when subjected to a shock impulse of input torque. In the upper trace, Fig.(5.4a), the generator is operating with a conventional winding and integral cycle blanking. The shock torque sets up an oscillation at the natural frequency of the system which leads to pulling out of synchronism. When the divided winding is used, the system recovers after a much more severe input impulse as shown in Fig.(5.4b). The results given in Fig.(5.4) were obtained when the machine was driven by a d.c. motor. Impulse torques were applied by the application of an impulse armature current while the shunt field was maintained constant.

To simulate wind gusts, the prime mover armature current was programmed to vary in proportion to the square of the wind velocity. Traces of the machine response to a simulated wind gust have been recorded using the Evershed pen recorder to trace the simulated wind input torque and the doubly-fed generator speed variation against the time.

Torque records were obtained by taking a signal from an electronic torque transducer "TMGR, British Hovercraft Co.Ltd." to the pen recorder. The torque transducer utilises a network of bonded foil strain gauges as the torsion sensing element. The gauges are cemented to the high tensile torsion machine shaft and are protected for life by a resin film. The gauges are connected in a full bridge circuit in such a way that an electrical bridge unbalance is created by torsional strain. The arrangement is such that the shaft strains due to bending, thrust and temperature are self-cancelling and do not contribute to the electrical output. The
Fig. 5.4a Effect of input torque impulse standard winding, \( f_2 = 13.33 \text{ Hz}. \)

Fig. 5.4b Effect of input torque impulse divided winding, \( f_2 = 13.33 \text{ Hz}. \)
transducer output voltage signal (20 mV) was insufficient to drive the pen recorder and a d.c. operational amplifier with a gain of 10 was used. The speed-time traces were obtained by feeding the d.c. tachometer (attached to the shaft) output into the second channel of the Evershed pen recorder.

The time-dependent variations were determined from traces of typical wind-turbine outputs. Fig.(5.5) shows the operation of the system when subject to large input oscillation near to fundamental synchronous speed. The inertia of the two coupled machines smooth out the generator speed profile. Fig.(5.6) and (5.7) show the effect of the impulse torques produced by input impulses and steps, a semi-wind gust condition. These results are contrasted with the wind velocity variation during a storm (Fig.5.8) at Costa Hill, Orkney. The trace indicates how steeply the wind increases during a gust.

Having operated successfully with oscillating impulse and step inputs, a series of tests based on site wind data were carried out. This information of the wind pattern under gusty conditions is essential to predict the rates of change of wind velocity which are likely to occur during gusts, and to indicate whether this range can be covered by the cycloconverter frequency.

Fig.(5.9) shows the traces of two records obtained from a gust anemometer developed by the Electrical Research Association. The records refer to measurements of wind velocity made at the top of a 30 ft. tower at the summit of Costa Hill, Orkney, during a period when the wind was very gusty, following the passage of a fast-moving cold front. The mean speed during the test period is just over 40 m.p.h. It will be seen from the record (a) that the highest rate of change was from 52 m.p.h. to 85 m.p.h. in ½ sec. Record (b) shows the rise and decay of a gust, with a maximum speed of 70 m.p.h., during some 4 sec. following a period of very steady wind speed.
Fig. 5.5 Oscillatory wind velocity

Fig. 5.6 Slow rise and decay with impulse torque
Input torque, Nm

Fig. 5-7 Step response contrasted with Costa Hill, Orkney, storm condition

Portion of record from special cup generator anemometer installed on Costa Hill, Orkney. The record shows gusts up to 125 m.p.h. during a storm.
The wind velocity characteristics of a typical, very gusty period converted into shaft torques and velocities, having the same sharp, high rate of change, have been applied in the experimental system as shown in Fig.(5.10). The highest increase in wind velocity in the Costa Hill records is 163% ($\frac{85}{52}$) in $\frac{1}{4}$ sec. This will increase the input torque (proportional to the square of the wind speed) by 267% in the same time. An increase of 400% of the input torque of the doubly-fed machine in $\frac{1}{5}$ sec has been applied as shown in the third impulse of Fig.(5.10). Over 5.5 sec a very sharp simulated wind gust was applied to the machine and then followed by steady state operation. Fig.(5.9) contrasts the wind velocity pattern with the simulated operation effects in the experimental system of Fig.(5.10). The doubly-fed machine copes well with the simulated wind energy input over a speed range which strictly exceeds the permissible range of the cycloconverter. The generator was brought up to 2400 rev/min. Then it accelerated quickly through fundamental speed, fell back to 1000 rev/min and returned to the same top speed of 2400 rev/min. Continuous transient operation for two different wind gusts over 10 sec. and 120 sec. periods are shown in Fig.(5.11b) and (5.12b) in contrast with wind gust records of (5.11a) and (5.12a) respectively. Fig.(5.13) shows the effect of a step increase during a steady-state operation.

5.7 Conclusions

The doubly-fed machine with a divided-winding secondary excited enables a cycloconverter to operate in the continuous circulating current mode. This has been shown to be an effective wind energy transducer directly coupled to the grid. As a complete system, the following advantages over synchronous and link-inverter, slip-ring systems have been demonstrated.
Fig. 5.9 Gust records from Costa Hill, Orkney

Fig. 5.10 Operation with simulated wind gusts
Fig. 5.12a
Gust records from Costa Hill, Orkney

Fig. 5.12b Longer term operation
Fig. 5.13 Operation with controlled small step changes
(i) The pilot machine needed to start the fixed-pitch windmill is unnecessary. The doubly-fed generator system can be started by using the doubly-fed generator as an induction motor. The associated high starting current of the induction machine can be avoided if a cycloconverter is used as a low frequency supply to accelerate the machine from standstill. In this, the secondary is used as the primary. Care must be taken to ensure that the machine "cuts-in" at the correct wind speed.

(ii) The three-phase supply can be permanently connected to the cycloconverter and the slip-rings. If the system is asynchronised and the reference generator is removed the generator operates as an induction machine with an open circuit secondary (because of the high output impedance of the cycloconverter) drawing only the magnetising current. The turbine will be accelerating the system inertia, which will require a mechanical brake if the supply is not restored within seconds.

(iii) During acceleration, the reference generator signal must be applied at the moment at which the wind speed is high enough to accelerate the system (cut-in speed). The cycloconverter will then synchronise the machine to the system by compensating the difference between its frequencies, taking the phase sequence into account and controlling the load angle to maintain synchronism by a non-linear exciting voltage speed control function. Automatic synchronisation will be easy to achieve.

(iv) In addition to a mechanical brake acting in case of failure of the supply, regenerative electrical braking in case of loss of synchronism due to overloading can be provided by increasing the secondary resistance effectively by changing the cycloconverter current form factor.

Continuous operation through fundamental synchronous speed necessitates the change of phase rotation and a peak d.c. component to maintain power/$(\text{speed})^3$ relationship at zero induction power. This change may cause
oscillation and so operation above \( \frac{f_1}{p} \) is preferred. It allows for the cut-in wind speed to be adjusted to \( \frac{f_1}{p} \), i.e. at a minimum induction current with no possibility of induction motoring. The complexity of passing through the \( \frac{f_1}{p} \) speed will be dispensed with.

Pole amplitude changing has been applied to increase the super-synchronous speed range operating with a half-wave cycloconverter excitation system. The simpler 2-1 pole switching using Dahlander winding has been used to increase the speed range in sub- and super-synchronous operating modes (with passing through the fundamental synchronous speed). However, the changeover of pole numbers occurs at a cycloconverter frequency demand beyond the limit of normally accepted harmonics.

The machine (DFG) has been subjected to a completely and uniformly distributed wind as well as to very gusty wind conditions. A series of tests related to the Costa Hill, Orkney, wind velocity profiles have been carried out. The experimental doubly-fed generator system copes adequately with all steady-state and the most extreme storm-gust conditions.
Chapter 6
Assessment of the Complete System

The maximum conversion efficiency of a wind powered electrical generator can be achieved when the energy transducer can fluctuate in speed in sympathy with the wind-speed variation. This has been achieved with a doubly-fed machine operating as a generator with velocity controlled excitation. Synchronism throughout the operating range is maintained by automatic frequency control of the exciting cycloconverter. A novel feature of the control system is the independent amplitude control of the cycloconverter. The amplitude control function has been matched in a shaper network to enable the retarding torque of the generator to match the turbine shaft torque. Torque matching is achieved with high system stability due to the high mechanical source impedance.

The cycloconverter excited generator has a capability of withstanding step and impulse power inputs caused by wind gusts, believed to be far in excess of link inverter and integral cycle blanking cycloconverter excited systems. This is due to the electrical separation of the positive and negative thyristor group circuits by the use of a divided-winding machine secondary, used for the first time in a generator system.

A solid state 3-phase signal generator designed and constructed in TTL logic has eliminated the inertia time-constants of the conventional electro-mechanical reference system. Greatly increased stability results.
6.1 The use of the divided winding in the doubly-fed wind generator

It was shown in Chapter 4 that one way of preventing most input line short circuits caused by simultaneous firing of the positive and negative thyristor groups when a sudden load torque is applied (by a wind gust) is to electrically separate the thyristor group circuits. The associated disadvantage of increased copper loss and reduced efficiency is not a serious problem because the cycloconverter current in the divided winding is mainly exciting current in the doubly-fed generator system. Ideally, the electrically separate, system should produce the same air gap flux as that produced by the same machine with a standard winding. Suppose a machine has a double layer stator winding, each layer having \( N_2 \) turns per phase belt excited by a current \( I_{22m} \sin \omega_2 t \). The resultant m.m.f. will be \( 2N_2 I_{22m} \sin \omega_2 t \), if the upper layer carrying positive group current and the lower layer carrying negative group current carry the same peak current as the standard winding. The peak current required to produce the same m.m.f. will be \( 2I_{22m} \). Each stator phase belt resistance is \( r_2 \) ohms per winding layer. In the standard winding the copper loss dissipation per phase belt will be

\[
\frac{I_{22m}^2}{2} \cdot 2r_2 = I_{22m}^2 r_2 \text{ watts.}
\]

The r.m.s. value of the current in a thyristor group circuit of amplitude, \( 2I_{22m} \), will be

\[
I_{\text{rms}} = \left[ \frac{1}{2\pi} \int_0^\pi (2I_{22m} \sin \omega_2 t)^2 \cdot \omega_2 \cdot dt \right]^{\frac{1}{2}} = I_{22m}
\]

(6.1)

Thus the dissipation in the stator winding of a divided winding machine is \( 2I_{22m}^2 r_2 \), twice the value incurred in the same machine with standard stator connections.
In the present system, the stator winding has been considered as the secondary winding, and as shown in Chapter 2, the secondary current is controlled to be less than 25% of the primary current. Three powers are generated, when considering voltage excitation systems, synchronous power $P_s$ and two induction powers $P_{I1} + P_{I2}$. The induction power $P_{I2}$ is mainly excitation power $\ll P_{I1}$. The divided winding in this case acts as an additional external resistance for $P_{I1}$. In addition to the important advantage of preventing line to line short circuits, the following advantages to the wind generator system are gained. The divided winding

(i) stabilises the doubly-fed generator by moving the peak induction generating torque to a higher negative slip,

(ii) increases the efficiency above 1800 rev/min, (for 4 pole machine) because of the increase of unidirectional synchronous power,

(iii) reduces the induction components of primary and secondary power and current, and

(iv) improves the power factor.

Fig.(6.1) shows a computed comparison based on equations (2-18) of the induction power and synchronous power contrasting standard and divided winding techniques. In standard winding operation, the synchronous power changes from generating to motoring power around the fundamental synchronous speed to make up the difference between the induction power and the input power. This change of mode of synchronous power from generation to motoring can cause inherent instability of operation due to this "tunnelling" characteristic. The increased effective resistance of the divided winding stabilises the machine by moving the peak induction power to a higher speed and
Fig. 6.1 Breakdown of powers into synchronous and induction power.
allows a steady increase of synchronous power with a single sense
(always -ve with $\omega$). This also improves the efficiency at speeds
above 1800 rev/min. as shown in Fig.(6.2). The effect of a divided
winding on the excitation side (secondary) reduces the current but
demands an increase of excitation voltage as shown in the computed
figures (6.3) and (6.4).

At each speed, the induction power has been reduced due to the
moving of the peak power to a higher speed by the divided winding.
This allows more synchronous power to be produced, improving the power
factor and reducing the primary current as shown in Figs.(6.5) and (6.6).
The divided winding carries out the mutually coupled role of the con-
ventional inter-group reactor allowing continuous circulating current
operation. Continuous circulating current operation reduces the har-
monic content of the exciting voltage and extends the operating range
as previously shown in Chapter 4. Integral cycle blanking and bulky,
costly external inter-group reactors are also eliminated.

6.2. The use of the cycloconverter and its suggested improved technique

The cycloconverter has been used as an exciter, developing a
load angle dependent excitation voltage at each speed to minimise the
power through the cycloconverter and to improve the machine stability.
The cycloconverter is naturally commutated. Forced commutation
components i.e. capacitors or chokes are not necessary. Cycloconverter
short circuits will not be possible because of the special machine
windings and so reactors are also unnecessary. Magnetic coupling of
the electrically isolated windings eliminates harmonics and permits
good circuit waveforms to be generated. The cycloconverter used is a
half-wave cycloconverter with a neutral point connected to a star-delta
transformer. With twice as many devices, a full-wave cycloconverter
Fig 6.2  Effect of the divided winding on the doubly-fed wind generator efficiency
Fig 6.3 Secondary current when excitation voltage of Fig 6.4 is used.

Fig 6.4 Excitation voltage-speed function for power-speed operation.
Fig. 6.5 The primary power factor as affected by synchronous power variation of the D.F.M.
Fig. 6.6 Primary current minimisation corresponding to power factor improvement of Fig. 6.5.
may be used and the star-delta transformer eliminated.

The use of a three-phase solid state reference generator eliminates the electromechanical time constants associated with the electromechanical reference generator (a Velodyne driving a Magslip reference generator).

6.3. Assessment on System Stability

In general, wind turbine generators comprise a turbine, mechanical transmission (usually a gear box) and a generator. The turbine, each stage of the gearbox, and the generator may be represented by a simple lumped torsional inertia \( J \), interconnected by flexible shafts of torsional stiffness \( K_s \), and a damping coefficient \( D \) as shown in Fig.(6.7). Preliminary calculations given in reference 12 show that there is sufficient difference between the turbine torsional natural frequencies and the aerodynamic forcing frequencies to suggest that as a first approximation flexure and damping in the power train can be neglected. Based on this assumption the mechanical power train was modelled using the following general form of equations governing the motion of each lumped inertia in the system.

\[
\begin{align*}
J \frac{d\omega}{dt} &= T_A - T_e
\end{align*}
\]

where \( T_A \) is the aerodynamic driving torque, and \( T_e \) is the electrical doubly-fed machine generating torque.

Chapter 3 defines the optimum power line in the form

\[
P_o = K_o \omega_o^3.
\]

The corresponding torque values are

\[
T_A (P = P_o) = K_o \omega_o^2.
\]
From (3.1) and (3.2),

\[
\frac{C_p}{\mu} = \frac{T_A}{\frac{1}{2} \rho \pi R^3 V_1^2} = C_Q \tag{6.4}
\]

where \( C_Q \) is the torque coefficient.

Taking

\[
K_A = \frac{1}{2} \rho \pi R^3
\]

\[
T_A = K_A C_Q(\mu)V_1^2 \tag{6.5}
\]

Substituting Equation (6.5) into (6.2) gives

\[
J \frac{\partial^2 \omega_g}{\partial t^2} = K_A C_Q(\mu)V_1^2 - T_e \tag{6.6}
\]

It was shown in Chapter 2 that the doubly-fed generator rotates synchronously at the sum or the difference of the two applied frequencies. The two e.m.f's \( E_1 \) and \( E_2 \) rotate at the same speed with the difference angle (load angle) \( \alpha \). The phasor, \( E_{1_{\text{max}}} \) rotates at a mechanical angular velocity \( \omega_g \) and the phasor \( E_{2_{\text{max}}} \) rotates at electrical synchronous angular velocity \( \omega \), as shown in Fig.(6.8) at time \( t \).

If the wind torque momentarily exceeds the maximum electrical torque and the stiction torque, the machine must not pull out of synchronism within the operating speed range of the DFG. If a step torque is applied by the windmill sufficient to accelerate the machine, the cycloconverter (which is commanded by a velocity feedback) will maintain an appropriate frequency and naturally adjust itself to the new power factor in a continuous circulating current system. Steady state operation results.

When a small perturbation of input velocity, \( \Delta \omega_g \), occurs \( E_{1_{\text{max}}} \) in Fig.(6.8) will rotate at a mechanical angular velocity of \( \omega_g + \Delta \omega_g \), while \( E_{2_{\text{max}}} \) will rotate nearly at the same speed \( \omega \) (\( \omega = \omega_1 + \omega_2 \)), taking a small perturbation of \( \Delta \), \( \Delta \omega = 0 + \Delta \omega_2 \) where \( \Delta \omega_2 << \omega \). To maintain synchronism, the load angle \( \alpha \) must increase beyond the
pull-out value \( \frac{\pi}{2} \) by \( \Delta a \). Fig.(6.8) shows that,

\[
\Delta \theta = (a + \Delta a) - (a - \omega \Delta t), \\
\Delta \theta = \omega \Delta t + \Delta a, \\
\frac{\Delta \theta}{\Delta t} = \omega + \frac{\Delta a}{\Delta t}
\]

In the limit as \( \Delta t \to 0 \),

\[
\frac{\Delta \theta}{\Delta t} = \omega \quad \text{and} \quad \frac{\Delta a}{\Delta t} = \frac{da}{dt}
\]

whence,

\[
\omega = \omega + \frac{da}{dt}
\]

and

\[
\frac{da}{dt} << \omega
\]

Hence,

\[
\frac{d\omega}{dt} = \frac{d^2 a}{dt^2}
\]

and

\[
\Delta \omega = \frac{d}{dt} (\Delta a) = \Delta \dot{a}
\]

Equation (6.7) shows that the DFM behaves as a synchronous machine
(\( \omega \) in the synchronous machine is \( \omega_r \)). When the doubly-fed machine
is connected to an infinite busbar, the stiffness and damping coeffic­
ients must be considered. The dynamic equation will then be,

\[
J_m \ddot{a} + D \dot{a} + Fa = T_m + T_e
\]

where \( J_m \) is the polar moment of inertia of the generator, and \( D \) and
\( F \) are mechanical and electrical damping coefficients. \( T_m \) and \( T_e \)
are the mechanical torque (- representing motor action and + generator
action) and the electro-magnetic torque (+ representing motor action and
- generator action) respectively. The solution (given by reference 42)
of Equation (6.10) shows that the machine will be an unstable second
Fig. 6.7  Mechanical power train of WTG system

Fig. 6.8  Power angle and angular velocities change for DFG.

Fig. 6.9  Low pass circuit characteristics for step input.
order system if it is operated as a motor on infinite busbars and that any oscillation will increase or decay exponentially as a sine function. Holmes and Alston (ref. 47) have extended the stability region of the DFM operating as a motor by minimising the excitation current, which has been considered in this work.

When a doubly-fed machine is driven by a windmill, the dynamic equation will be as given by Equation (6.6). Considering small perturbations $\Delta V$ and $\Delta \omega (= \Delta \dot{\omega})$ about a steady-state condition, $V_o$ and $\omega_o$; and linearising equation (6.6) gives:

$$J \Delta \dot{\omega} = \Delta T_A - \Delta T_e$$  \hspace{1cm} (6.11)

From Equation (6.5),

$$\Delta T_A = 2K_a C_a \mu V_o \Delta V + K_a V_o^2 C_a - (\mu_o) \Delta \mu$$  \hspace{1cm} (6.12)

and referring back to Equation (3.1),

$$\mu_o = \frac{\omega_o R}{V_o}$$

$$\Delta \mu = \frac{R(V_o \Delta \omega - \omega_o \Delta V)}{V_o^2}$$  \hspace{1cm} (6.13)

It has been shown in Chapter 2 that the electrical torque, $T_e$, of the doubly-fed machine can be divided into two components. One component is load angle dependent (synchronous torque, $T_s$) and the other is speed dependent (induction torque, $T_i$), and that the total torque,

$$T_e = T_i + T_s$$

A small perturbation, $\Delta T_e = T_i'(\omega) \Delta \omega + T_s'(\alpha) \Delta \alpha$, and so

$$\Delta T_e = \Delta \omega \left[ T_i'(\omega) + T_s'(\alpha) \frac{d\alpha}{d\omega} \right]$$  \hspace{1cm} (6.14)
For an uncontrolled machine where the exciting voltage is independent of speed, \( \frac{d\alpha}{d\omega} \) is zero in Equation (6.14). Combining Eqns. (6.14), (6.13), (6.12) and (6.11) gives

\[
\tau \Delta \dot{\omega} + \Delta \omega = G \Delta V ,
\]

where the time constant of the system

\[
\tau = \frac{J}{T_I^*(\omega) - K_A R V^C o Q(\mu_o)}
\]

and the gain,

\[
G = \frac{2 K_A V C_o Q(\mu_o) - K_A^2 R C_Q(\mu_o)}{T_e^*(\omega) - K_A R V^C o Q(\mu_o)}
\]

For a controlled square-law torque characteristic, Equation (6.14) will become

\[
\Delta T_e = 2 K_A \omega \Delta \omega = T_e^*(\omega) \Delta \omega .
\]

The time constant \( \tau \) and the gain \( G \) of the controlled system may be obtained by replacing \( T_I^*(\omega) \) by \( T_e^*(\omega) \) in Equations (6.16) and (6.17) respectively.

Transforming Equation (6.15) through Laplace we get

\[
\Delta \omega(p)(1 + pr) = G \Delta V(p) ,
\]

and expressing the equation in terms of \( V_o \) and \( \omega_o \),

\[
\frac{\Delta \omega(p)}{\omega_o} = \frac{C_G}{\Delta V(p)} \frac{V_o}{V_o} (1 + pr) ,
\]

where \( C_G = G \frac{V_o}{\omega_o} \). The system can therefore be seen to act as a low-pass filter (ref. 40) with variable gain \( G \) and variable time constant \( \tau \), the values of which are dependent on the load torque, the position on the \( C_Q/\mu \) curve and the polar moment of the system inertia \( J \).
For a step torque input, the system response is shown in Fig.(6.9).

The system stability effects can be explained in terms of the time constant of response (Eqn.6.16). Eqn.(6.16) tells us that the time constant of the system for small changes is dependent primarily on the denominator, which is the difference between the slopes of the electrical machine and the wind rotor torque curves. $C_Q(\mu)$ is negative and so $\tau$ will be positive if the slope of the wind rotor torque is greater than the slope of the induction torque and stable operation will be obtained. This gives a dynamic explanation of Fig.(2.15) and the use of the divided winding as a stabiliser for the machine. Reduction of the induction torque slopes reduces the time constant and stabilises the machine.

For a controlled machine, the closer the load is matched to the ideal cubic power relationship the easier it becomes for sudden gusts to increase the time constant of the system, but it must be borne in mind that any wind-turbine will be unable to extract maximum power and operate under optimum conditions when wind gust conditions occur. This must be considered when the wind gust rises above a steady wind speed or drops below as shown in Fig.(6.10). For any increase in wind speed ($\mu < \mu_{\text{max}}$), the extracted wind power $P_m$ and the rotational speed $\omega_0 + \Delta\omega$ are shown in Fig.(6.10). At this rotational speed, the doubly-fed machine (being controlled to the following maximum power line, $P_{go}$) power output, $P_e > P_m$ and a negative time constant may result.

A significant advantage of the cycloconverter with independent amplitude control is that it enables the DFG to generate a family of cube law power characteristics at each speed. The solution adopted here is to measure the tip speed ratio $\mu$ (using an anemometer for the wind speed $V$, and a tachometer for rotational speed $\omega$) and compare it with $\mu_{\text{max}}$. If $\mu = \mu_{\text{max}}$, the steady state technique can be applied
during the wind gust. If \( \mu < \mu_{\text{max}} \), the excitation will be reduced by reduction of the cycloconverter reference signal which in turn reduces \( P_{e1} \) to \( P_{e2} \) (see Fig.(6.10)). A new value of the excitation voltage may be specified to allow for a large difference between the wind-rotor torque and the DFG torque (in Eqn.(6.16)) to reduce the time constant \( \tau \) and allow sufficient time for the system to reach its new stable operating point. This is a priority in any future work.

For any drop in wind speed, where \( \mu > \mu_{\text{max}} \), the slope of \( C_Q/\mu \) curve is fairly linear and \( C_Q \) will be constant and the system time constant will remain steady.

The above solution is based upon linearising the dynamic equation (6.10). When the doubly-fed machine generates mainly synchronous torque, and when it is connected to a large system with negligible damping, use may be made of a graphical interpretation of the energy stored in the rotating mass as an aid to determining the maximum angle of swing and to solving the question of maintenance of synchronism.

From Equation (2.36) the generating power for a sine function of \( \alpha_v \), may be represented as shown in Fig.(6.11). The important condition defining the size of disturbance that will not cause a loss of synchronism may be determined by the equal-area criterion. This equal-area method provides a ready means of finding the maximum permissible angle of swing. It also provides a simple indication of whether synchronism is maintained and a rough measure of the margin of stability. In Fig.(6.11) under steady state operation \( (\alpha_{\nu_0}) \), when the mechanical input \( (P_{m_0}) \) equal to the electrical output \(-P_{e_0}\), the operating point travels along the sinusoid OBC. Consider the shaft power to be increased suddenly by a wind gust to \( P_m \), the generator accelerates and the operating point travels along the sinusoid OBG. If synchronism is maintained, the maximum value of \( \alpha_v \) is at \( \alpha_{v_{\text{max}}} \) and it finally comes to rest at point
Fig. 6.10  Power-speed characteristics under wind gust condition.
B with a new torque angle (load angle) $\alpha_{vC}$. To reach this new operating point, the generator must accelerate at least momentarily under the influence of the difference, $P_m - P_e \sin \alpha_v$, between the power given by the load and that resulting from electromechanical conversion. The area $OAB$ of Fig.(6.11) is then proportional to the energy supplied by the rotating mass during the initial period when electromagnetic energy conversion is insufficient to oppose the shaft load. Acting under this momentum, the rotor must swing after point $B$ until an equal amount of energy is recovered by electromagnetic conversion. The result is that the rotor swings to point $C$ and the angle $\alpha_{v_{\text{max}}}$ at which

Area $BCD = \text{area } OAB$

If the area $OAB > BCD$, the momentum can never be overcome, the angle-time curve follows curve $A$ of Fig.(6.12) and synchronism is lost. On the other hand if the area $OAB < BCD$, synchronism is maintained with a margin indicated by the difference in areas and the angle time curve follows curve $B$. Equal areas gives the critical curve $C$.

A typical example is given by using the experimental machine performance under constant current excitation. The power-load angle curve computed from Equation (2.36) to balance the input wind power $(= 1.92 \times 10^{-4} \omega^3_R)$ is shown by the top curve of Fig.(6.13). Consider the doubly-fed synchronous generator operating against a mechanical torque of $P_{m_o} = 2400$ watt at 2206 rev/min, and $\alpha_{vO} = 39^\circ$. A very fast wind gust suddenly increases $P_{m_o}$ to $P_{m_1}$ without allowing any speed increase of the rotating shaft. The mechanical input power is now greater than the electrical power, the load angle $\alpha_v$ increases to increase $P_{e_o}$ and recovers the energy excess on the rotor. $\alpha_v$ increases to $64^\circ$ (which makes the two cross-hatched areas at $P_{m_1}$ equal). The machine will oscillate momentarily between $39^\circ$ and $64^\circ$ representing the transient
Fig. 6.11 Synchronous DFG power load angle and power from wind turbine

Fig. 6.12 Simple synchronous DFG swing curves showing instability (curve A), stability (curve B), and the marginal or critical case (curve C)
behaviour case given by Curve B of Fig. (6.12). Synchronism is
maintained by a margin equal to the area, $C_1C_2D_3D_4$. The maximum
step input power can be applied to the machine operating on the curve,
oOC_1C_2 at $K_g = 1.92 \times 10^{-4}$ without loss of synchronism was found
to be 3900 watt, at a power coefficient of $-2.72 \times 10^{-4}$ i.e. 162% of the
full load at the operating curve as shown in Fig. (6.13). In this case
the machine oscillation is represented by the critical curve $C$ of
Fig. (6.12). Any operation at a higher power coefficient $> -2.71 \times 10^{-4}$
will pull the machine out of synchronism as shown by curve A of Fig. (6.12).

Voltage excitation produces considerable induction power and
the equal area criterion is not applicable in this case. However
the stability analysis given earlier in this chapter allows the stability
to be assessed.

6.4. The system efficiency and its improvement

Chapter 2 shows that operation at sub-synchronous speed is
inefficient because of the induction motoring power drawn from the supply.
However the induction power components can be greatly reduced if constant
current source secondary excitation is employed. The positive induction
power is eliminated throughout the operating range. Current-source
excitation has been shown to be a preferred system, effectively minimising
induction powers and giving up to a 10% increase in efficiency. The
efficiencies given in Chapter 2 are those of a laboratory teaching machine
with a "gramme-ring" winding and a large air gap. In large schemes, the
machine resistances are much less than the inductances. Hence more
synchronous power may be gained and efficiency levels of over 90% can be
expected with schemes of, say, 250 kW and above, with standard slip-ring
machines using conventional inner slot windings.

A further way of improving the system efficiency considered was
$K_g = 1.92 \times 10^{-4}$

$-2.39 \times 10^{-4}$

$-2.72 \times 10^{-4}$

$-3.14 \times 10^{-4}$

$2206 \text{ rev/min}$

$1973 \text{ rev/min}$

Fig. 6.13 Stability margin for different wind gusts using equal area criterion
the use of tuning capacitors in the primary. Tuning capacitors have
been used to improve the efficiency of induction and synchronous
machines as shown in reference (59) and to reduce the excitation voltage
of a field modulated generator by reference (11). In a doubly-fed
machine, tuning capacitors connected in the primary circuit may have the
following advantages;

(i) The primary current "V" curves minimise at a lower cycloconverter
excitation voltage to produce a given torque. Fig.(6.14) shows a predicted reduction of exciting current of up to 50%,
the reduction being a direct function of the capacitance.

(ii) Increasing capacitance reduces the exciting current requirement
(i.e. reduces the power rating of the solid state devices of the
cycloconverter), and the overall system efficiency may be
increased. However capacitors are costly and their use is
limited to relatively small sized systems (50 kW).

(iii) Improving the primary power factor, especially when a constant
current source cycloconverter is applied. As the load torque
increases the primary power factor will become less leading or
lagging. An increase of capacitance can restore a leading
power factor as shown in Fig.(6.15).

The results given in Figs.(6.14) and (6.15) have been taken by
inserting the capacitors in the stator winding (considered as the
primary) to reduce the secondary exciting voltage. In the present
experimental system, the primary winding is the low voltage, high current
side requiring high current rating capacitors. The use of the six
slip ring rotor as the secondary, excited by the cycloconverter, will
enable the capacitors to be connected to the high voltage low current
primary side.
Fig. 6.14  Primary current variation with excitation current and capacitance (T=3.3 Nm)

Fig. 6.15  Power factor variation with torque and capacitance at constant excitation current (I_f=15A)
A novel suggestion is the division of the secondary winding into two isolated windings. One of two thirds and one of a third of the full winding. This arrangement uses the same number of conductors as the continuous winding but one third of the winding is used as an isolated tertiary capacitor tuning system as shown in Fig.(6.16), to reduce the secondary current (i.e. the current passing through the two-thirds winding). Fig.(6.17) shows that the secondary current and the tertiary current, $I_{cc}$, can be optimised for minimum input (or output when generating is considered) by an appropriate choice of capacitance. Thus an appropriate selection of capacitor can reduce the input excitation power and lead to operation at a higher efficiency as shown in Fig.(6.18).

The disadvantage of the constant current converter excitation is that the maximum power output is lower than the power that may be obtained by voltage excitation. Tuning capacitors can reduce the exciting current. Alternatively, the full load output can be increased for the same excitation. Fig.(6.19) shows that the pull-out torque has been increased and greater loads can be applied before the generator falls out of synchronism. This can set off the disadvantage of stability limits during a wind gust.

6.5. Power Distribution

In the early, variable speed wind generators of references (1,20), the main disadvantage is the high power passing through the solid state devices. In the present system, the machine produces one synchronous power, which goes mainly through the primary (directly connected to the grid), since the cycloconverter excites the machine through the secondary. The main induction power (presented only in voltage source excitation systems) is generated in the primary with the secondary
Fig. 6.16 The secondary winding arrangement with one third isolated winding tuned by a capacitor
**Fig. 6.17** Excitation current variation with tertiary current and torque

**Fig. 6.18** Efficiency variation with torque and excitation current (\(C = 20 \mu F\))
Fig. 6.19  Load angle variation with torque and capacitance at constant excitation current ($I_e = 15A$)
effectively short-circuited through the cycloconverter. The induction power passing through the cycloconverter is small, mainly caused by a motoring condition with the rotor acting as a primary short-circuited through the grid.

In constant current excitation systems, the induction powers are minimised and the required solid-state device ratings are halved, operating with divided windings carrying mainly exciting current \( \ll \) rated current. The system seems to give an economic solution for the variable speed constant frequency wind turbine-grid interface with the low power solid-state devices controlling the machine.

6.6. Conclusion

The cycloconverter excited doubly-fed generator system is both electrically and mechanically stable. Electrically, the system can accept a sudden malfunction of thyristors due to an input current surge in the cycloconverter. Line to line short-circuits through simultaneously conducting devices cannot occur. Momentary interruptions of the supply do not cause catastrophic failure of the exciter which may occur in a link-inverter system. The control system constantly matches the generator output to the turbine power, feeding power into the grid at constant frequency.

The great advantage of amplitude control independent of frequency control leads to a natural match between the doubly-fed generator and the driving turbine, increasing the efficiency effectively. The control technique used in the present system has the advantage of maintaining a unidirectional synchronous torque throughout the operating range. Unidirectional synchronous torque gives increased stability, reduces excitation and improves efficiency.
Increased stability due to elimination of the electromechanical time constants in the feedback reference network by replacing the Magslip-Velodyne reference generator by a 3-phase solid-state reference generator has been achieved. A full stability analysis of a wind turbine doubly-fed generator system has been derived in both voltage excitation and constant current excitation systems. The analysis shows that the system acts as a low pass filter with a time constant dependent on the difference between the input and the output torque slopes.

Control under wind gust conditions requires the excitation voltage to be changed due to the change of the tip speed ratio. A feedback signal from wind speed using an anemometer to command a new value of the excitation voltage is suggested.

The equal area criterion for maximum step-inputs to a synchronous machine has been adopted to predict the maximum permissible step input to the constant-current doubly-fed generator system.

Voltage source excitation is able to withstand a higher wind gust than current source excitation at the expense of a reduced efficiency.

Tuning capacitors connected to the primary can effectively reduce the secondary excitation current and improve the machine efficiency. However, their use is limited to relatively small sized systems. Use of capacitors as a tertiary tuning of one-third isolated winding of the secondary with the two-thirds winding excited by the cycloconverter is adopted. It greatly reduces the exciting current, increasing the efficiency and allows for the constant excitation current system to be applied to a higher input before the system falls out of synchronism. This tertiary tuning capacitor can be applied in larger systems where only one-third of the exciting current passes through the capacitor.

The great advantage of the present system is that the power rating
of the cycloconverter is much reduced, since it is only the exciting power that is dealt with by the cycloconverter. This exciting power is mainly caused by a generating condition with the rotor acting as a primary short-circuited through the grid.
A general theory of the doubly-fed machine operating as a generator has been developed from the established motor theory of Prescott and Raju. This new generator theory enables the steady state performance of the generator to be predicted over the complete speed range. The theory of the doubly-fed generator has been further developed to show that constant current secondary excitation virtually eliminates and makes independent of slip the induction power components.

Predictions from this theory show that the doubly-fed generator is able to operate stably over a speed range not far short of the one theoretically wanted for a wind generator. The doubly-fed generator has been shown to be an ideal wind power transducer when directly connected to the grid. As a wind power transducer the present system has several advantages over systems that have been used or proposed up to date. The following essential advantages can be listed:

1. Variable-speed operation with reduced turbine, generator and maintenance costs and direct feeding of generated power into the grid:
   a. Reduced turbine cost. The doubly-fed machine is controlled to generate power at constant frequency from a variable speed turbine rotor. This eliminates the most expensive pitch position control system and allows a constant blade pitch turbine to be used with no need for an external starter because the doubly-fed generator can start up the system as an induction motor.

   b. Reduced generator and electronic control system cost.
      This has been achieved as follows:
(i) The solid state excitation controller in the present system only conducts approximately 20% of the total power through the semiconductor devices, whereas a direct conversion system requires devices of 100% power rating.

(ii) The use of a naturally commutated cycloconverter eliminates the large and bulky commutating capacitors and choke in the d.c. link of an inverter.

(iii) The cycloconverter output harmonics have been minimized. This eliminates the need of the large L.C. filters required in d.c. link inverter systems.

(iv) The use of the secondary machine winding connected to the cycloconverter as a reactor by means of a divided system eliminates the bulky reactor usually required to maintain continuous circulating current operation. Integral cycle blanking and zero current detection are not required in the cycloconverter.

(c) **Reduced maintenance cost.** The cycloconverter exciter contains no parts which are subject to wear. Subsystems which are the dominating factors in the overall maintenance cost, can be dispensed with when the wind turbine is equipped with a static frequency converter. Such subsystems are, for example,

(i) Hydrostatic or hydrodynamic transmission systems.

(ii) Variable gears ratio.

(iii) Electromechanical or hydraulic torque control.

(iv) Blade pitch position systems, and

(v) Mechanical service brakes.
(2) Improved safety and availability of the wind power plant operation is as follows:

(a) A decisive improvement in the availability of the operation is achieved by electrical separation of the solid state devices with opposite polarities. This effectively eliminates the most common and potentially catastrophic fault condition of line-to-line short-circuiting. Consequently the surge currents demanded by rapid acceleration of a wind driven generator will not cause system failure requiring restarting from standstill.

(b) The cycloconverter is naturally commutated, therefore any momentary disconnection from the grid will cause no commutation failure which may require resynchronisation in this case.

(c) The important and desirable property for wind energy generators is their ability to cope with gusts. This has been achieved in the present system by cycloconverter continuous current excitation. The system is able to withstand large wind gusts (above 400% of the full load) while synchronism is maintained.

(d) Faulty synchronisation is not possible. The system is linked to the wind velocity by means of a feedback control system.

(e) Fading out the critical speeds, by controlling the machine to avoid stalling points. The significant advantage of the independent frequency and amplitude control of the cycloconverter enables the generator to operate under a different
power coefficient, avoiding the critical value at which the furling point is reached.

(f) Regenerative braking performs a task important to the protection of the wind turbine. This has been achieved over a wide speed range by effectively increasing the secondary resistance by using current form factor modification.

(g) The system has a further great advantage for wind turbine safety consideration. This is because there is no possibility for the doubly-fed machine to produce a motoring torque on the turbine shaft under any fault condition. During this condition the large output impedance of the grid connected cycloconverter represents the secondary side as an open circuit and allows the primary to be permanently connected to the grid. With zero reference voltage, the doubly-fed machine only draws the magnetising current. Thus the wind turbine is protected against load surges in the network. Super-synchronous operation with cut in wind speed at zero slip ensures that the power flow will be in only one direction from the machine to the supply, providing the phase rotation of the excitation frequency is in the right direction to enable the machine to rotate at the sum of the applied frequencies.

(h) No power surge when switching on. For the same reason (high cycloconverter output impedance) no power surges can occur when switching on, since only the magnetising current can flow.
(3) **Increased power generation due to more efficient utilisation of the system.**

With a given wind conversion concept, the cycloconverter-excited doubly-fed generator system increases the power generation in various ways:

(a) Optimum power generation by controlling the generator to follow the optimum power locus at which the turbine extracts maximum wind power. This has been achieved by controlling the cycloconverter excitation voltage independently of its frequency. In addition this excitation voltage controls the load angle and minimises the current passing through the cycloconverter. The generator efficiency was maximised by a near elimination of the induction power, leaving the generator operating effectively as a synchronous machine with a constant secondary a.c. current excitation. However, the voltage source excited doubly-fed machine is able to generate a higher peak power than the constant current source excited doubly-fed machine over the whole operating range. This is because the increase of load angle for a given power in the voltage excited system is less than that of the current excited system for the same power.

(b) Restraining the breakaway torque of the wind turbine by commanding the generator to begin operation at the cut in wind speed. This has been achieved by a velocity feedback signal, taken from the tachometer attached to the rotating shaft. The use of an electronic reference generator allows for a fast enough response to
synchronise the machine to the system at the appropriate time.

(c) Reduction of "shut-down". The ability of the machine to withstand strong wind gusts by preventing the electrical power from exceeding the applied mechanical power will minimise the possibilities of shutting the plant down. "Shut-down" will now only be determined by the stress consideration of the turbine blade.

(d) Improved optimisation for the entire system. Use of the cycloconverter at the condition of optimum operation permits the optimum gear transmission ratio to be used (a fixed gear ratio) and ensures independence of the coarsely graded steps of the rated generator speeds when variable ratios are used.

(4) Elimination of the damping torque and speed oscillations over a wide speed range.

   This has been achieved by shifting the induction power peak to a higher negative slip value and shaping the excitation voltage control function to constrain the synchronous torque to be unidirectional all over the operating range. In a constant current source excitation system, the generated power has one direction only (from the machine to the supply) providing that the load angle does not exceed the pull-out value.

   The system has been shown to be viable in operation over a wide speed range with simulated wind turbines. In size the experimental system is compatible with the Rutherford Laboratory aeroturbine. The next
step in the work should be trials on a real aeroturbine. Then the system can be seen to be a model which can be extrapolated to large sizes for design in the MW power ranges.
Appendix A1

(Al.1) The experimental machine

The doubly-fed experimental machine is an educational laboratory machine with a double layer secondary (stator) winding with six terminals brought out and three-phase, wound primary (rotor). The machine parameters were measured by standard techniques described by Vickers. D.c. current tests were performed to evaluate winding resistance, and a.c. open circuit, short circuit (locked rotor) and mean transformation ratio tests were performed to evaluate a.c. parameters.

Every care was taken to ensure accuracy in the readings owing to the extreme sensitivity of the theoretical analysis to small variations in parameters. The primary and secondary inductance vary with the degree of magnetization of the machine, so the full load values have been taken as representative. The measured machine parameters are given below in per phase per layer quantities

- primary resistance \( r_1 = 1.546 \) ohm
- secondary resistance \( r_2 = 4.55 \) ohm
- primary leakage inductance \( l_1 = 0.002689 \) Henry
- secondary leakage inductance \( l_2 = 0.00413802 \) Henry
- mutual inductance primary/secondary or secondary/primary \( M = 0.0636619 \)
- no load primary resistance \( R_{mr} = 35 \) ohm
- no load secondary resistance \( R_{ms} = 85 \) ohm
- primary/secondary turns ratio \( N = 1.257 \)

Other important details about the induction motor are as follows:
- primary full load current = 50 amp.
- secondary full load current = 16 amp.
- secondary full load voltage = 240 Volt/phase
(Al.2) The cycloconverter

3-phase, 50 Hz, 120 V input, half-wave using a common neutral, 10 A per phase rating. Thyristor groups electrically separate, capable of continuous circulating current operation or circulating current-free operation.

(Al.3) The prime mover

The power to the d.c. dynamometer was provided by a half-controlled thyristor bridge fed from 240 V, 50 Hz mains. Constant field excitation was maintained.
Appendix A2

Steady state performance in terms of terminal voltages

The $d-q$ transformation matrices are given as follows:

\[
|c_1| = \sqrt{2/3} \begin{bmatrix}
\cos \theta_1 & \cos(\theta_1 - 2\pi/3) & \cos(\theta_1 + 2\pi/3) \\
-sin \theta_1 & -\sin(\theta_1 - 2\pi/3) & -\sin(\theta_1 + 2\pi/3) \\
1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\] (A2.1)

\[
|c_2| = \sqrt{2/3} \begin{bmatrix}
\cos \theta_2 & \cos(\theta_2 - 2\pi/3) & \cos(\theta_2 + 2\pi/3) \\
-sin \theta_2 & -\sin(\theta_2 - 2\pi/3) & -\sin(\theta_2 + 2\pi/3) \\
1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\] (A2.2)

where $\theta_1$ is the angle between the winding axis of the stator a phase and the $d$ axis, and $\theta_2$ is the angle between the winding axis of the rotor a phase and the $d$ axis.

The primary and secondary voltages and currents are:

\[
\begin{bmatrix}
v_{a1} \\
v_{b1} \\
v_{c1}
\end{bmatrix} = \frac{\sqrt{2}}{v_1} \begin{bmatrix}
\cos \omega_1 t \\
\cos(\omega_1 t - 2\pi/3) \\
\cos(\omega_1 t + 2\pi/3)
\end{bmatrix}
\] (A2.3)

and for voltage-source excitation,

\[
\begin{bmatrix}
v_{a2} \\
v_{b2} \\
v_{c2}
\end{bmatrix} = \frac{\sqrt{2}}{v_2} \begin{bmatrix}
\cos(\omega_2 t - \alpha) \\
\cos(\omega_2 t - \alpha - 2\pi/3) \\
\cos(\omega_2 t - \alpha + 2\pi/3)
\end{bmatrix}
\] (A2.4)
The transformation system results in the following expression for the d and q voltages

\[
\begin{bmatrix}
    v_{d1} \\
    v_{q1}
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
    v_1 \\
    0
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
    v_{d2} \\
    v_{q2}
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
    \cos \alpha \\
    -\sin \alpha
\end{bmatrix}
\]

Inverting (2.1) yields

\[
\begin{bmatrix}
    i_{d1} \\
    i_{q1} \\
    i_{d2} \\
    i_{q2}
\end{bmatrix} = \frac{1}{D(s)} \begin{bmatrix}
    A_1 & A_2 & A_3 & A_4 \\
    -A_2 & A_3 & -A_4 & A_3 \\
    A_5 & A_6 & A_7 & A_8 \\
    -A_6 & A_5 & -A_8 & A_7
\end{bmatrix} \begin{bmatrix}
    v_{d1} \\
    v_{q1} \\
    v_{d2} \\
    v_{q2}
\end{bmatrix}
\]

but

\[
\begin{bmatrix}
    v_{d1} \\
    v_{q1}
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
    v_1 \\
    0
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
    v_{d2} \\
    v_{q2}
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
    \cos \alpha \\
    -\sin \alpha
\end{bmatrix}
\]

Substituting in A2.5

\[
\begin{bmatrix}
    i_{d1} \\
    i_{q1} \\
    i_{d2} \\
    i_{q2}
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
    A_1 & A_2 & A_3 & A_4 \\
    A_2 & A_1 & -A_4 & A_3 \\
    A_5 & A_6 & A_7 & A_8 \\
    -A_6 & A_5 & -A_8 & A_7
\end{bmatrix} \begin{bmatrix}
    v_1 \\
    0 \\
    v_2 \cos \alpha \\
    -v_2 \sin \alpha
\end{bmatrix}
\]

(A2.6)
A2.3

where

\[ D(s) = \left( r_{12} - s(x x - x_2^2) \right)^2 + \left( r_{12} + sr_{12} x \right)^2 \]

\[ A_1 = r_{12}^2 + sr_{12} x + s^2 r_{12} x^2 \]

\[ A_2 = r_{12}^2 x + s^2 x x - s^2 x x^2 \]

\[ A_3 = x_{m}(r_{21} - sr_{12} x) \]

\[ A_4 = r_{12} r_{21} - sx_{m} x + sx_{m}^3 \]

\[ A_5 = -sx_{m}(r_{21} - sr_{12} x) \]

\[ A_6 = sx_{m} [r_{12} r_{21} - s(x_{1} x_{2} - x_{m}^2)] \]

\[ A_7 = s^2_{m} r_{21} + sr_{12} x_{m}^2 + r_{21} x_{m}^2 \]

\[ A_8 = sr_{12} x_{m}^2 + sx_{m} x_{2} - sx_{m} x_{2}^2 \]

Torque derivation

Using (2.7), (2.8), (2.10) and (2.11) and substituting in

(2.13) gives

\[ Te = \frac{3PM}{D^2(s)} \left\{ \begin{array}{c}
[A_2 v_1 + v_2 (A_4 \cos a + A_3 \sin a)] [A_5 v_1 + v_2 (A_7 \cos a - A_8 \sin a)]

- [A_1 v_1 + v_2 (A_3 \cos a - A_4 \sin a)] [A_6 v_1 + v_2 (A_7 \cos a + A_8 \sin a)] \end{array} \right\} \]

\[ Te = \frac{3PM}{D^2(s)} \left\{ (A_2 A_5 + A_3 A_6) v_1^2 + v_2^2 (A_4 A_7 \cos^2 a - A_3 A_8 \sin^2 a + A_3 A_7 \cos a \sin a - A_2 A_8 \cos a \sin a - A_3 A_8 \cos^2 a + A_4 A_7 \sin^2 a + A_4 A_8 \cos a \sin a - A_3 A_8 \sin a \cos a + A_2 v_1 v_2 (A_7 \cos a - A_8 \sin a) + A_5 v_1 v_2 (A_4 \cos a + A_3 \sin a) - A_1 v_1 v_2 (A_7 \cos a + A_7 \sin a) - A_6 v_1 v_2 (A_3 \cos a - A_4 \sin a)] \right\} \]

\[ Te = \frac{3P_{x_m}}{\omega_{1} D^2(s)} \left\{ v_1^2 (A_2 A_5 + A_3 A_6) + v_2^2 (A_4 A_7 - A_3 A_8) + v_1 v_2 [A_2 (A_7 \cos a - A_8 \sin a) + A_5 (A_4 \cos a + A_3 \sin a) - A_1 (A_8 \cos a + A_7 \sin a) - A_6 (A_3 \cos a - A_4 \sin a)] \right\} \]

(A2.8)

From Equation (A2.8) it can be seen that the two induction torques are
\[ T_{I_1} = \frac{3P_x v_1^2}{\omega_1 D^2(s)} (A_2 A_5 + A_4 A_6) \quad (A2.9) \]

and
\[ T_{I_2} = \frac{3P_x v_2^2}{\omega_1 D^2(s)} (A_7 - A_3 A_8) \quad (A2.10) \]

Substituting from (A2.7) in (A2.9) and (A2.10) gives
\[ T_{I_1} = \frac{3P_x v_1^2 r_2}{\omega_1 D(s)} = k(s) s r_2 v_1^2 \quad (A2.11) \]
\[ T_{I_2} = -\frac{3P_x v_2^2 r_1}{\omega_1 D(s)} = -k(s) r_1 v_2^2 \quad (A2.12) \]

The synchronous torque \( T_s \) is
\[ T_s = \frac{3P_x v_1 v_2}{\omega_1 D^2(s)} \left[ A_2 (A_7 \cos a - A_3 \sin a) - A_1 (A_6 \cos a + A_7 \sin a) + A_3 (A_4 \cos a + A_3 \sin a) - A_6 (A_3 \cos a - A_4 \sin a) \right] \]
\[ T_s = \frac{3P_x v_1 v_2}{\omega_1 D^2(s)} \left[ (A_2 A_7 + A_3 A_4 - A_1 A_8 - A_3 A_6) \cos a + (A_5 A_6 + A_3 A_5 - A_2 A_8 - A_1 A_7) \sin a \right] \quad (A2.13) \]

Substituting on \( A_1, A_2, A_3, A_4, A_5, A_6, A_7 \) and \( A_8 \) from (A2.7) into (A2.13) gives
\[ T_s = -\frac{k(s)}{x_m} v_1 v_2 (r_1 r_2 + s(x_1 x_2 - x_m)^2) \sin a - [s x_2 r_1 - r_2 x_1] \cos a \]
\[ (A2.14) \]
Appendix A3

Constant current excited DFG performance derivations

In constant current converter excitation, the primary dq voltage will be the same as given in Equation (2.5), where

\[
\begin{bmatrix}
v_{d1} \\
v_{q1}
\end{bmatrix} = \sqrt{3} v_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

The secondary excitation voltage will be replaced by current excitation current, as given in Equation (2.31), where

\[
\begin{bmatrix}
id_2 \\
iq_2
\end{bmatrix} = \sqrt{3} I_2 \begin{bmatrix} \sin \alpha_v \\ -\cos \alpha_v \end{bmatrix}
\]

Equation (2.1) may be rewritten in current excitation form to define the dq primary current as follows (where \( p = \frac{d}{dt} \))

\[
\begin{bmatrix} \sqrt{3} v_1 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 + jx_1 & -x_1 & jx_m & -x_m \\ x_1 & r_1 + jx_1 & x_m & jx_m \end{bmatrix} \begin{bmatrix} id_1 \\ iq_1 \\ id_2 \\ iq_2 \end{bmatrix}
\]

then

\[
\sqrt{3} v_1 = id_1(r_1 + jx_1) - iq_1x_1 + jx_m id_2 - x_m iq_2
\]

\[
0 = id_1x_1 + iq_1(r_1 + jx_1) + x_m id_2 + jx_m iq_2
\]
From (A3.1) and substituting in (A3.3) and (A3.4) on \( i_d \) and \( i_q \) gives

\[
\sqrt{3} v_1 = i_d (r_1 + jx_1) - i_q x_1 + j\sqrt{3} I_m x_m \sin \phi_v + j\sqrt{3} I_2 x_m \cos \phi_v \tag{A3.5}
\]

\[
o = i_d x_1 + i_q (r_1 + jx_1) - \sqrt{3} I_m x_m \sin \phi_v - \sqrt{3} I_2 x_m \cos \phi_v \tag{A3.6}
\]

Rearranging (A3.5) and (A3.6) gives

\[
i_d x_1 + i_q (r_1 + jx_1) = \sqrt{3} I_m x_m \sin \phi_v + j \sqrt{3} I_2 x_m \cos \phi_v \tag{A3.7}
\]

\[
i_d x_1 + i_q (r_1 + jx_1) = \sqrt{3} I_m x_m \sin \phi_v + j \sqrt{3} I_2 x_m \cos \phi_v \tag{A3.8}
\]

Multiply (A3.7) by \((r_1 + jx_1)\) and (A3.8) by \(x_1\) and eliminating \( i_q \) then

\[
i_d \left[ (r_1 + jx_1)^2 + x_1^2 \right] = \sqrt{3} v_1 (r_1 + jx_1) - \sqrt{3} I_m x_m \left\{ \left( j \sin \phi_v + \cos \phi_v \right) r_1 + \right. \\
\left. \left( \sin \phi_v - j \cos \phi_v + \sin \phi_v + j \cos \phi_v \right) x_1 \right\} \\
\ldots \quad i_d = \frac{\sqrt{3} \left\{ v_1 (r_1 + jx_1) - I_2 x_m r_1 (j \sin \phi_v + \cos \phi_v) \right\}}{\left[ x_1^2 + (r_1 + jx_1)^2 \right]} \tag{A3.9}
\]

On multiplying Equation (A3.7) by \(x_1\) and (A3.8) by \((r_1 + jx_1)\) and eliminating \( i_d \) then

\[
-i_q \left[ x_1^2 + (r_1 + jx_1)^2 \right] = \sqrt{3} v_1 x_1 - \sqrt{3} I_2 x_m \left\{ x_1 (j \sin \phi_v + \cos \phi_v) + (r_1 + jx_1) (-\sin \phi_v + j \cos \phi_v) \right\} \\
\ldots \quad i_q = \frac{\sqrt{3} \left[ -v_1 x_1 - I_2 x_m r_1 (\sin \phi_v - \cos \phi_v) \right]}{\left[ x_1^2 + (r_1 + jx_1)^2 \right]} \tag{A3.10}
\]
On substitution of \( i_{d1}, i_{q1}, i_{d2} \) and \( i_{q2} \) in the torque equation

\[
T_e = RL(\frac{3PM}{x_1^2 + (r_1 + jx_1)^2} (v_1 \sin a_v + I_2 x_m r_1 \sin a_v (\sin a_v - j \cos a_v) - v_1 (r_1 + j x_1) \cos a_v + I_2 x_m r_1 \cos a_v (j \sin a_v + \cos a_v)) \}
\]

\[
= - RL \left\{ \frac{3PM I_2}{x_1^2 + (r_1 + jx_1)^2} (v_1 (x_1 \sin a_v - (r_1 + j x_1) \cos a_v) + I_2 x_m r_1 \sin^2 a_v - j \sin a_v \cos a_v + j \sin a_v \cos a_v + \cos^2 a_v) \right\}
\]

\[
= - RL \left\{ \frac{3PM I_2}{x_1^2 + (r_1 + jx_1)^2} (v_1 [x_1 \sin a_v - (r_1 + j x_1) \cos a_v] + I_2 x_m r_1) \right\}
\]

\[
= - RL \left\{ \frac{3PM x_m}{r_1^2 + 2 r_1 x_1} (v_1 [x_1 \sin a_v - (r_1 + j x_1) \cos a_v] + I_2^2 x_m r_1) \right\}
\]

multiplying by \( \frac{r_1^2 - 2 j r_1 x_1}{r_1^2 - 2 j r_1 x_1} \), taking the real part, then

\[
T_e = - \frac{3P}{\omega_1} \left( \frac{x_m r_1^2}{r_1^4 + 4 x_1^2 r_1^2} (v_1 I_2 [x_1 \sin a_v - \left( \frac{r_1^2 + 2 x_1^2}{r_1} \right) \cos a_v + I_2^2 x_m r_1]) \right)
\]

\[
T_e = - \frac{3P}{\omega_1} \left( \frac{x_m}{r_1^2 + 4 x_1^2} (v_1 I_2 [x_1 \sin a_v - \left( \frac{r_1^2 + 2 x_1^2}{r_1} \right) \cos a_v + I_2^2 x_m r_1]) \right)
\]

when

\[
\left( r_1 + \frac{2 x_1^2}{r_1} \right) \left( r_1^2 + 4 x_1^2 \right) \ll 1
\]

or simply when \( r_1 \ll x_1 \), then

\[
T_e = - \frac{3PM}{4 x_1} v_1 I_2 \sin a_v
\]
Appendix A4

Construction of a family of $\text{power-}(\text{speed})^3$ characteristics for the near 6 kW-RAL Site 1980 curve of Rutherford Laboratory

$\mu_{\text{max}} = 5.14 \ , \ R = 3 \text{ m}$

<table>
<thead>
<tr>
<th>wind speed, $V_1$, m/sec</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega = \frac{\mu_{\text{max}} V_1}{R}$, 1 rad/sec</td>
<td>5.14</td>
<td>5.99</td>
<td>6.85</td>
<td>7.71</td>
<td>8.566</td>
<td>10.28</td>
</tr>
<tr>
<td>Power, watt</td>
<td>1000</td>
<td>1600</td>
<td>2500</td>
<td>3700</td>
<td>5150</td>
<td>5850</td>
</tr>
<tr>
<td>$K = \frac{P}{\omega^3}$</td>
<td>7.38</td>
<td>7.4</td>
<td>7.7</td>
<td>8</td>
<td>8.18</td>
<td>5.38</td>
</tr>
<tr>
<td>$n = \frac{\omega \times 60}{2\pi}$, rev/min</td>
<td>49</td>
<td>57.2</td>
<td>65.44</td>
<td>73.62</td>
<td>81.74</td>
<td>98.16</td>
</tr>
</tbody>
</table>

Table 2
Appendix A5

Harmonic analysis of the cycloconverter output

(i) Harmonic analysis with circulating current free operation

The solution of Equation (4.3) after the substitution of the firing function defined by Equation (4.5) can be evaluated by the use of a number of trigonometrical identities given by Pelly in reference 53. These are:

\[
\sin((6p_v-1)\sin^{-1}(r \sin \omega t)) = a_{(6p_v-1)} \sin \omega t + a_{(6p_v-1)3} \sin 3\omega t + a_{(6p_v-1)(6p_v-1) \sin(6p_v-1)\omega t} \tag{A5.1}
\]

\[
\sin((6p_v+1)\sin^{-1}(r \sin \omega t)) = a_{(6p_v+1)} \sin \omega t + a_{(6p_v+1)3} \sin 3\omega t + a_{(6p_v+1)(6p_v+1) \sin(6p_v+1)\omega t} \tag{A5.2}
\]

\[
\cos(\left[3(2p_v-1)-1\right]\sin^{-1}(r \sin \omega t)) = a_{\left[3(2p_v-1)-1\right]0} + a_{\left[3(2p_v-1)-1\right]2} \cos 2\omega t + a_{\left[3(2p_v-1)-1\right][3(2p_v-1)-1] \cos 3(2p_v-1)-1\omega t} \tag{A5.3}
\]

\[
\cos(\left[3(2p_v+1)+1\right]\sin^{-1}(r \sin \omega t)) = a_{\left[3(2p_v+1)+1\right]0} + a_{\left[3(2p_v+1)+1\right]2} \cos 2\omega t + a_{\left[3(2p_v+1)+1\right][3(2p_v+1)+1] \cos [3(2p_v+1)+1]\omega t} \tag{A5.4}
\]

The coefficients of Equations A5.1 to A5.4 are defined in general terms as follows:
\[
a^{(6p_{\nu}+1)(2n_{\nu}-1)} = \frac{1}{2\pi} \int_{0}^{2\pi} \sin \left[ (6p_{\nu}+1)(\sin^{-1} r \sin \omega_{2t}) \right] \sin(2n_{\nu}-1)\omega_{2t} \, d\omega_{2t}
\]  
(A5.5)

\[
a^{[3(2p_{\nu}-1)+1]}_o = \frac{1}{2\pi} \int_{0}^{2\pi} \cos \left[ (3(2p_{\nu}-1)+1)(\sin^{-1} r \sin \omega_{2t}) \right] d\omega_{2t}
\]  
(A5.6)

and

\[
a^{[3(2p_{\nu}-1)+1]}_{2n} = \frac{1}{2\pi} \int_{0}^{2\pi} \cos \left[ (3(2p_{\nu}-1)+1)(\sin^{-1} r \sin \omega_{2t}) \right] \cos 2n_{\nu}\omega_{2t} \, d\omega_{2t}
\]  
(A5.7)

\[
\cos \left[(6p_{\nu}+1)\sin^{-1} r \sin \omega_{2t}\right] = a^{(6p_{\nu}-1)}_o + a^{(6p_{\nu}+1)}_2 \cos 2\omega_{2t} + a^{(6p_{\nu}-1)}_{2n_{\nu}} \cos 2n_{\nu}\omega_{2t} + \text{ etc.}
\]  
(A5.8)

\[
\cos \left[(6p_{\nu}+1)\sin^{-1} r \sin \omega_{2t}\right] = a^{(6p_{\nu}+1)}_o + a^{(6p_{\nu}+1)}_2 \cos 2\omega_{2t} + a^{(6p_{\nu}+1)}_{2n_{\nu}} \cos 2n_{\nu}\omega_{2t} + \text{ etc.}
\]  
(A5.9)

\[
\sin \left[(3(2p_{\nu}-1)-1)\sin^{-1} r \sin \omega_{2t}\right] = a^{(3(2p_{\nu}-1)-1)}_1 \sin \omega_{2t} + a^{(3(2p_{\nu}-1)+1)}_3 \sin 3\omega_{2t} - a^{(3(2p_{\nu}-1)-1)}_{2n_{\nu}-1} \sin(2n_{\nu}-1)\omega_{2t} + \text{ etc.}
\]  
(A5.10)

\[
\sin \left[(3(2p_{\nu}-1)+1)\sin^{-1} r \sin \omega_{2t}\right] = a^{(3(2p_{\nu}-1)+1)}_1 \sin \omega_{2t} + a^{(3(2p_{\nu}-1)+1)}_3 \sin 3\omega_{2t} - a^{(3(2p_{\nu}-1)+1)}_{2n_{\nu}-1} \sin(2n_{\nu}-1)\omega_{2t} + \text{ etc.}
\]  
(A5.11)

where

\[
a^{(6p_{\nu}+1)}_o = \frac{1}{2\pi} \int_{0}^{2\pi} \cos((6p_{\nu}+1)\sin^{-1} r \sin \omega_{2t}) \, d\omega_{2t}
\]  
(A5.12)

\[
a^{(6p_{\nu}+1)}_{2n} = \frac{1}{2\pi} \int_{0}^{2\pi} \cos((6p_{\nu}+1)\sin^{-1} r \sin \omega_{2t}) \cos 2n_{\nu} \, d\omega_{2t}
\]  
(A5.13)

and

\[
a^{(3(2p_{\nu}-1)+1)(2n-1)} = \frac{1}{2\pi} \int_{0}^{2\pi} \sin[(3(2p_{\nu}-1)+1)\sin^{-1} r \sin \omega_{2t}] \sin(2n_{\nu}-1)\omega_{2t} \, d\omega_{2t}
\]  
(A5.14)
The expression for the output voltage of a three-pulse cycloconverter operating in the circulating current-free mode is now,

$$V_2 = \frac{3\sqrt{3}V_M}{2\pi} \left[ r \sin \omega_2 t + \frac{1}{2} \sum_{p_v=1}^{P_v=\infty} \frac{a(3(2p_v-1)+1)(2n_v)}{3(2p_v-1)+1} \left[ \sin(3(2p_v-1)\omega_1 t-2n_v\omega_2 t)+\sin(3(2p_v-1)\omega_1 t-2n_v\omega_2 t) \right] + \right.$$  

$$\left. \sum_{n_v=0}^{2n_v+1} \frac{a(6p_v-1)(2n_v-1)}{(6p_v-1)} + \frac{a(6p_v+1)(2n_v)}{(6p_v+1)} \left[ \sin(6p_v\omega_1 t+2n_v\omega_2 t) \right] - \right.$$  

$$\sin(6p_v\omega_1 t-(2n_v+1)\omega_2 t) \right] +$$

$$\left. \frac{2}{\pi} \sum_{n_v=0}^{P_v=\infty} \frac{a(3(2p_v-1)-1)(2n_v+1)}{3(2p_v-1)-1} + \frac{a(6p_v+1)(2n_v+1)}{3(2p_v-1)+1} \left[ \frac{2\cos(2n_v+1)\phi_{22}}{(2n_v+1)} \cos(3(2p_v-1)\omega_1 t) \right] \right.$$  

$$\left. + \frac{2}{\pi} \sum_{m_v=1}^{\infty} \sum_{n_v=1}^{\infty} \frac{1}{2n_v+1-2m_v} \left[ \frac{a(3(2p_v-1)-1)(2n_v+1)}{3(2p_v-1)-1} + \frac{a(3(2p_v-1)+1)(2n_v+1)}{3(2p_v-1)+1} \right] \right.$$  

$$\left. \left[ \cos(3(2p_v-1)\omega_1 t-(2n_v+1-2m_v)\phi_{22}) + \cos(3(2p_v-1)\omega_1 t+(2n_v+1-2m_v)\phi_{22}) \right] + \sum_{m_v=1}^{\infty} \sum_{n_v=1}^{\infty} \frac{1}{2n_v+1+2m_v} - \frac{a(3(2p_v-1)-1)(2n_v+1)}{3(2p_v-1)+1} \right.$$  

$$\left. + \frac{a(3(2p_v-1)+1)(2n_v+1)}{3(2p_v-1)+1} \left[ \cos(3(2p_v-1)\omega_1 t-(2n_v+1+2m_v)\phi_{22}) + \cos(3(2p_v-1)\omega_1 t+(2n_v+1+2m_v)\phi_{22}) \right] \right.$$  

$$+ \ldots \ldots \ldots \text{continued}$$
\[ + \frac{2}{\pi} \sum_{m_y=0}^{\infty} \sum_{n_y=0}^{\infty} \left[ \frac{1}{2n_y^2 + 1} \right] \left[ \frac{a(6p_y-1)2n_y}{6p_v - 1} + \frac{a(6p_v+1)2n_y}{6p_v + 1} \right] \]

\[ \cos(6p_y\omega_1 t - [(2m_y+1)\omega_2 t - (2n_y-2m_y-1)\xi_{22}]) + \]

\[ \cos(6p_y\omega_1 t + (2m_y+1)\omega_2 t - [(2n_y+1-2m)\xi_{22}]) \]

\[ + \frac{2}{\pi} \sum_{m_y=0}^{\infty} \sum_{n_y=0}^{\infty} \left[ \frac{1}{2n_y^2 + 2m_y} \right] \left[ \frac{a(6p_y-1)2n_y}{6p_v + 1} + \frac{a(6p_v+1)2n_y}{6p_v + 1} \right] \]

\[ \cos(6p_y\omega_1 t - [(2m_y+1)\omega_2 t + (2n_y+2m_y+1)\xi_{22}]) - \]

\[ \cos(6p_y\omega_1 t + [(2m_y+1)\omega_2 t + (2n_y+2m_y+1)\xi_{22}]) \]

\[(A5.15)\]

(ii) Harmonic analysis with continuous circulating current

The output voltage \( v_2 \) is given by

\[ v_2 = \frac{3\sqrt{3} \omega_1}{2\pi} \left[ \sin f_1(\omega_2 t) + \frac{1}{2} \sin 3 \omega_1 t \cos 2f_1(\omega_2 t) + \frac{1}{4} \sin 3 \omega_1 t \cos 4f_1(\omega_2 t) + \frac{1}{5} \cos 6 \omega_1 t \sin 5f_1(\omega_2 t) + \frac{1}{7} \cos 6 \omega_1 t \sin 7f_1(\omega_2 t) + \text{etc.} \right] \]

\[(A5.16)\]

The solution of equation (A5.16) gives the identities A5.1 to A5.7 and eliminates the rest of the sub harmonics of A5.8 to A5.14.

The substitution of identities A5.1 to A5.7 into equation A5.16 gives the following expression for a three-pulse cycloconverter output voltage, when operating with continuous circulating current.
\[ v_z = \frac{3\sqrt{3}v_M}{2\pi} \left[ \sqrt{\sin \omega_2 t} + \frac{1}{2} \sum_{p_v=0}^{p_v=\infty} \left\{ \sum_{n_v=0}^{2n_v=3(2p_v-1)+1} \left[ \frac{a[3(2p_v-1)+1]2n_v}{3(2p_v-1)+1} \right] \sin(3(2p_v-1)\omega_1 t + 2n_v\omega_2 t) + \sin(3(2p_v-1)\omega_1 t - 2n_v\omega_2 t) \right\} \right] \]

\[ 2n_v+1=6p_v+1 \]

\[ \sum_{n_v=0}^{2n_v+1=6p_v+1} \left[ \frac{a(6p_v-1)(2n_v-1)}{(6p_v-1)} + \frac{a(6p_v+1)(2n_v+1)}{(6p_v+1)} \right] \left\{ \sin(6p_v\omega_1 t + (2n_v+1)\omega_2 t) - \sin(6p_v\omega_1 t - (2n_v+1)\omega_2 t) \right\} \]

\[ (A5.17) \]
Appendix A6. The cycloconverter pulse circuits

Fig A.6.1 Pulse circuit

Fig A.6.2 Equivalent circuit of pulse board timing
Appendix A7

Digital computation programs
Appendix A7.1

PROGRAM NADIA(INPUT, OUTPUT, TAPE5=INPUT)

... THIS PROGRAM IS TO CALCULATE THE PERFORMANCE OF DOUBLY FED GENERATOR CONTROLLED BY VOLTAGE SOURCE EXCITATION.
... TO EXAMINE THE LOAD ANGLE EFFECT ON THE MACHINE CHARACTERISTICS UNDER CONSTANT VOLTAGE EXCITATION AND VARIABLE LOAD ANGLE.

REAL L1, L2, LS, LR, LSD, L2D, M, N, NS, NR, LRD, IS1, IS2, IR1D, IR2, IS, IR

.. SUBSCRIPT "S" DENOTES TO THE SECONDARY SIDE.
.. SUBSCRIPT "R" DENOTES TO THE PRIMARY SIDE.
.. MACHINE PARAMETERS ...

RS=4.55
RR=1.546
L2D=1.3/(6.28318*50.0)
L1=1.3/(6.28318*50.0)
N=1.257
M=20/(6.28318*50.0)
RRD=RR*N*N
RSD=RS/(N*N)
LS=L1+M
LSD=((L1/(N*N))+(M/N))
LRD=(L2D+N*M)
L2=L2D/(N*N)
LR=L2+M

.. PLOTTING REQUIREMENTS ...

CALL PAPER(1)
CALL DENTSY(2)
CALL CTRMAG(8)
CALL PSPACE(0.4,0.75,0.2,0.75)
DO 33 K=1,5
  IF(K.EQ.1)GO TO 25
  IF(K.EQ.2)GO TO 26
  IF(K.EQ.3)GO TO 27
  IF(K.EQ.4)GO TO 28
  IF(K.EQ.5)GO TO 31
25 CALL MAP(0.0,3000.0,-10000.0,2000.0)
CALL AXESSI(500.0,2000.0)
GO TO 29
26 CALL FRAME
  CALL PSPACE(0.4,0.75,0.2,0.75)
  CALL MAP(0.0,3000.0,-2000.0,200.0)
  CALL AXESSI(500.0,200.0)
GO TO 29
27 CALL PSPACE(0.4,0.75,0.2,0.75)
  CALL MAP(0.0,3000.0,-2000.0,200.0)
  CALL AXESSI(500.0,200.0)
GO TO 29
28 CALL FRAME
  CALL PSPACE(0.1,0.5,0.54833,0.88666)
  CALL MAP(0.0,3000.0,0.0,15.0)
  CALL AXESSI(500.0,2.0)
GO TO 29
31 CALL PSPACE(0.1,0.5,0.14,0.44833)
  CALL MAP(0.0,3000.0,0.0,15.0)
  CALL AXESSI(500.0,2.0)
GO TO 29
29 CONTINUE
.. MACHINE PERFORMANCE CALCULATION ..

WR=-50.0*6.28318
VR=62.0
AL=-9.0*0.0174532
DO 60 LW=1,11
AL=AL+9.0*0.0174532
WS=-314.0
DO 30 MW=1,190

WS=WS+3.0
W=WS-WR
SS=(WS-W)/WS
NR=W*60.0/(2.0*6.28318)
SR=1.0/SS
S=SR
S1=SS
S2=SR
A=(RS*RRD)+(WR*WS*((M*M*N*N)-(LS*LRD)))
B=(LS*RRD*WS)+(RS*LRD*WR)
C=(RR*RSD)+(WR*WS*((M*M)/(N*N))-(LR*LSD)))
D=(RR*LSD*WS)+(RSD*LR*WR)
V6=20.0
IS1=VS*SQRT(((A*RRD)+(B*LRD*WR))**2)+((LRD*WR*A)-(B*RRD))**2)/
*((A*A)+(B*B))
IS2=-(M*WS*VR/(SQRT((C*C)+(D*D))*N)
IR1D=N*M*WR*VS/(SQRT((A*A)+(B*B)))
IR2=VR*SQRT(((C*RSD)+(D*LSD*WS))**2)+((LSD*WS*C)-(D*RSD))**2)/
*((C*C)+(D*D))

.. ERDS=INDUCED E.M.F IN SECONDARY FED SYSTEM ..
ERDS=M*WR*IS1
ESDS=M*WS*IR1D

.. ES2S=INDUCED E.M.F IN PRIMARY FED SYSTEM ..
ES2S=-M*WS*IR2
ER2S=M*WR*IS2D

P3=(3*M*WS*VR*W/(((A*A)+(B*B))*((C*C)+(D*D)))*)((RS*LRD*WR)-
*(RR*LS*WS))*((A*C)+(B*D))*COS(AL)-((A*D)-(B*C))*SIN(AL)+
*((RS*RR)+(LS*LR*WR*WS))*(((A*D)-(B*C))*COS(AL)+((A*C)+(B*D))*
SIN(AL))
P4=(3*M*WS*VR*W/(((A*A)+(B*B))*((C*C)+(D*D)))*)((M*M*WR*WS)*
*(((A*D)-(B*C))*COS(AL)+((A*C)+(B*D))*SIN(AL)))
PS=PS+P4

.. P1=EXCITATION INDUCTION POWER ..
P1=3.0*IR1D*IR1D*RRD*(1-S1)/S1

.. P2=PRIMARY INDUCTION POWER ..
P2=3.0*IS2D*IS2D*RSD*(1-S2)/S2
P=PS+P1+P2

.. CL1=TOTAL PRIMARY COPPER LOSSES ..
CL1=3.0*(((IR2*IR2*RR)+(IR1D*IR1D*RRD))

.. CL2=TOTAL SECONDARY COPPER LOSSES ..
CL2=3.0*(((IS1*IS1*RS)+(IS2D*IS2D*RSD))

B1=VS*(((A*RRD)+(B*WR*LRD))/((A*A)+(B*B)))
B2=-(M*WS*VR*(((C*SIN(AL))-(D*COS(AL)))/(N*(((C*C)+(D*D)))))
B3=VS*(((A*WR*LRD)-(B*RRD))/((A*A)+(B*B)))
B4=M*VR*WS*(((C*SIN(AL))+(D*COS(AL)))/(N*(((C*C)+(D*D))))
IS=SQRT(((B1+B2)*(B1+B2))+((B3-B4)*(B3-B4)))
CL=VR*(((RSD*C)+(D*WS*LSD))/(((C*C)+(D*D))))
\[ C_2 = V_R \cdot \left( \frac{(C \cdot WS \cdot LSD) - (D \cdot RSD)}{(C \cdot C) + (D \cdot D)} \right) \]
\[ C_3 = M \cdot N \cdot \left( \frac{(A \cdot \sin(\alpha L)) - (B \cdot \cos(\alpha L))}{(A \cdot A) + (B \cdot B)} \right) \]
\[ C_4 = -M \cdot N \cdot \left( \frac{(A \cdot \cos(\alpha L)) + (B \cdot \sin(\alpha L))}{(A \cdot A) + (B \cdot B)} \right) \]
\[ R = \sqrt{((C_1 + C_3) \cdot (C_1 + C_3)) + ((C_2 - C_4) \cdot (C_2 - C_4))} \]

.. RMS = NO LOAD (MAGNETIZING) RESISTANCE IN PRIMARY FED SYSTEM.
RMS = 85.0
PIS = 3.0 * (ES2S) * (ES2S) / RMS
RMR = 27.9

.. RMR = NO LOAD (MAGNETIZING) RESISTANCE IN SECONDARY FED SYSTEM.
PISR = 3.0 * (ERDS) * (ERDS) / RMR
PI = PIS + PISR
PIN = P + C1 + PI
PING = -P + C1 + PI
PINM = P + C1 + PI

EFPG = P * 100.0 / PING
EFFM = P * 100.0 / PINM

FIS = ATAN2((B3 - B4), (B1 + B2))
FISR = ATAN2((C2 - C4), (C1 + C3))
PFPG = COS(FIS)
PFR = COS(FISR)

IF(K.EQ.1) GO TO 15
IF(K.EQ.2) GO TO 16
IF(K.EQ.3) GO TO 17
IF(K.EQ.4) GO TO 18
IF(K.EQ.5) GO TO 19
15 IF(MW.GT.1) GO TO 35
CALL POSITN(NR, P)
GO TO 30
35 CALL JOIN(NR, P)
GO TO 30
16 IF(MW.GT.1) GO TO 36
CALL POSITN(NR, P1)
GO TO 30
36 CALL JOIN(NR, P1)
GO TO 30
17 IF(MW.GT.1) GO TO 37
CALL POSITN(NR, P2)
GO TO 30
37 CALL JOIN(NR, P2)
GO TO 30
18 IF(MW.GT.1) GO TO 38
CALL POSITN(NR, IS)
GO TO 30
38 CALL JOIN(NR, IS)
GO TO 30
19 IF(MW.GT.1) GO TO 39
CALL POSITN(NR, IR)
GO TO 30
39 CALL JOIN(NR, IR)
30 CONTINUE
60 CONTINUE
33 CONTINUE
CALL GREND
STOP
END
PROGRAM NADIA(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

..THIS PROGRAM IS TO MINIMISE THE FUNCTION FC GIVEN BY
   EQUATION 2.30 TO ZERO. MINIMIZATION IS SUBJECT TO
   LOAD ANGLE VARIATION.
..NUMERICAL MINIMIZATION PROGRAM USING NAG LIB. ROUTINE
   ..CONSTRAINED MINIMIZATION..

SUBROUTINE E04JAF IS USED

MARK 6 RELEASE.NAG COPYRIGHT 1977.

LOCAL SCALARS..
REAL F,IS2D,IR2,IR1D
INTEGER IBOUND, IFAIL, J, LIW, LW, N, NOUT

LOCAL ARRAYS..
REAL BL(3), BU(3), W(39), X(3)
REAL NR,NRP,ISP,IRP
REAL IS,IS1P
REAL IR
REAL KD
REAL IS1
INTEGER IW(5)
DIMENSION NRP(206),PP(206),P1P(206),P2P(206),ISP(206),IRP(206)
DIMENSION PPS(206),PFRP(206),EFFGP(206),WSP(206),VSP(206)
DIMENSION PSP(206)
DIMENSION IS1P(206),ALFP(206),PINGP(206),FISDP(206),FIRD(206)
DIMENSION V2P(206)
COMMON/AS/IS,FISD,FIRD,FR,V2
COMMON/SN/P,P1,P2,PS,IS2D,IR2,IR1D
COMMON/Z/KD
COMMON/SH/WS
COMMON/AB/IR,ALF,VS
COMMON/FN/NR
COMMON/MM/PPS,PFR
COMMON/AE/EFFG
COMMON/AG/IS1,PING

.. SUPROUTINE REFERENCES..

E04JAF

DATA NOUT /6/
N=3
WRITE(NOUT,99999)
X(1)=20.60E+0
X(2)=+40.0*0.0174532E+0
X(3)=-4.239E-4
IBOUND=0
BL(1)=20.54E+0
BU(1)=20.64E+0
BL(2)=0.0
BU(2)=90.0*0.0174532E+0
BL(3)=-5.239E-4
BU(3)=-5.2389E-4
LIW=5
LW=39
\[ WS = -314.0 \]
\[ DO 30 M W = 1, 206 \]
\[ WS = WS + 3.0 \]
\[ IF A I F A L = 1 \]
\[ CALL E04JAF(N, IBOUND, BL, BU, X, F, IW, LIW, W, LW, IFAIL) \]
\[ C \] \[
\text{C SINCE IFAIL WAS SET TO 1 BEFORE ENTERING E04JAF, IT IS} \]
\[ C \] \[
\text{ESSSENTIAL TO TEST WHETHER IFAIL IS NON-ZERO ON EXIT} \]
\[ IF (IFAIL.EQ.1) GO TO 20 \]
\[ CALL FUNCT1(N, X, F) \]
\[ IF (IFAIL.NE.0) WRITE(NOUT, 99998) IFAIL \]
\[ WRITE(NOUT, 99997) F, IS, P, WS, IR, PFS, PFR, EFFG, IS1, ALF, NR, VS \]
\[ +, PISD, FIRD, FR, PS, P1, P2, V2, IS1, IS2D, IR2, IR1D \]
\[ WRITE(NOUT, 99996) (X(J), J=1,N) \]
\[ 99999 FORMAT(///31H E04JAF EXAMPLE PROGRAM RESULTS/) \]
\[ 99998 FORMAT(///16H ERROR EXIT TYPE, I3, 22H SEE ROUTIN DOCUMEN, \]
\[ + 1HT) \]
\[ 99997 FORMAT(///27H FUNCTION EXIT VALUE ON EXIT IS , F15.10, \]
\[ + 3X, 3HIS=, F9.3, 3X, 2HF=, F15.3, 3X, 3HWS=, F9.3, 3X, 3HIR=, F9.3, /, 3X, 4HPF \]
\[ +S=, F7.4, 3X, 4HPFR=, F7.4, 3X, 5HEFFG=, F9.4, 3X, 4HIS1=, F9.4, 3X, 4HALF=, \]
\[ +F9.4, 3X, 3HNR=, F15.4, 3X, 3HVS=, F9.4, /, 5X, 5HFISD=, F9.3, 2X, 5HFIRD=, \]
\[ +F9.3, 3X, 3HFR=, F9.3, 3X, 3HPS=, F15.3, 3X, 3HP1=, F15.3, 3X, 3HP2=, F15.3, / \]
\[ *', 5X, 3HV2=, F15.3, 5X, 4HIS1=, F15.3, 3X, 5HIS2D=, F9.4, 4HIR2=, \]
\[ * F12.3, 3X, 5HIR1D=, F12.3, /) \]
\[ 99996 FORMAT(13H AT THE POINT, 3F20.13,/) \]
\[ NRP(MW) = NR \]
\[ PP(MW) = P \]
\[ PSP(MW) = P \]
\[ P1P(MW) = P1 \]
\[ P2P(MW) = P2 \]
\[ ISP(MW) = IS \]
\[ IRP(MW) = IR \]
\[ PFS(MW) = PFS \]
\[ PFRP(MW) = PFR \]
\[ EFFG(MW) = EFFG \]
\[ WSP(MW) = WS \]
\[ VSP(MW) = VS \]
\[ IS1P(MW) = IS1 \]
\[ V2P(MW) = V2 \]
\[ ALFP(MW) = ALF \]
\[ PINGP(MW) = PING \]
\[ PISDP(MW) = PISD \]
\[ FIRD(MW) = FIRD \]
\[ 30 CONTINUE \]
\[ CALL PAPER(1) \]
\[ CALL PSPAC{E(0.4,0.75,0.2,0.75) \]
\[ CALL GPSTOP(14) \]
\[ CALL MAP(0.0,3000.0,-10000.0,100.0) \]
\[ CALL CURVEO(NRP, PP, 1, 206) \]
\[ CALL AXES \]
\[ CALL FRAME \]
\[ CALL MAP(0.0,3000.0,-500.0,200.0) \]
\[ CALL CURVEO(NRP, P1P, 1, 206) \]
\[ CALL AXES \]
\[ CALL FRAME \]
\[ CALL MAP(0.0,3000.0,-400.0,1000.0) \]
\[ CALL CURVEO(NRP, P2P, 1, 206) \]
\[ CALL AXES \]
\[ CALL FRAME \]
\[ CALL MAP(0.0,3000.0,0.0,10.0) \]
CALL CURVEO(NRP,ISP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,0.0,15.0)
CALL CURVEO(NRP,IRP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,-1.0,1.0)
CALL CURVEO(NRP,PFSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,-1.0,1.0)
CALL CURVEO(NRP,PFRP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,0.0,100.0)
CALL CURVEO(NRP,EFFGP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,90.0,0.0,40.0)
CALL CURVEO(ALFP,VSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,-3000.0,400.0)
CALL CURVEO(NRP,PSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(-324.0,324.0,0.0,40.0)
CALL CURVEO(WSP,VSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,-324.0,324.0)
CALL CURVEO(NRP,WSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(0.0,3000.0,0.0,35.0)
CALL CURVEO(NRP,VSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(-120.0,0.0,0.0,40.0)
CALL CURVEO(ALFP,VSP,1,206)
CALL AXES
CALL GREN
20 STOP
END

C SUBROUTINE FUNCT1(N, XC, FC)
C FUNCTION EVALUATION ROUTINE FOR E04JAF EXAMPLE PROGRAMS-
C THIS ROUTINE MUST BE CALLED FUNCT1
C ..SCALAR ARGUMENTS ..
REAL NT,IR1D,IS1,LRD,LSD,IR2,IS2D,L2D,L1,L2,NR
REAL LS,LR,KD,M,WR,WS,W
REAL IS,IR,FC,XC(N)
INTEGER N
COMMON/AS/IS,FISD,FIRD,FR,V2
COMMON/SN/P,P1,P2,PS,IS2D,IR2,IR1D
COMMON/Z/KD
COMMON/SH/WS
COMMON/AB/IR, ALF, VS
COMMON/FG/NR
COMMON/MM/PFS, PFR
COMMON/AA/EEFG
COMMON/AG/TS1, PING
.. ARRAY ARGUMENTS ..
...
.. LOCAL SCALARS ..
...
.. LOCAL DIMENSION ..
VR=62.0
RS=4.55
RR=1.546
M=20.0/(6.28318*50.0)
VS=XC(1)
AL=XC(2)
KD=XC(3)
ALF=AL/0.0174532
L2D=1.3/(6.28318*50.0)
L1=1.3/(6.28318*50.0)
NT=1.257
RRD=RR*NT*NT
RSD=RS/(NT*NT)
LS=L1+M
LSD=((L1/(NT*NT))+(M/NT))
LRD=(L2D+(NT*M))
L2=L2D/(NT*NT)
LR=L2+M
WR=-50.0*6.28318
WZ=WS-WR
WD=WZ/2.0
NR=(WS-WR)*60.0/(2.0*6.28318)
SS=(WS-W2)/WS
SR=1.0/SS
S1=SS
S2=SR
S=S2
A=(RS*RRD)+(WR*WS*((M*M*NT*NT)-(LS*LRD)))
B=(LS*RRD*WS)+(RS*LRD*WR)
C=(RR*RSD)+(WR*WS*((M*M)/(NT*NT))-(LR*LSD))
D=(RR*LSD*WS)+(RSD*LR*WR)
IS2D=M*WS*VR/(SQRT((C*C)+(D*D)))*NT
IS1=VS*SQRT(((A*RRD)+(B*LRD*WR))**2)+(((LRD*WR*A)-(B*RRD))**2)/
    *(C*C)+(D*D))
IR1D=NT*M*MR*VS/(SQRT((A*A)+(B*B)))+
IR2=VR*SQRT(((C*RSD)+(D*LSD*WS))**2)+(((LSD*WS*C)-(D*RSD))**2)/
    *(C*C)+(D*D))
ERSD=M*MR*IS1
ESDS=M*WS*IR1D
ES2S=M*WS*IR2
ERZS=M*MR*IS2D
B1=VR*((A*RRD)+(B*WR*LRD))/((A*A)+(B*B))
B2=(M*WS*VR*((C*SIN(AL))-(D*COS(AL)))/(NT*((C*C)+(D*D))))
B3=VS*((A*WR*LRD)-(B*RRD))/((A*A)+(B*B))
B4=M*VR*WS*((C*COS(AL))+(D*SIN(AL)))/(NT*((C*C)+(D*D))))
I S=SQRT(((B1+B2)*B1+B2)+(B3-B4)*(B3-B4))
C1=VR*((RSD*C)+(D*WS*LSD))/((C*C)+(D*D))
\[ C_2 = V_R \cdot \left( \frac{C \cdot W_S \cdot L_S}{D \cdot R_S} \right) \cdot \left( \frac{(C \cdot C + (D \cdot D))}{((C \cdot C) + (D \cdot D))} \right) \]

\[ C_3 = M \cdot N \cdot V_S \cdot W_S \cdot (A \cdot \sin(AL) - B \cdot \cos(AL)) \cdot \left( \frac{(A \cdot A + (B \cdot B))}{((A \cdot A) + (B \cdot B))} \right) \]

\[ C_4 = M \cdot N \cdot V_S \cdot W_R \cdot (A \cdot \cos(AL) + B \cdot \sin(AL)) \cdot \left( \frac{(A \cdot A + (B \cdot B))}{((A \cdot A) + (B \cdot B))} \right) \]

\[ I_R = \sqrt{\left( \frac{(C_1 + C_3) \cdot (C_1 + C_3)}{(C_2 - C_4) \cdot (C_2 - C_4)} \right)} \]

\[ P_3 = \left( 6.0 \cdot M \cdot V_S \cdot V_R \cdot W_D \cdot (A \cdot A + (B \cdot B)) \cdot ((C \cdot C) + (D \cdot D)) \right) \cdot \left( \frac{(R_S \cdot L_S \cdot W_S) - (R_S \cdot L_S \cdot W_R)}{((A \cdot A) + (B \cdot B)) \cdot ((C \cdot C) + (D \cdot D))} \right) \]

\[ P_4 = \left( 6.0 \cdot M \cdot V_S \cdot V_R \cdot W_D \cdot (A \cdot A + (B \cdot B)) \cdot ((C \cdot C) + (D \cdot D)) \right) \cdot \left( \frac{(M \cdot W_R \cdot W_S)}{((A \cdot A) + (B \cdot B)) \cdot ((C \cdot C) + (D \cdot D))} \right) \]

\[ P_S = P_3 + P_4 \]

\[ P_1 = 3.0 \cdot I_{R1D} \cdot I_{R1D} \cdot R_R \cdot (1 - S_1) / S_1 \]

\[ P_2 = 3.0 \cdot I_{S2D} \cdot I_{S2D} \cdot R_S \cdot (1 - S_2) / S_2 \]

\[ P = P_1 + P_2 + P_S \]

\[ C_{L1} = 3.0 \cdot I_{R2} \cdot I_{R2} \cdot R_R \cdot I_{R1D} \cdot I_{R1D} \cdot R_R \]

\[ C_{L2} = 3.0 \cdot I_{S1} \cdot I_{S1} \cdot R_S \]

\[ C_L = C_{L1} + C_{L2} \]

\[ R_{MS} = 85.0 \]

\[ P_{IS} = 3.0 \cdot (E_{S2S}) \cdot (E_{S2S}) / R_M \]

\[ R_{MR} = 35.9 \]

\[ P_{IR} = 3.0 \cdot (E_{RDS}) \cdot (E_{RDS}) / R_M \]

\[ P_{I} = P_{IS} + P_{IR} \]

\[ P_{IN} = P + P_{CL} + P_{I} \]

\[ E_{FIF} = P \cdot 100.0 \cdot P_{IN} \]

\[ E_{FIF} = E_{FIF} \]

\[ F_{IS} = ATAN2(B_3 - B_4, (B_1 + B_2)) \]

\[ F_{ISD} = F_{IS} / 0.0174532 \]

\[ P_{FS} = \cos(F_{IS}) \]

\[ F_{IR} = ATAN2(C_2 - C_4, (C_1 + C_3)) \]

\[ F_{IRD} = F_{IR} / 0.0174532 \]

\[ P_{FR} = \cos(F_{IR}) \]

\[ F_r = W_S / 6.28318 \]

\[ F_C = (P - (K_D \cdot (W_D \cdot 3.0))) \cdot 2.0 \]

RETURN

END OF FUNCTION EVALUATION ROUTINE

END
PROGRAM NADIA(INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)

..THIS PROGRAM IS TO MINIMISE THE FUNCTION FC GIVEN BY

EQUATION 2.30 TO ZERO. MINIMIZATION IS SUBJECT TO

EXCITATION VOLTAGE RELATED TO THE LOAD ANGLE (ALFA)

AT UNITY SECONDARY POWER FACTOR.

..NUMERICAL MINIMIZATION PROGRAM USING NAG LIB. ROUTINE

..COSTRAINED MINIMIZATION..

...............................

SOURoutine E04JAF IS USED

MARK 6 RELEASE. NAG COPYRIGHT 1977.

..LOCAL SCALARS..

REAL F
INTEGER IBOUND, IFAIL, J, LIW, LW, N, NOUT

..LOCAL ARRAYS..

REAL BL(2), BU(2), W(39), X(2)
REAL NR
REAL IS
REAL IR, IR1D, IR2
REAL KD
REAL IS1, NRP, ISP, IS1P, IRP, IS2D
INTEGER IW(5)
DIMENSION NRP(206), PP(206), P1P(206), P2P(206), ISP(206), IRP(206)
DIMENSION PS(206), PFRP(206), EFFGP(206), WSP(206), VSP(206)
DIMENSION IS1P(206), ALFP(206), PINGP(206), FISDP(206), FIRD(206)
DIMENSION FRP(206), PPS(206), VS(206)
COMMON/AS/IS, FISD, FIRD, IR1D, IR2, V2
COMMON/DK/S1, S2, IS2D, ES1, ES2, ER2, ES2, ERDS, ESDS
COMMON/SN/P, P1, P2, PS
COMMON/Z/KD
COMMON/SH/WS
COMMON/AB/IR, ALF, VS
COMMON/FG/NR
COMMON/MM/PFS, PFR
COMMON/AA/EFFG
COMMON/AG/IS1, PING, FR

..SUPROUTINE REFERENCES..

E04JAF

..DATA NOUT /6/

N=2
WRITE(NOUT, 99999)
X(1)=-45.0*0.0174532E+0
X(2)=-3.39E-4
IBOUND=0
BL(1)=-90.0*0.0174532E+0
BU(1)=90.0*0.0174532E+0
BL(2)=-3.399E-4
BU(2)=-3.398E-4
LIW=5
LW=39
WS=314.0
DO 30 MW=1,206
WS=WS+3.0
IFAIL=1
CALL E04JAF(N, IBOUND, BL, BU, X, F, LW, W, LW, IFAIL)
C SINCE IFAIL WAS SET TO 1 BEFORE ENTERING E04JAF, IT IS
C ESSENTIAL TO TEST WHETHER IFAIL IS NON-ZERO ON EXIT
IF (IFAIL.EQ.1) GO TO 20
CALL FUNCT(N,X,F)
IF (IFAIL.NE.0) WRITE(NOUT,99998) IFAIL
WRITE(NOUT,99997) F,I,S,P, WS,IR,IFS,FR,FSD,IS1,ALF,NR,VS,FSD,
+FIRD,FR,IS1,IS2,ERDS,IS2D,ES1,ES2S,ER2S,ES2,PS,P1,P2,IR1D,IR2,V2
WRITE(NOUT,99996) (X(J),J=1,N)
20 CONTINUE
C CALL PAPER(1)
C CALL PSSPACE(0.4,0.75,0.2,0.75)
C CALL GPSSTOP(13)
C CALL MAP(600.0,2250.0,-6000.0,100.0)
C CALL CURVEO(NRP,PP,1,206)
C CALL CTRMAG(8)
C CALL AXESSI(500.0,500.0)
C CALL PLOTCS(3250.0,0.0,"SPEED; R.P.M.",12)
C CALL PLOTCS(-250.0,150.0,"POWER; WATT",10)
C CALL FRAME
C CALL MAP(600.0,2250.0,-500.0,200.0)
C CALL CURVEO(NRP,P1P,1,206)
C CALL AXES
CALL FRAME
CALL MAP(600.0,2250.0,-4000.0,300.0)
CALL CURVEO(NRP,P2P,1,206)
CALL AXES
CALL FRAME
CALL MAP(600.0,2250.0,0.0,15.0)
CALL CURVEO(NRP,ISP,1,206)
CALL AXESSI(500.0,2.0)
CALL FRAME
CALL MAP(600.0,2250.0,0.0,15.0)
CALL CURVEO(NRP,IRP,1,206)
CALL AXESSI(500.0,2.0)
CALL FRAME
CALL MAP(600.0,2250.0,-1.0,1.0)
CALL CURVEO(NRP,PFSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(600.0,2250.0,0.0,100.0)
CALL CURVEO(NRP,EFFGP,1,206)
CALL AXES
CALL FRAME
CALL MAP(-90.0,90.0,0.0,50.0)
CALL CURVEO(ALFP,VSP,1,206)
CALL AXES
CALL FRAME
CALL MAP(600.0,2250.0,-4000.0,400.0)
CALL CURVEO(NRP,PSP,1,206)
CALL CTRMAG(8)
CALL AXESSI(500.0,500.0)
CALL FRAME
CALL MAP(600.0,2250.0,-50.0,50.0)
CALL PLOTCS(500.0,-60.0,"STATOR FREQUENCY_SPEED",23)
CALL PLOTCS(3600.0,0.0.0,"N,RPM",5)
CALL PLOTCS(-250.0,55.0,"FS,HZ",5)
CALL CTRMAG(8)
CALL AXESSI(500.0,5.0)
CALL CURVEO(NRP,FRP,1,206)
CALL PLOTCS(500.0,-60.0,"STATOR FREQUENCY_SPEED",22)
CALL FRAME
CALL MAP(600.0,2250.0,0.0,50.0)
CALL CTRMAG(8)
CALL AXESSI(500.0,5.0)
CALL CURVEO(NRP,VSP,1,206)
CALL PLOTCS(250.0,-5.0,"EXCITATION VOLTAGE_SPEED",24)
CALL PLOTCS(3250.0,0.0.0,"N,RPM",5)
CALL PLOTCS(-250.0,35.0,"VS,VOLT",7)
CALL FRAME
CALL MAP(0.0,10.0,0.0,10.0)
CALL AXES
CALL CURVEO(ISP,IRP,1,206)
CALL GRENDE
20 STOP
END

C

SUBROUTINE FUNCT1(N, XC, FC)
FUNCTION EVALUATION ROUTINE FOR E04JAF EXAMPLE PROGRAMME

THIS ROUTINE MUST BE CALLED FUNCT1

..SCALAR ARGUMENTS..
REAL NT,IRD,IS1,LRD,LSD,IRD2,IS2D,L2D,L1,L2,NR
REAL LS,LR,KD,M,WR,WS,W
REAL IS
REAL IR
REAL FC
REAL XC(N)
INTEGER N
COMMON/AS/IS,FISD,FIRD,IRD2,IRD2,V2
COMMON/DK/S1,S2,IS2D,ES1,ES2D,ES1,ES2,ER2S,ES2,ES2S,ERDS,ESDS
COMMON/SN/P,P1,P2,PS
COMMON/Z/KD
COMMON/SH/WS
COMMON/AB/IR,ALF,VS
COMMON/FG/NS
COMMON/MM/PFS,PFR
COMMON/A2/EFFG
COMMON/AG/IS1,PING,FR

.. ARRAY ARGUMENTS..

.. LOCAL SCALARS..

.. LOCAL DIMENSION..
VR=62.0
RS=4.55
RR=1.546
NT=1.257
M=2.0/(6.28318*50.0)
AL=XC(1)
KD=XC(2)
ALF=AL/0.0174532
L2D=1.3/(6.28318*50.0)
L1=1.3/(6.28318*50.0)
RRD=RR*NT*NT
RSD=RS/(NT*NT)
L1=L1+(M)
LSD=((L1/(NT*NT))+(M/NT))
LRD=(L2D+(M*NT))
L2=L2D/(NT*NT)
LR=L2+(M)
WR=-50.0*6.28318
WS=WS-WR
WD=WZ/2.0
NR=(WS-WR)*60.0/(2.0*6.28318)
FF=WS/6.28318
SS=(WS-WZ)/WS
SR=1.0/SS
S1=SS
S2=(WR+WZ)/WR
A=(RS*RRD)+(WR*WS*((M*M/NT*NT)-(LS*LRD)))
B=(LS*RRD*WS)+(RS*LRD*WR)
C=(RR*RSD)+(WR*WS*((M*M/(NT*NT))-(LR*LSD)))
D=(RR*LSD*WS)+(RS*LR*WR)
VS=VR*M*WS*(((COS(AL))+(D*SIN(AL)))*((A**2)+(B**2)))/
+(((A*WR*LRD)-(B*RRD))*NT*(((C*C)+(D*D))
I S1=VS*SQRT(((A*RRD)+(B*LRD*WR)**2)+(((LRD*WR*A)-(B*RRD)**2))/
*(((A*A)+(B*B))}
A7.13

\[ IS2D = -M \times WS \times VR / (\sqrt{(C \times C) + (D \times D) \times NT}) \]
\[ IRLD = N \times M \times WR \times VS / (\sqrt{(A \times A) + (B \times B)}) \]
\[ IR2 = VR \times \sqrt{((C \times RSD) + (D \times LSD \times WS)) \times 2 + ((LSD \times WS \times C) - (D \times RSD)) \times 2}} / (*) ((C \times C) + (D \times D)) \]
\[ ERDS = M \times WR \times IS1 \]
\[ ESDS = M \times WS \times IRLD \]
\[ ES2S = -M \times WS \times IR2 \]
\[ ER2S = M \times WR \times IS2D \]
\[ ES1 = S1 \times ESDS \]
\[ ES2 = S2 \times ER2S \]
\[ B1 = VS \times (((A \times RRD) + (B \times WR \times LRD))/((A \times A) + (B \times B))) \]
\[ B2 = -(M \times WS \times VR \times ((C \times SIN(\theta)) - (D \times COS(\theta))))/(NT \times ((C \times C) + (D \times D))) \]
\[ B3 = VS \times ((A \times WR \times LRD) - (B \times RRD))/((A \times A) + (B \times B)) \]
\[ B4 = M \times VR \times WS \times ((C \times COS(\theta)) + (D \times SIN(\theta)))/(NT \times ((C \times C) + (D \times D)) \]
\[ IS = \sqrt{((B1 + B2) \times (B1 + B2)) + ((B3 - B4) \times (B3 - B4))} \]
\[ V2 = IS \times ((RS*2) + (1.3**2)) \]
\[ C1 = VR \times (((RS*SD) + (D \times WS \times LSD))/((C \times C) + (D \times D))) \]
\[ C2 = VR \times (((C \times WS \times LSD) - (D \times RSD))/((C \times C) + (D \times D))) \]
\[ C3 = M \times NT \times VS \times VR \times ((A \times SIN(\theta)) + (B \times COS(\theta)))/((A \times A) + (B \times B)) \]
\[ C4 = -M \times NT \times VS \times WR \times ((A \times COS(\theta)) + (B \times SIN(\theta)))/((A \times A) + (B \times B)) \]
\[ IR = \sqrt{(C1 \times C3) * (C1 + C3)) + (C2 - C4) \times (C2 - C4)) \]
\[ P3 = (6.0 \times IS2D \times VR \times WD) / (((A \times A) + (B \times B)) \times ((C \times C) + (D \times D))) \]*
\[ (RS \times LR \times WR - ((C \times RSD) + (D \times WS) \times WS) \times ((A \times C) + (B \times D))) \]
\[ P4 = (6.0 \times IS2S \times VR \times WD) / (((A \times A) + (B \times B)) \times ((C \times C) + (D \times D))) \]
\[ (M \times WS \times WR) \times ((A \times D) - (B \times C)) \]
\[ \times SIN(\theta)) \]
\[ P5 = (P3 + P4) \]
\[ P1 = 3.0 \times IRLD \times IRLD \times RRD \times (1 - S1) / S1 \]
\[ P2 = 3.0 \times IS2D \times IS2D \times RSD \times (1 - S2) / S2 \]
\[ P = P1 + P2 + P5 \]
\[ CL1 = 3.0 \times ((IIR2 \times IIR2 \times RR) + (IRLD \times IRLD \times RRD)) \]
\[ CL2 = 3.0 \times ((IS1 \times IS1 \times RS) + (IS2D \times IS2D \times RSD)) \]
\[ CL = CL1 + CL2 \]
\[ RMS = 85.0 \]
\[ PI = 3.0 \times (ES2S) \times (ES2S) / RMS \]
\[ RMR = 27.9 \]
\[ PI = 3.0 \times (ERDS) \times (ERDS) / RMR \]
\[ PI = PI + PI \]
\[ FPI = -PI + PI \]
\[ EFF = 1.0 \times 100.0 / PING \]
\[ EFF = -EFF \]
\[ FIS = ATAN2((B3 - B4), (B1 + B2)) \]
\[ FISD = FIS / 0.0174532 \]
\[ PFS = COS(FIS) \]
\[ FIR = ATAN2((C1 + C3), (C1 + C3)) \]
\[ FA = 90.0 \times 0.0174532 \]
\[ IF(FA > 35) \]
\[ IF = 180.0 \times 0.0174532 \]
\[ FIR = IF - 35 \]
\[ PFR = COS(FIR) \]
\[ FC = (P - (KD \times (WD \times 3.0))) \times 2.0 \]
\[ RETURN \]

C END OF FUNCTION EVALUATION ROUTINE
END
PROGRAM NADIA(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
POWER(SPEED)**3 OPTIMISATION, CONSTANT CURRENT EXCITATION SYSTEM.
MINIMISATION IS SUBJECT TO LOAD ANGLE VARIATION.
E04JAF NAG LIB. ROUTINE TO BE USED.
MARK 6 RELEASE NAG COPYRIGHT 1977.

LOCAL Scalars..
REAL F,IR2P,IR2
INTEGER IBOUND, IFAIL, J, LIW, LW, N, NOUT

LOCAL ARRAYS..
REAL BL(3), BU(3), W(39), X(3)
REAL NR,NRP,ISP,IS,KD
INTEGER IW(5)
DIMENSION NRP(206),PP(206),ISP(206),W2P(206),VSP(206)
DIMENSION ALFP(206),PINF(206),IR2P(206),EFFGP(206)
COMMON/AS,FR,VS
COMMON/SN/P,IR2,ALF
COMMON/Z/KD,W2,NR
COMMON/AG/PINF,EFFG

SUBROUTINE REFERENCES..
E04JAF

DATA NOUT /6/
N=3
WRITE(NOUT,99999)
X(1)=3.60E+0
X(2)=+40.0*0.0174532E+0
X(3)=-1.699E-4
IBOUND=0
BL(1)=3.54E+0
BU(1)=3.64E+0
BL(2)=0.0
BU(2)=90.0*0.0174532E+0
BL(3)=-1.699E-4
BU(3)=-1.6989E-4
LIW=5
LW=39
W2=-314.0
DO 30 MW=1,206
W2=W2+3.0
IFAIL =1
CALL E04JAF(N, IBOUND, BL, BU, X, F, IW, LIW, W, LW, IFAIL)
ESSENTIAL TO TEST WHETHER IFAIL IS NON-ZERO ON EXIT
IF (IFAIL.EQ.1) GO TO 20
CALL FUNCT1(N,X,F)
IF (IFAIL.NE.0) WRITE(NOUT,99998) IFAIL
WRITE(NOUT,99997)F,IS,P,W2,IR2,EFFG,ALF,NR,VS
WRITE(NOUT,99999) (X(J),J=1,N)
99999 FORMAT(///31H E04JAF EXAMPLE PROGRAM RESULTS/) 
99998 FORMAT(///16H ERROR EXIT TYPE,13,22H SEE ROUTIN DOCUMEN, 
+ 1HT)
99997 FORMAT(///27H FUNCTION VALUE ON EXIT IS , F15.10, 
+FPG=,F7.4,3X,4HALF=,F9.3,3X,3HNR=,F9.3,3X,3HNR=,F9.3,1)/
99996 FORMAT(13H AT THE POINT, 3F20.13,/) 
NR(MW)=NR
PP(MW)=P
ISP(MW)=IS
IR2P(MW) = IR2
EFFGP(MW) = EFG
W2P(MW) = W2
VSP(MW) = VS
ALFP(MW) = ALF
PINGP(MW) = PING

30 CONTINUE
CALL PAPER(1)
CALL PSSPACE(0.4, 0.75, 0.2, 0.75)
CALL GPSTOP(8)
CALL MAP(0.0, 3000.0, -4000.0, 100.0)
CALL CURVEO(NRP, PP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 3000.0, 0.0, 10.0)
CALL CURVEO(NRP, ISP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 3000.0, 0.0, 15.0)
CALL CURVEO(NRP, IR2P, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 3000.0, 0.0, 100.0)
CALL CURVEO(NRP, EFFGP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 90.0, 0.0, 40.0)
CALL CURVEO(ALFP, VSP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(-324.0, 324.0, 0.0, 40.0)
CALL CURVEO(W2P, VSP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 3000.0, -324.0, 324.0)
CALL CURVEO(NRP, W2P, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(0.0, 3000.0, 0.0, 35.0)
CALL CURVEO(NRP, VSP, 1, 206)
CALL AXES
CALL FRAME
CALL MAP(-120.0, 0.0, 0.0, 40.0)
CALL CURVEO(ALFP, VSP, 1, 206)
CALL AXES
CALL GREN
20 STOP
END

SUBROUTINE FUNCT1(N, XC, FC)
FUNCTION EVALUATION ROUTINE FOR E04JAF EXAMPLE PROGRAM-
THIS ROUTINE MUST BE CALLED FUNCT1

SCALAR ARGUMENTS ..
REAL NT, LRD, LSD, IR2, L2D, L1, L2, NR
REAL IS, IR, LS, LR, KD, M, W
REAL FC
REAL XC(N)
INTEGER N
COMMON/AS/IS, FR, VS
COMMON/SN/P, IR2, ALF
COMMON/Z/KD,W2, NR
COMMON/AG/PING, EFGG
  .. ARRAY ARGUMENTS ..
  .. LOCAL SCALARS ..
  .. LOCAL DIMENSION ..
  SUBSCRIPTS IN MACHINE PARAMETERS MEANS TOTAL SECONDARY TERM
  PER PHASE (STATOR)
  SUBSCRIPTS R IN MACHINE PARAMETERS MEANS TOTAL PRIMARY TERM PER
  PHASE (ROTOR)
VR=62.0
RS=4.55
RR=1.546
M=20.0/(6.28318*50.0)
IS=X*C(1)
AL=X*C(2)
KD=X*C(3)
ALF=AL/0.0174532
L2D=1.3/(6.28318*50.0)
L1=1.3/(6.28318*50.0)
NT=1.257
RRD=RR*NT*NT
RSD=RS/(NT*NT)
LS=L1+M
LSD=((L1/(NT*NT))+(M/NT))
LRD=(L2D+(NT*M))
L2=L2D/(NT*NT)
LR=L2+M
W1=-50.0*6.28318
W2=W1
WD=WZ/2.0
NR=(W2-W1)*60.0/(2.0*6.28318)
SS=(W2-WZ)/W2
SR=1.0/SS
A=(RS*RRD)+(W1*W2*((M*M*NT*NT)-(LS*LRD)))
B=(LS*RRD*W2)+(RS*LRD*W1)
C=(RR*RRD)+(W1*W2*((M*M/(NT*NT))-(LR*LSD)))
D=(RR*ISC*W2)+(RSD*LR*W1)
VS=(IS/SQRT(((A*RRD)+(B*LRD*W1))**2)+(((LRD*W1*A)-(B*RRD))**2))*
  *((A*A)+(B*B))
IR2=VR*SQRT(((C*RSD)+(D*LSD*W2))**2)+(((LSD*W2*C)-(D*RSD))**2)/
  *((C*C)+(D*D))
C2=VR*(((C*W2*LSD)-(D*RSD))/((C*C)+(D*D)))
C1=VR*((RSD*C)+(D*W2*LSD))/((C*C)+(D*D))
C3=M*NT*VS*W1*((A*SIN(AL))+(B*COS(AL))/((A*A)+(B*B))
C4=-M*NT*VS*W1*((A*COS(AL))+(B*SIN(AL))/((A*A)+(B*B))
IR=SQRT(((C1+C3)*(C1+C3))+(C2-C4)*(C2-C4))
P=(-3.0*WZ*M*VR*IS*SIN(AL)/(4.0*1.3))
CL1=3.0*(IR2*IR2*RR)
CL2=3.0*((IS*IS*RS))
CL=CL1+CL2
PING=-P+CL
EFGG=P*100.0/PING
FIR=ATAN2((C2-C4),(C1+C3))
FIRD=FIR/0.0174532
PFR=COS(FIR)
FR=W2/6.28318
FC=(P-(KD*(WD**3.0)))*2.0
RETURN
C END OF FUNCTION EVALUATION ROUTINE
END
Appendix A7.5a

PROGRAM EPROM(INPUT,OUTPUT,TAPE7=INPUT,TAPE2=OUTPUT)
C DIMENSIONING STORAGE SPACE FOR THE EIGHT BINARY BITS
DIMENSION J(128)
C PRINTING OF TITLE
WRITE(2,5)
5 FORMAT(1H ,"BINARY CODED AMPLITUDES OF A SINE WAVE(PHASE B")
WRITE(2,6)
6 FORMAT("************************************************************")
WRITE(2,10)
C SET THETA TO -120 DEGREE OR -2.08621 RAD
C SET COUNT TO ZERO
THETA=-2.08621
COUNT=0
C OBTAIN VALUE OF PI
PIE=ATAN(1.0)*4
DO 50 I=1,256
   A=SIN(THETA)
50   SCALE=A*255
C OBTAIN MODULUS OF SCALED UP VALUE
AMOD=ABS(SCALE)
C TRUNCATING THE MODULUS TO AN INTEGER VALUE
AMOD=AMOD+0.5
IDEC=INT(AMOD)
C BECAUSE I WANT IDEC TO BE PRINTED OUT, I USE ANOTHER VARIABLE
C WHICH TAKES THE VALUE OF IDEC, BUT WHICH WILL ALSO CHANGE ITS
C VALUE IN THE FOLLOWING CALCULATIONS.
N=IDEC
C SET ALL THE BINARY BITS TO ZERO; THESE WILL REMAIN ZERO UNLESS
C SPECIFICALLY CHANGED
J(1)=0
J(2)=0
J(4)=0
J(8)=0
J(16)=0
J(32)=0
J(64)=0
J(128)=0
C USE A VARIABLE K IN THE FOLLOWING CALCULATIONS TO INDICATE
C THE CORRESPONDING BINARY BIT. THE VALUE OF THE MOST
C SIGNIFICANT BIT IS 128; SO SET K=128
K=128
IF(IDEC)60,200,11
C TO CONVERT FROM DENARY TO BINARY, THE VALUE OF N IS COMPARED WITH
C EACH BINARY BIT IN TURN, STARTING WITH THE MOST SIGNIFICANT BIT;
C IF N>= TTAT BIT, THEN THAT BIT IS SET TO '1'. THE VALUE OF THIS
C BIT IS THEN SUBTRACTED
11 IF(N-K)25,15,20
15 J(K)=1
   GOTO200
20 N=N-K
   J(K)=1
25 K=K/2
   GOTO 11
200 WRITE(2,30)COUNT,THETA,A,IDE...
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**Note:** The values represent decimal approximations of sine wave amplitudes at different angles measured in radians. Each row corresponds to a specific angle (theta) and its binary-coded amplitude.
PROGRAM EPROM(INPUT,OUTPUT,TAPE7=INPUT,TAPE2=OUTPUT)
C DIMENSIONING STORAGE SPACE FOR THE EIGHT BINARY BITS
DIMENSION J(128)
C PRINTING OF TITLE
WRITE(2,5)
5 FORMAT(1H,"BINARY CODED AMPLITUDES OF A SINE WAVE(PHASE C)"
WRITE(2,6)
6 FORMAT("")
WRITE(2,10)
C SET THETA TO -120 DEGREE OR -2.08621 RADS
C SET COUNT TO ZERO
THETA=2.08621
KOUNT=0
C OBTAIN VALUE OF PI
PIE=ATAN(1.0)*4
DO 50 I=1,256
A=SIN(THETA)
C SCALING UP SIN(THETA) TO WITHIN THE RANGE 0 TO 255
SCALE=A*255
C OBTAIN MODULUS OF SCALD UP VALUE
AMOD=ABS(SCALE)
C TRUNCATING THE MODULUS TO AN INTEGER VALUE
AMOD=AMOD+0.5
IDEC=INT(AMOD)
C BECAUSE I WANT IDEC TO BE PRINTED OUT, I USE ANOTHER VARIABLE
N=IDEC
C SET ALL THE BINARY BITS TO ZERO; THESE WILL REMAIN ZERO UNLESS
C SPECIFICALLY CHANGED
J(1)=0
J(2)=0
J(4)=0
J(8)=0
J(16)=0
J(32)=0
J(64)=0
J(128)=0
C USE A VARIABLE K IN THE FOLLOWING CALULATIONS TO INDICATE
C THE CORRESPONDING BINARY BIT. THE VALUE OF THE MOST
C SIGNIFICANT BIT IS 128; SO SET K=128
K=128
IF(IDEC)60,200,11
C TO CONVERT FROM DENARY TO BINARY, THE VALUE OF N IS COMPARED WITH
C EACH BINARY BIT IN TURN, STARTING WITH THE MOST SIGNIFICANT BIT;
C IF N>= THAT BIT, THEN THAT BIT IS SET TO '1'. THE VALUE OF THIS
C BIT IS THEN SUBTRACTED
11 IF(N-K)25,15,20
15 J(K)=1
GOTO200
20 N=N-K
J(K)=1
25 K=K/2
GOTO 11
200 WRITE(2,30)KOUNT,THETA,A,IDEC,J(128),J(64),J(32),J(16),J(8),J(4),J(2),J(1),IDEC
30 FORMAT(2X,I3,4X,F8.5,4X,F9.5,7X,I3,10X,8I1,8X,22)
KOUNT=KOUNT+1
THETA=THETA+PIE/128
IF(THETA-(2*PIE+2.08621))50,60,60
50 CONTINUE
60 STOP
END
### Binary Cod Amplitudes Of A Sine Waveform (E)

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**Appendix A7.6.b**

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Papers represented in
UPEC Conferences
A doubly-fed generator operating as a wind-energy transducer

with unity-power factor and optimum phase angle control

N.A. Elsonbaty and P.G. Holmes
University of Leicester.

1.0. Introduction

A slip-ring induction motor fed by a fixed-frequency primary supply and a secondary supply of variable amplitude and frequency can operate as a synchronous generator at a synchronous speed, \( w_1 \pm w_2 \), dependent upon \( w_2 \). The power generated is a function of speed and the phase angle between the induced primary and secondary voltages in the air gap. This phase angle, known as the "load" angle is the principal control function by which a generated power proportional to the cube of the speed can be achieved.

2.0. Operation with minimum stator current

The preferred operation of the system shown in Fig. 1 is with the cycloconverter supplying mainly exciting current and power. This condition corresponds to unity power factor in the secondary circuit. In the experimental system, the power electronic device rating requirements are reduced by operating the machine with the slip-ring rotor as the primary at 50Hz.

Fig. 2 represents one phase of the system and Fig. 3 shows the phasor relationship of the currents and voltages with the "load" angle \( \alpha \) indicated. An expression for the generated power at unity power factor can be developed from the torque-speed relationships at unity power factor by Alston and Holmes.

The condition for unity stator power factor is obtained by equating the imaginary component of \( I_s \) to zero. This defines a required ratio of stator to rotor voltages,

\[
\frac{V_s}{V_R} = \frac{(C \cos \alpha + D \sin \alpha)}{(A \omega L + B \omega R)} \cdot \frac{M(A^2 + B^2)}{N(C^2 + D^2)}
\]

where \( A, B, C, D, M, N, L \) and \( R \) are machine parameters, \( \alpha \) is the "load" angle, \( \omega_L \) and \( V_R \) are the rotor frequency and voltage. Figs. 4 and 5 show the variation of stator and rotor current with "load" angle at a range of fixed stator frequencies.

3.0. Generated power

The total generated power consists of synchronous power and two induction powers. If the stator impedance is low, the induction power will be small compared with the synchronous power. A generated power proportional to the cube of the speed can be approached by constraining the synchronous power to obey the cubic law.

The synchronous power \( P_s \) can be expressed as:

\[
P_s = \frac{3P_{MW} V_s w}{(A^2 + B^2)(C^2 + D^2)} \left[ \sum_{s} \sum_{R} \left( R_L (w_s - w) + R_L (w_s + w) \right) \left( (AC + BD) \cos \alpha - (AD - BC) \sin \alpha \right) + [M^2 (w_s - w) (w_s + w)] \left( (AD - BC) \cos \alpha + (AC + BD) \sin \alpha \right) \right]
\]

UPEC, 1982
where \( w_s \) and \( w \) are the stator and shaft angular frequencies.

Variations in wind power cause the speed of a wind turbine to vary over a speed range of up to 7 to 1. With appropriate gearing, the maximum power capability of the electrical transducer system must be matched to the expected maximum wind turbine speed. The matching point of speed for the doubly-fed machine is \( 1.3f/p \), i.e. fundamental synchronous speed + 30%. At lower speeds, the transducer power requirement is to respond to the law,

\[
P_{\text{Total}} = Kw^3
\]  

(3)

Figs. 4 and 5 show the variation of stator and rotor current with load angle at constant stator frequency values.

The value of stator voltage needed to constrain \( P_s \) to obey equation (3) with the induction power added varies with stator frequency as the non-linear function shown in Fig. 6. If the load angle can be measured, and expressed as a voltage, then the stator voltage supplied by the cycloconverter can be demanded to maintain the cube law. This is possible if the e.m.f. generated in an electrically isolated co-linear stator coil is compared with the cycloconverter output voltage. The phase-difference between the two e.m.f.s can be sensed and expressed as the width of a rectangular pulse. In the present experimental system, tooth ripple blurred the edges of the pulse and caused instability.

A more successful solution to the problem has been used in the experimental system. The "load" angle, \( \alpha \), is a non-linear function of the stator voltage as shown in Fig. 7. This relationship has been burnt into an EPROM to provide an electronic control loop to demand a value of \( V \) related to speed and the required load angle. If saturation can be avoided in the machine, and the machine parameters are reasonably constant, then the required load angle can be demanded as a direct function of cycloconverter voltage.

4.0. Experimental results

Figs. 8 and 9 show the minimisation of stator current and the power generated related to speed contrasted with the required cube-law relationship. In the laboratory system, satisfactory operation from the speed \( 1.3f/p \) has been achieved down to near synchronous speed \( f/p \). Theoretically, there is no reason why the system should not operate through and below synchronous speed. This requires the cycloconverter to excite the machine with d.c. at synchronous speed and to reverse the phase rotation at lower speeds.

An alternative solution is close-ratio pole changing in stator and rotor by pole-amplitude modulation or other means. This would effectively provide an electrical "gear box".

5.0. Conclusions and possibilities for developing the system

It has been shown that the "load" angle is the principle control function in a doubly-fed machine operating as a wind power transducer. The "load" angle is a function of the excitation voltage, and a cube-law power/speed characteristic has been achieved by excitation control. However, the experimental machine was constrained within the linear range of the magnetisation characteristic. The non-linearities caused by saturation make the relationship between the "load" angle and the excitation voltage a load-dependent function. Direct feedback from an accurately sensed "load" angle would overcome this problem.

6.0. References

Appendix

Parameters of the Experimental Machine

The experimental machine is a Mawdsley Educational Induction Motor fitted with a 4-pole wound rotor. The stator winding consisted of a conventional 4-pole double layer winding with two electrically separate layers.

Parameters found by experiment:

- Stator resistance $R_s = 4.55 \Omega$
- Rotor resistance $R_r = 1.546 \Omega$
- Stator leakage inductance $L_1 = 0.00414$ henry
- Rotor leakage inductance $L_2 = 0.002$ henry
- Mutual Inductance $M = 0.064$ henry
- Turns ratio 1.26

Rated stator current, 16A, Rated full load current, 50A,
Rated stator voltage at 50Hz = 240 volt.
Fig. 1  Doubly-fed generator system

Fig. 2  Equivalent circuit

Fig. 3  Phasor diagram
Fig. 4  Stator current - load angle, super synchronous operation

Fig. 5  Rotor current - load angle, super synchronous operation

Fig. 6  Cycloconverter voltage - frequency at L. ang = 0 to -90

Fig. 7  Cycloconverter voltage as affected by L. ang choice, super synchronous operation
**Fig. 8** Stator current vs. speed

**Fig. 9** Total generated power-speed
CONSTANT CURRENT EXCITATION OF A DOUBLY-FED-GENERATOR
OPERATING AS A WIND ENERGY TRANSUDER

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University of Leicester
England

N. Elsonbaty
University of El Minia
Egypt

INTRODUCTION

A wound rotor induction motor with variable frequency excitation can act as a doubly-fed generator with a variable synchronous speed. As a wind energy transducer feeding the grid, it is required to generate power roughly in proportion to the cube of the wind speed. A slip range of $0.2 > s > -0.3$ will for most wind regimes lead to an energy capture not far short of the one theoretically possible with a much wider rotor speed range. This is because the number of wind hours in the low speed range and in the high speed range is relatively small when related to the median speeds.

The experimental system shown in Fig. 1 is a 5 kW generator test facility with a separately excited d.c. motor as the prime mover. Secondary excitation is provided by a cycloconverter with electrically separate positive and negative thyristor group circuits to prevent transient line to line short-circuits through the cycloconverter. This enables the system to withstand severe input surges.

![Fig. 1 Doubly-fed generator schematic](image-url)
1.0. OPERATION OF THE EXCITED TRANSUDER

The cycloconverter output frequency is controlled by velocity feedback to maintain the angular velocity relationship,

\[ \omega = \frac{\omega_1 - \omega_2}{p} \]  

(1)

where \( \omega \) is the angular velocity of the shaft, \( \omega_1 \) is the primary angular frequency, \( \omega_2 \) is the secondary angular frequency and \( p \) the number of pole pairs. Continuous current operation through a divided winding of magnetically coupled layers minimises the low-frequency harmonics.

When the machine is synchronised, the speed will be,

\[ \omega = \frac{\omega_1 \pm \omega_2}{p} \]  

(2)

the negative values of \( \omega_2 \) are values of reversed phase sequence obtained at speeds below synchronous speed.

The doubly-fed machine operates both synchronously and inductively. Two separate supplies, one of which must vary in frequency and amplitude produce rotating fields. The two fields will be rotating at equal angular velocities and their interaction will generate power dependent on the relative position of the two fields in space. Their relative displacement is known as the flux or load angle, \( \alpha \), and a synchronous power component will be produced.

The two fields may be stationary relative to each other, but they are travelling with respect to each winding. Two induction power components will be generated, one due to the primary supply and one due to the secondary supply. A full steady state analysis may be derived from the torque equations of Prescott and Raju. The analysis may be simplified if harmonics higher than the fundamental and the effect of commutation on the cycloconverter output are neglected. Using these assumptions, the two-axis equations for a symmetrical induction machine with synchronous rotating reference axes are:

\[
\begin{align*}
\begin{bmatrix}
V_{d1} \\
V_{q1} \\
V_{d2} \\
V_{q2}
\end{bmatrix} &= 
\begin{bmatrix}
r_1 + L_1 p & -\omega_1 L_1 & M_p & -\omega_1 M_p \\
\omega_1 L_1 & r_1 + L_1 p & \omega_1 N_p & M_p \\
M_p & -s\omega_1 M_p & r_2 + L_2 p & -s\omega_1 L_2 \\
s\omega_1 M_p & M_p & s\omega_1 L_2 & r_2 + L_2 p
\end{bmatrix}
\begin{bmatrix}
id_1 \\
iq_1 \\
id_2 \\
iq_2
\end{bmatrix}.
\end{align*}
\]  

(3)

and the developed power is,

\[
T_m = P_u M (i_{q1} i_{d2} - i_{d1} i_{q2})
\]  

(4)

1.1. VOLTAGE SOURCE EXCITATION

When the cycloconverter is operating as a voltage-source, the fundamental voltage equations, after dq transformation are,
where $\alpha$ is the flux or load angle, $p$ is the differential operator and all other symbols have their usual meanings. The steady-state power generated is then the sum of three components obtained from equations (3) to (6) as follows:

$$T_\omega = \omega [T_{I_1} + T_{I_2} + T_S] ,$$

where $T_{I_1}$ and $T_{I_2}$ are induction torque components dependent upon slip, but independent of load angle and $T_S$ is the synchronous torque.

$$T_{I_1} = K(s)sr_2V_1^2 ,$$

$$T_{I_2} = - K(s)r_1V_2^2 ,$$

and

$$T_S = \left[ \frac{K(s)}{X_m} \right] V_1 V_2 \left[ r_1 r_2 + s(X_1 X_2 - X_m^2) - [sX_2 r_1 - r_2 X_1] \cos \alpha \right] ,$$

where

$$D(s) = \left[ r_1 r_2 - s(X_1 X_2 - X_m^2) \right]^2 + (r_2 X_1 + sr_1 X_2)^2 ,$$

$$K(s) = \frac{3P X_m^2}{\omega_1 D(s)} ,$$

and $X_1 = \omega_1 L_1$, $X_2 = \omega_2 L_2$ and $X_m = \omega_1 M$. 

Fig. 2 shows computed and measured torques corresponding to a value of minimum secondary resistance when the mechanical input varies as the cube of the speed. The large induction generating peak torque forces the synchronous torque to change sense from a generating torque to a motoring torque backing off the induction torque. Clearly this is wasteful of energy and likely to cause hunting when the speed changes.

Increasing the secondary resistance will maintain a unified sense of synchronous torque at the expense of increased copper loss as shown in Fig. 3.

1.2. CONSTANT CURRENT EXCITATION

Current source excitation has been used in a doubly-fed motor system to obtain greater transient stability. A similar technique can be used to minimise induction generation in a doubly-fed generator. The rotor dq currents are now given as,

$$\begin{bmatrix} id_2 \\ iq_2 \end{bmatrix} = - \sqrt{3} I_2 \begin{bmatrix} \sin \alpha \\ \cos \alpha \end{bmatrix} ,$$

where $I_2$ is the fundamental component of the secondary current.
Fig. 2  Doubly fed generator torques/speed at minimum secondary resistance

Fig. 3  Doubly-fed generator torques/speed at twice minimum secondary resistance
From equations 3, 4 and 9, the generated power is now,

\[ \omega T = \frac{3p}{\omega_1} \frac{X_m}{(r_1 + 4X_1^2)} \left[ V_1 I_2 \left( X_1 \sin \alpha + \frac{r_1^2 + 2X_1^2}{r_1} \cos \alpha \right) - I_2^2 r_1 X_m \right] \]  

(10)

If \( \frac{r_1^2 + 2X_1^2}{r_1} X_m < 1 \), \( \omega T = \frac{3p}{4X_1} V_1 I_2 \sin \alpha \). \hspace{1cm} (11)

The last term in equation 10 represents induction torque which is now independent of slip. Clearly the induction torques will be minimised if the secondary currents can be minimised and held constant. This can be achieved by operation at the minimum current level of the secondary "V" curve.

2.0. SYSTEM OPERATION

Fig. 4 contrasts the system performance under conditions of the voltage-source (B) excitation necessary for cube-law generation and with constant minimum secondary current (C). Constant current excitation reduces the secondary power through the cycloconverter to less than half its former value at a slip of -0.2. The primary power fed into the grid is practically the same in both cases until the upper speed limit \( s = -0.3 \) is reached. Fig. 5 shows the reduced secondary power of the constant current system increases the overall system efficiency by up to 10%.

3.0. CONCLUSIONS

It has been shown that constant minimum current excitation of a cycloconverter excited doubly-fed machine can maintain induction power at a low, slip-independent level which allows the system to operate synchronously throughout the sub- and super-synchronous speed range.

A change of sense of synchronous power is prevented giving greater stability with increased efficiency.
4.0. ACKNOWLEDGEMENTS

The authors are grateful to Professor G.D.S. MacLellan for the provision of facilities and to the Government of the Egyptian Republic for financial support.

5.0. REFERENCES


6.0. APPENDIX

The basic machine is a Mawdsley Educational Induction Motor fitted with a 4-pole slip-ring rotor. Excitation is by a 3-phase, 50 Hz, 120 V input, half-wave cycloconverter rated at 10 A r.m.s. per phase.