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WIND POWER GENERATION BY VARIABLE SPEED AC COMMUTATOR MACHINE

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a dissertation entitled, "Wind Power Generation by Variable Speed AC Commutator Machine" submitted by Nazar Singh Mangat in partial fulfillment of the requirements for the degree of Master of Engineering.

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N.S.M.

To My Wife Pavitra

and

Children Joty and Sonia

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NOMENCLATURE

WECS	Wind Energy Conversion System/s
ACCM	AC Commutator Machine
CSCF	Constant Speed Constant Frequency
VSCF	Variable Speed Constant Frequency
CVVF	Constant Voltage Variable Frequency
AVR	Automatic Voltage Regulator
ρ	density of atmosphere
A	area swept by turbine blades
P	power
S_1	wind speed at a considerable distance upwind
S_2	wind speed at a considerable distance downwind
C_p	power coefficient
I, i	current
V, v	voltage
Z	impedance
Z_L	load impedance in ohms
R_L	load resistance in ohms
X_L	load reactance in ohms
s	subscript for stator

r	subscript for rotor
d	subscript for direct-axis
q	subscript for quadrature-axis
n	$\frac{d\theta}{dt}$, speed of the rotor
R	resistance in ohms
L	inductance in henries
X	reactance in ohms
M	mutual inductance in henries
p	d/dt, derivative operator
V_t	rotor terminal voltage
V_s	stator voltage
I_t	terminal/load current
V_{ref}	reference voltage
V_d	desired voltage
V_a	variable dc voltage
t	time in Secs.
K	gain
T	time constant
m	modulation index
f	frequency in Hz
$[Z],[V],[I]$	matrix form of impedance, voltage and current respectively etc.

T_m	mechanical torque
T_e	electrical torque
T_a	accelerating torque
J	moment of inertia
ω	synchronous speed in rad./sec.

CHAPTER 1

INTRODUCTION

1.1. GENERAL

The increasing energy demand throughout the world has led scientists to explore renewable energy sources. With the drive towards the development of renewable sources, wind energy conversion systems (WECS) are being considered as one of the more viable alternatives. With growing recognition of wind energy as a proven renewable and non-polluting energy resource, it is becoming economically attractive for locations with good winds. Wind powered equipment as a means of energy conversion may, in principle, be considered a potential power source in any application - electrical, thermal or mechanical within the limits of unit rated capacity currently feasible. Since 1950, studies have been carried out ranging from design studies, to control methods, the actual testing and to cost analysis on small or full scale wind energy systems, and extensive literature is available on wind energy conversion schemes. In this context, interest is focused on the utilization of wind energy to generate electric power.

Studies show that the cost of generating electricity using wind gradually grew more competitive with conventional resources, and as utilities noticed the successes, their interest in wind began to increase [1]. Wind, hydro and solar power are the only alternative sources which, it can be claimed, the electric utilities are already integrating into their systems. Furthermore, the estimate of cost per kW of installed capacity of a WECS compares far more favorably than the cost of solar energy conversion [2]. Wind energy is being investigated as a supplemental source to meet growing energy demands. Most of the wind power plants of the past were of small size to pump water or to generate electricity in conjunction with battery storage. Interest has been revived to investigate wind energy as a viable supplementary source. Though wind energy has been with civilization for a long time, the question of large wind power generation has been raised only now with the necessary seriousness mainly due to the energy crunch. Major developments in wind energy conversion are taking place around the world and systems are developing sufficiently rapidly for wind power to become a viable source of its energy.

Control of wind energy conversion systems is complicated by the variable nature of the energy source and by the nature of wind turbine characteristics. Most of the control schemes developed have dwelled upon the mechanical control of the turbine (e.g. by changing the blade pitch). However, alternate possibilities exist. For example, electric power can be controlled at the generator end and variable-pitch control on the turbine removed.

The electrical aspects of interconnecting wind plants to utility transmission systems have been far less problematic than in the early days. The large utility diverse power systems are more able to accommodate substantial increments of power rising and diminishing with the wind than the less extensive utility systems that have more constrained transmission capacity and in which wind plants would represent a much larger fraction of total generation [1].

Initially, it was feared that the use of induction-type generators in WECS would cause voltage control problems because they would draw large amounts of reactive power from the utility grid, dragging down voltage levels and choking a transmission line's current-carrying capacity. That has been largely eliminated by equipping the wind plant power collection systems with capacitors that compensate for their reactive power consumption. But a large amount of wind capacity feeding the remote end of a long transmission line can still cause voltage control problems.

Both to improve operating economics by capturing more energy and to reduce dynamic fatigue stresses, a few wind turbines over the years have been designed for variable-speed operation [1]. In early variable-speed machines, cyclo-converters or rotor-slip energy recovery systems enabled the turbine rotor to operate at variable speed as the wind speed changed, thus capturing more of the available energy while maintaining a constant frequency, 60 Hz electrical output. But the electronics used in most early variable-speed machines can create another problem. They can inject significant amounts of harmonic current onto the utility line, affecting customer loads nearby and posing a damaging overload potential as a result of harmonic resonance within the utility system.

Studies described in reference [3] explore the applications of variable-speed wind turbine driven machines (e.g. synchronous machine, induction machine and double output induction generator (DOIG)). In these applications the machines were driven by fixed pitch variable-speed turbine and control strategy was developed on the electrical side of the system.

1.1.1. Advantages of a Variable-Speed Wind Turbine.

Conventional wind turbines are designed to operate over a very narrow speed range in order to maintain a constant-frequency power output to the grid. Wind gusts can result in a speed higher than the design speed and increase the torsional stresses in the drive train. An advanced variable-speed turbine employs a power electronic converter between the generator and the utility line. This allows the rotor and the generator to speed up with gusting or stronger winds. The increased rotational energy is then converted into more electricity without increasing the torque on the drive train. The converter maintains a constant frequency line output despite the generator's variable output frequency. In the case of an AC commutator generator, the output frequency is independent of the rotor speed and the output voltage is controlled by controlling field flux in the stator winding of the machine. Such a scheme is proposed in this dissertation.

1.1.2. Interconnection With Utility

Electrical power is mostly obtained from a power system composed of a large number of interconnected synchronous machines. The large utility diverse power systems are able to accommodate substantial increments of power rising and diminishing with the wind, without inducing instabilities. As the wind power generating facilities, in most of the cases, constitute a small percentage of the large utility system, the in-coming or out-going operation of wind-turbine driven machine causes a hardly detectable change of voltage and frequency; the system behaves like a large generator having virtually zero internal impedance and infinite rotational inertia and such a system is called an infinite-busbar system.

It is demonstrated in Chapter 4 that the proposed generation scheme is capable of controlling the terminal voltage within tolerable limits and the frequency of the output power is constant as well. Because the impedance of the infinite system connected to the terminals is zero, the proposed system can easily be operated in a dispersed mode.

1.1.3. Absence of Harmonics

Because of the use of converter and rectifier in most of the wind power generation schemes discussed in reference [3], harmonics are expected to be generated and cause undesirable effects on the machine performance like overheating and loss of power. The solid state devices have non-linear characteristics. The major effect of these devices is to create considerable harmonic distortion on the system.

Performance study of the wind power system relates to the fundamental frequency. The possibility of the presence of harmonics in the output power of the AC commutator machine, investigated in this dissertation, can be ignored because the output power itself is neither rectified nor inverted using solid state processing equipment at the terminals of the machine.

Because of the use of inverter circuits in the excitation control system the possibility of the existence of harmonics in the machine can not be ruled out. But the presence of harmonics can be minimized to the point where they approach zero using appropriate pulse modulation technique and filter circuits. The order of the frequency of harmonics to be attenuated determines the size of the filter circuit elements.

Thus, the absence of electronic power equipment on the machine terminals seems to alleviate the problem of harmonics usually of concern to the utility companies to which such systems are connected.

1.2. OBJECTIVES OF THE DISSERTATION

In this dissertation, various wind power generation schemes have been discussed. Primarily, attention is paid to the investigation of variable speed power generation schemes and having control on the electrical side of the system. Voltage and frequency control is of particular concern in applications employing variable speed turbines. It is a well known fact that in the case of an AC commutator machine the output frequency is that of excitation and is completely independent of the machine speed. Therefore, the only variable that needs to be controlled is the output terminal voltage.

The principal objective of this dissertation is to describe the development of solid state excitation control to control the output terminal voltage of the AC commutator generator under the conditions of varying turbine speed. A mathematical model for the excitation control system has been developed. Simulation studies using the mathematical model for excitation control, in conjunction with the machine model, have been performed.

The results of the study of the complete system, when subjected to rapid transients due to the variable speed nature of wind, are presented in Chapter 5.

1.3. DISSERTATION OUTLINE

The necessity of the wind energy conversion systems is introduced in Chapter 1. This Chapter also explores the reasons for the trend towards wind energy conversion schemes. A review of the scope of the work proposed in this research is given. In brief the prime objective of the project is outlined.

Chapter 2 reviews the trends in wind energy source. Certain aerodynamic principles associated with wind turbines are explained. Classification of Constant Speed Constant Frequency (CSCF) and Variable Speed Constant Frequency (VSCF) wind power generation schemes is established with a review of the schemes lately published in the wind energy conversion literature.

In Chapter 3, the basic theory of the polyphase commutator machines is presented. The machine under study is an AC commutator Machine (ACCM). In particular, the output terminal voltage equation is arranged to show that voltage is directly proportional to the product of the rotor speed and the main flux in the field winding. The application of an ACCM to a wind generator is discussed.

Existing literature shows that the use of ACCM has been restricted to constant speed systems and no clear-cut and effective solution to regulate its output voltage has been investigated so far. An investigation of its application in a variable speed wind energy conversion system is discussed in Chapter 4. Descriptions of the mathematical models for the machine itself and for the excitation control system are given.

In Chapter 5, the simulation studies are presented and the scheme is analyzed under transient conditions. The performance of the complete system is studied and results are presented.

A general review of the conclusions based on the study presented in this dissertation is given in Chapter 6.

CHAPTER 2

WIND ENERGY CONVERSION AND GENERATION SCHEMES

It seems appropriate to provide in this chapter an overall perspective of wind as an energy resource, the power available from the wind, and the transfer of power. Emphasis is laid on the classification of various electric generation schemes for wind energy conversion, using variable speed turbines, suitable for interconnection with a power grid.

2.1. WIND AS AN ENERGY RESOURCE

Wind energy is an indirect form of the extremely large solar energy received on earth. It is generated as a result of varying amounts of radiation received at the equatorial and polar regions which causes convection processes in the atmosphere. Estimates made by Putnam and their further refinements indicate about 10^6 MW of recoverable wind power which is about ten times the world's available hydro power [4]. The problems encountered in recovering energy on this scale are, of course, enormous. However, it is encouraging to know the vast size of the resource as wind energy conversion systems (WECS) are being developed.

The most advantageous application for wind energy is the generation of electricity by utilities as a supplement to their existing generating facilities. Such systems can be connected directly to the network and can provide from 5 to 15 percent of the network power without inducing instabilities [5]. On a short term basis and in an isolated or local area environment WECS can be considered as intermittent energy sources which require some backup if used in autonomous applications. However, statistical analysis shows that a number of WECS over a large area can contribute some element of firm power [6].

2.1.1. Available Power

Wind is merely air in motion. Air has mass-though its density is low - and when this mass has velocity the resulting wind has kinetic energy which is proportional to

$$\frac{1}{2}\,[\text{ mass x (velocity })^{2}].$$

Let ρ = air density

S_1 = velocity of wind

A = an area through which the wind passes normally

Therefore, the kinetic energy passing through the area in unit time is

$$P = \frac{1}{2}.\rho A S_1.S_1^2 \qquad (2.1)$$

$$= \frac{1}{2}\rho A S_1^3 \qquad (2.2)$$

This is the total power available, in the wind, for extraction by a wind driven machine [7]. Only a fraction of this power can actually be extracted.

2.1.2. Power Transferred in a Wind Turbine

Assuming that the direction of the wind speed through the rotor is axial and that the speed is uniform over the area 'A' swept by the rotor, the power extracted by the rotor is given by [7]

$$P = \rho \frac{A\ S_1^3}{4} \left[(1 + \alpha^1)\ (1 - \alpha^{1^2})\ \right] \tag{2.3}$$

where

$$\alpha^1 = \frac{S_2}{S_1}$$

S_1 being the wind speed at a considerable distance upwind and S_2 the wind speed at a considerable distance downwind from the rotor.

Power 'P' is maximum when $\alpha^1 = \frac{1}{3}$

i.e. when the downwind speed is one-third of the upwind speed. Therefore, the maximum power that can be recovered is

$$P_{\max} = \frac{8}{27}\ \rho A\ S_1^3 \tag{2.4}$$

in comparison to $\rho A \frac{S_1^3}{2}$ in the wind originally. Thus an ideal, unshrouded, wind turbine can extract $\frac{16}{27}$ or 59.3% of the power potential of the flow passing through the cross-sectional area (A) of the wind-turbine when the turbine is not present.

2.2. GENERATION SCHEMES FOR WIND ENERGY CONVERSION

Unlike conventional power generating systems, wind energy is intermittent and, without the provision of an energy storage system, has to be used as it occurs. Intermittency is not a major problem if the WECS is delivering power to a large utility system by proper load sharing with other generating systems in the grid [4]. However, variations in wind velocity may cause the turbine rotor to run at varying speeds. If there are no mechanical or electrical constraints, the prime mover rotates at varying speeds following the wind speed within the normal operating range of the turbine. The output of a usual AC generator with DC field excitation will then be of varying frequency which is unsuitable, of course, for interconnection with the power grid [2].

Electric generation schemes for wind power generating suitable for interconnection with the power grid can generally be classified as:

1. Constant Speed Constant Frequency (CSCF)
2. Variable Speed Constant Frequency (VSCF)

Historically, only CSCF systems have been used for large power generation in wind power plants. However, with the advent of power electronics and the availability of solid state devices capable of handling large amounts of power, VSCF systems are becoming competitive. Various schemes under each classification are discussed in brief. It is stressed, however, that the optimum choice of the generating scheme is not decided by considering the generator alone.

The optimum choice is one which minimizes the cost of energy generated by the wind power plants [2].

2.2.1. Constant Speed Constant Frequency Systems (CSCF)

Because the grid maintains constant voltage and constant frequency, a synchronous generator coupled to the mill rotor, in parallel with the grid, can run at only one speed, the synchronous speed. An induction generator on a power grid runs at speeds above synchronous but not very different from it. Hence, such systems, that are presently in operation, have been constrained by the network to maintain a nearly constant speed and are classified as CSCF systems. An independent mechanical blade pitch control mechanism could be devised to maintain constant speed which adds considerably to the cost of the turbine and induces stress on the turbine and generator [2]. Lately, variable-pitch variable-speed wind-turbines appear to be gaining favor over the fixed-pitch variety. They generally also have a greater annual output than fixed-pitch units of equal diameter.

2.2.1.1. Synchronous Machine

For a wind turbine driven synchronous machine, because the input power is fluctuating, a mechanical control mechanism is required to control the pitch of the rotor, so that the input power is held fairly constant. Power in the wind is proportional to the cube of wind velocity. During gusting, the machine is subjected to rapid changes in velocity and hence violent changes in input power. This necessitates the controller to be very sensitive to damp out these transient changes in input power so that the machine does not swing over the stability limit. This type of control requirement for stability considerations, besides complicating the system, contributes to the main cost of the WECS [2].

2.2.1.2. Induction Machine

Induction machines have been used in some prototypes. The gear ratio is chosen so that the generator is run above synchronous speed determined by the network frequency. The generator runs at slip speeds above synchronous speed corresponding to its power input. If the power input exceeds that corresponding to the pull-out torque, the region of stability will be trespassed. So, though a constant speed controller is not necessary, there must be a mechanism to spill the power above the safe value for the generator. This can be accomplished by having less stringent control.

2.2.2. Variable Speed Constant Frequency Systems (VSCF)

These are generating systems where there is no pitch control mechanism and the rotor is allowed to rotate freely with the wind. The actual speed of rotation, however, is determined by the speed-load characteristics of both the turbine rotor and the generator. The turbine rotor efficiency for converting wind energy to mechanical energy (denoted in wind literature as C_p) is optimum at only one value of the rotor speed/wind speed ratio. So it is possible in a VSCF system to let the turbine rotor rotate in constant proportion to wind speed by programming the electrical load on the generator to follow the wind speed. This yields an optimum solution to the problem of efficiency of conversion from aero to mechanical energy [2].

Generation schemes for variable-speed systems naturally are more complicated than constant speed systems. Variable frequency power has to be converted to that of constant frequency. Such conversion can now be done using power electronic techniques using thyristors. A brief discussion of generation schemes for VSCF systems follows.

2.2.2.1. AC-DC-AC Conversion System (ADA)

An AC generator with DC field excitation is coupled to the varying speed rotor. The generator output of varying frequency is rectified to get DC. This is converted to AC by an inverter to get constant frequency power. However, the variable voltage due to the rapid change in speed is still a problem to be resolved. Application of this scheme to WECS, though elegant, is limited by the cost of power-processing equipment. Therefore, an ADA scheme by itself will not be a viable candidate for the choice of generating systems for WECS [2].

2.2.2.2. Frequency Down Conversion System: ARH Scheme

ARH scheme has been proposed to generate power at a modulated frequency much higher than 60 Hz, then electronically processing down to obtain 60Hz output. The modulated output is demodulated in a bridge rectifier, inverted by an SCR inverter and filtered to get 60 Hz output [8]. Again, the power output with variable voltage, because of the variable speed, is not easily utilized and hence this serious problem needs to be resolved.

2.2.2.3. AC Commutator Generator

The suggestion of using AC commutator generator (ACCG) for wind energy generation was made by Kostenko in 1948 [9]. It is a well known fact that the output frequency of such a machine is independent of the rotor speed and is always equal to the frequency of the excitation voltage. This is achieved by commutator instead of power processing equipment. However, no clear-cut and effective solution to regulate its voltage output has been proposed so far [10]. This is the subject of research in this dissertation. The objective is to investigate a possible scheme to control output voltage effectively where the machine is being driven by a variable speed primemover. The control scheme is proposed in Chapter No. 4.

2.2.2.4. Induction Machine

A wind energy conversion scheme using an induction machine driven by a variable speed turbine has been proposed [11]. In this scheme a controlled inductor, in parallel with a capacitor connected to generator terminals, provides the self excitation which in turn keeps the terminal voltage constant regardless of the rapid transients in input power. This constant voltage variable frequency power can be further converted to constant voltage constant frequency power by using solid-state power processing equipment. A simple three-phase uncontrolled diode bridge for conversion to constant voltage DC and an inverter with very simple firing circuits for constant frequency AC was proposed. The inverter output can be used as an autonomous supply system. The performance of this generation scheme is effective over a wide speed range while loading the machine in such a way that maximum energy conversion is possible.

2.2.2.5. Synchronous Machine

A power generation scheme for a variable speed wind-turbine-driven synchronous machine with an excitation control system is proposed in reference [12]. The wind turbine is considered to have fixed pitch blades. Because of the varying speed, the power generated would have a variable voltage and variable frequency. Voltage at the machine terminals can be held constant by using an automatic voltage regulator (AVR). The constant voltage variable frequency (CVVF) AC output of the synchronous generator can be converted into constant voltage DC by using a simple three-phase diode bridge with an appropriate smoothing reactor. The fixed DC voltage is independent of the frequency variation at generator terminals. The DC voltage can be further inverted using a simple firing circuit to provide a constant voltage-constant frequency at output. The performance is effective over wide speed range and under wind gusting conditions. Study shows that it is feasible to use variable-speed fixed-pitch wind turbines to generate electric power.

2.2.2.6. An Adaptive Scherbius Induction Machine

A wind turbine driven variable speed power generation system using a static Scherbius scheme has been described in reference [13]. In this reference, a variable speed constant frequency wind power system using a double-output induction machine feeding into an electric utility system was analyzed. The proposed scheme incorporates a wound rotor induction generator with means for rotor power regeneration. Power generated from the stator is at the line frequency and is fed directly to the electric system. The terminals of the rotor of the induction machine are connected to an AC/DC/AC power converter. Rotor power at the slip dependent rotor voltage and slip dependent frequency is rectified to DC by an uncontrolled rectifier. The DC power is fed to a three-phase thyristor bridge inverter whose output terminals are connected to the mains. This scheme is also called a double-output induction generator (DOIG) scheme since the power output is derived both from the stator as well as the rotor.

Since the power is recovered from the rotor circuit by a power converter, the recovered power is reflected as an additional resistance in the rotor circuit. Because of this feature the operating speed range is widened compared with a standard squirrel cage induction machine and the system changes from that of a semiconstant to a variable speed WECS.

The firing angle of the inverter determines the power transferred from the rotor to the mains. Thus the apparent rotor circuit impedance can be varied by the variation of the firing angle of the inverter, and the induction machine characteristics can be adapted to the turbine characteristics.

2.3. CONCLUSIONS

Wind as an energy resource, the power available from wind and the amount of power that can be extracted by wind turbine, has been reviewed. A review of trends in wind energy conversion has been presented. Generation schemes have been categorized on the basis of their speed characteristics. The constant speed and variable speed classification has been further studied and appropriate literature related to research has been presented.

CHAPTER 3

THE POLYPHASE COMMUTATOR MACHINES

3.1. INTRODUCTION

Many types of electrical machines are used in connection with polyphase AC supply systems both as generators for supplying the electrical power, and as motors for converting it into mechanical power. Commutator machines meet additional requirements which cannot be met by the simpler and more common machines [14].

Polyphase commutator machines comprise those types of electrical rotating machine which have a commutator, and in which the commutator brush gear carries polyphase alternating currents. Therefore, this definition excludes single-phase and DC commutator machines. The important common feature of polyphase machines is that the general operation of all types can be explained in terms of a rotating field similar to that of the induction machine.

The polyphase commutator machine can, in general, be used either:

(a) as an independent motor, generator, or converter;

(b) as a regulating machine connected in the rotor circuit of an induction motor, for the purpose of regulating the speed or power factor of the induction motor.

The results obtained depend not only on the construction of the machine, but on the connection between its own windings, with other apparatus, and with the supply.

The polyphase commutator machines can be classified into three general groups. The three groups differ between themselves in the arrangement of other windings on rotor and stator, and the way in which they are connected.

(i) Polyphase shunt and series motors

(ii) Commutator frequency changer

(iii) Scherbius machine

The Scherbius machine is a polyphase AC generator in which the output voltage is generated in a rotor winding of the commutator type. The rotating field is set up by a polyphase exciting winding on the stator.

3.2. AC COMMUTATOR GENERATOR (ACCG)

The suggestion of using AC commutator generator (ACCG) for wind energy conversion was made by M.P. Kostenko [9] in 1948. It is a well known fact that the output frequency of such a machine is independent of the rotor speed and is always equal to the frequency of the excitation voltage. Furthermore, the machine has the advantage of lending itself to reactive power control [10]. This feature makes it a viable candidate for a VSCF wind generation scheme.

Unfortunately it has never been tried in any wind generating system especially by providing means to control the terminal voltage and keep it constant. The control on the excitation will contribute to holding the output voltage within a suitable tolerance limit by adjusting the field voltage. The study and analysis of the voltage control system is presented in the following chapter.

It can be shown that the voltage, E_a, produced across the brushes is the sum of the transformer voltage E_{tr} and the rotational voltage E_{rot} [14]. Writing more explicitly,

$$E_a = 4.44\, K_w\, f_e\, (\frac{Z}{2a})\, \phi_m \mp 4.44\, K_w\, f_r\, (\frac{Z}{2a})\, \phi_m \tag{3.1}$$

$$= 4.44\, K_w\, (f_e \mp f_r)\, \frac{Z}{2a}\, \phi_m \tag{3.2}$$

where

K_w - is the winding factor

f_e - the excitation frequency

f_r - the rotational frequency

Z - the number of conductors/phase

$2a$ - the number of parallel conductors

ϕ_m - the flux per pole

minus if the rotor is rotating in the same direction as the magnetic field and plus if the rotor is rotating in opposition to it.

For the compensated generator, taking the voltage induced in the compensating winding into consideration, an interesting result occurs, as

$$E_o = 4.44\, K_w\, f_{rot}\, (\frac{Z}{2a})\, \phi_m \tag{3.3}$$

where

E_o is the output voltage.

Therefore with complete compensation, the output voltage is directly proportional to the speed of the machine and main flux only [15].

3.3. APPLICATION OF ACCG IN WIND GENERATION

ACCG is, perhaps, the simplest means of deriving constant frequency output from a variable speed machine. In a wind generating station which is interconnected with a power grid, the excitation of ACCG can be derived from the grid. The output, being of the same frequency, i.e. the line frequency, can be directly connected to the grid. The ACCG achieves the facility to provide an output of the same frequency as the excitation because of the commutator [2].

The terminal voltage needs to be controlled especially for an isolated system. By inserting solid state control in the excitation, thus controlling the flux into the field windings, the terminal voltage of ACCG can be held constant. Of course, the solid state device handles only the excitation power and is similar in function to voltage regulator. The excitation voltage, which is the output of the solid state device, is being controlled by controlling the firing angle of the three-phase inverter. The regulator compares the terminal voltage of the generator with the desired reference voltage and determines the voltage error. This resulting error signal is the input to the gate of the inverter which in turn has control over the firing angle.

Furthermore, ACCG, with its characteristics similar to that of a DC generator, provides a very convenient and simple way of loading the machine as desired [2].

CHAPTER 4

VARIABLE SPEED WIND POWER GENERATION WITH THREE PHASE AC COMMUTATOR MACHINE

4.1. PROPOSED SCHEME

The proposed scheme is illustrated in Fig. 4.1. It employs an AC commutator machine driven by a wind turbine operating over a wide speed range. The wind turbine is considered to have fixed pitch blades. Because of the varying speed, the power generated would have a variable voltage but the frequency is independent of the rotor speed and is always equal to the frequency of the excitation voltage (refer to Chapter 3).

Voltage at the machine terminals can be held constant by a closed-loop excitation control system as discussed in Sec. 4.3. The control on the excitation will contribute in holding the output voltage within a suitable tolerance limit by adjusting the field voltage. The frequency of the output power, which is equal to the frequency of the excitation voltage, is constant which is achieved by commutator instead of power processing equipment. Thus, the power generated by such scheme is independent of voltage and frequency variations. This scheme is suitable for an autonomous system as well as for utility interconnection.

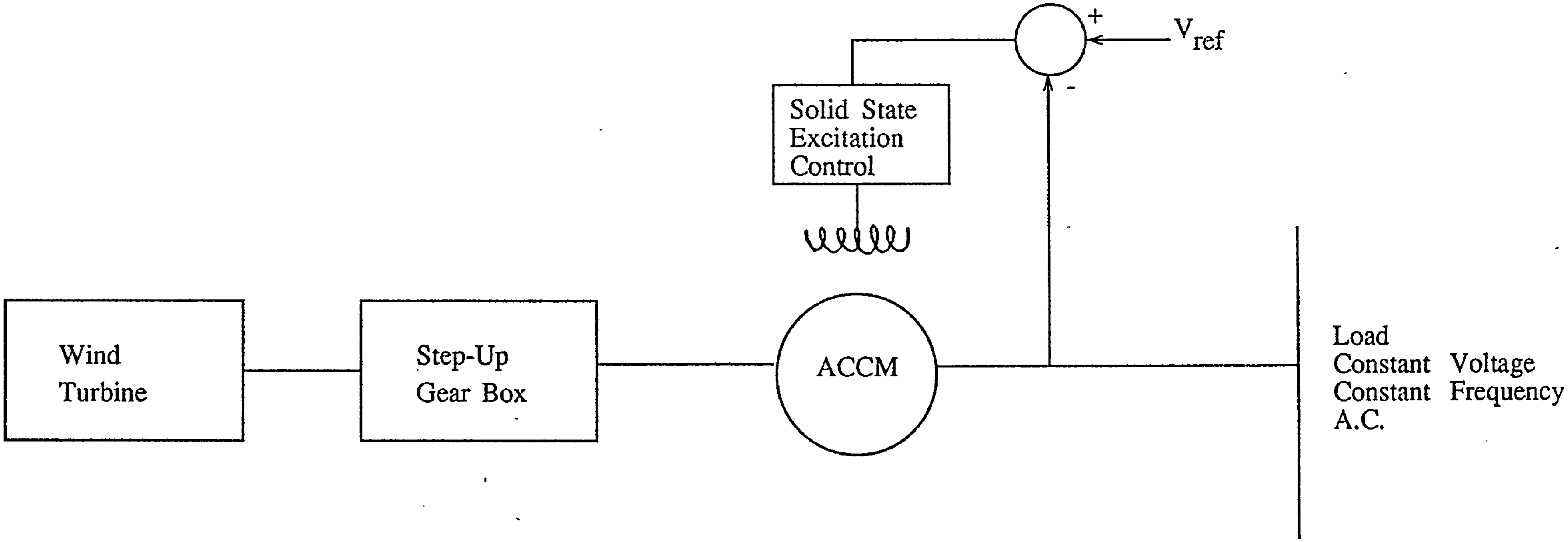


FIG. 4.1 VARIABLE SPEED WIND TURBINE - A.C. COMMUTATOR MACHINE FOR ENERGY CONVERSION

4.2. LINEAR ANALYSIS OF THE AC COMMUTATOR MACHINE

The machine to be analyzed is shown schematically in Fig. 4.2. For mathematical convenience, the analysis of a 2-phase AC commutator machine (ACCM) will be considered since the 3-phase machine can be easily replaced by its 2-phase equivalent using the appropriate transformation [16]. In this analysis, the 'd' and 'q' - axis windings of the stator and rotor, Fig. 4.3, constitute the two phases of the machine. The commutated rotor winding has a two-phase set of brushes which supply the load with the two phase currents i_{rd} and i_{rq}.

First transformation converts 3-phase to 2-phase as follows:

$$i^{\alpha\beta 0} = C_1 \, i^{ABC} \tag{4.1}$$

where C_1, the required transformation matrix from 3-phase to 2-phase currents, is given by

$$C_1 = \sqrt{(\frac{2}{3})} \quad \begin{array}{c} \\ \alpha \\ \beta \\ 0 \end{array} \begin{array}{c} \begin{array}{ccc} A & B & C \end{array} \\ \left[\begin{array}{ccc} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{array}\right] \end{array} \tag{4.2}$$

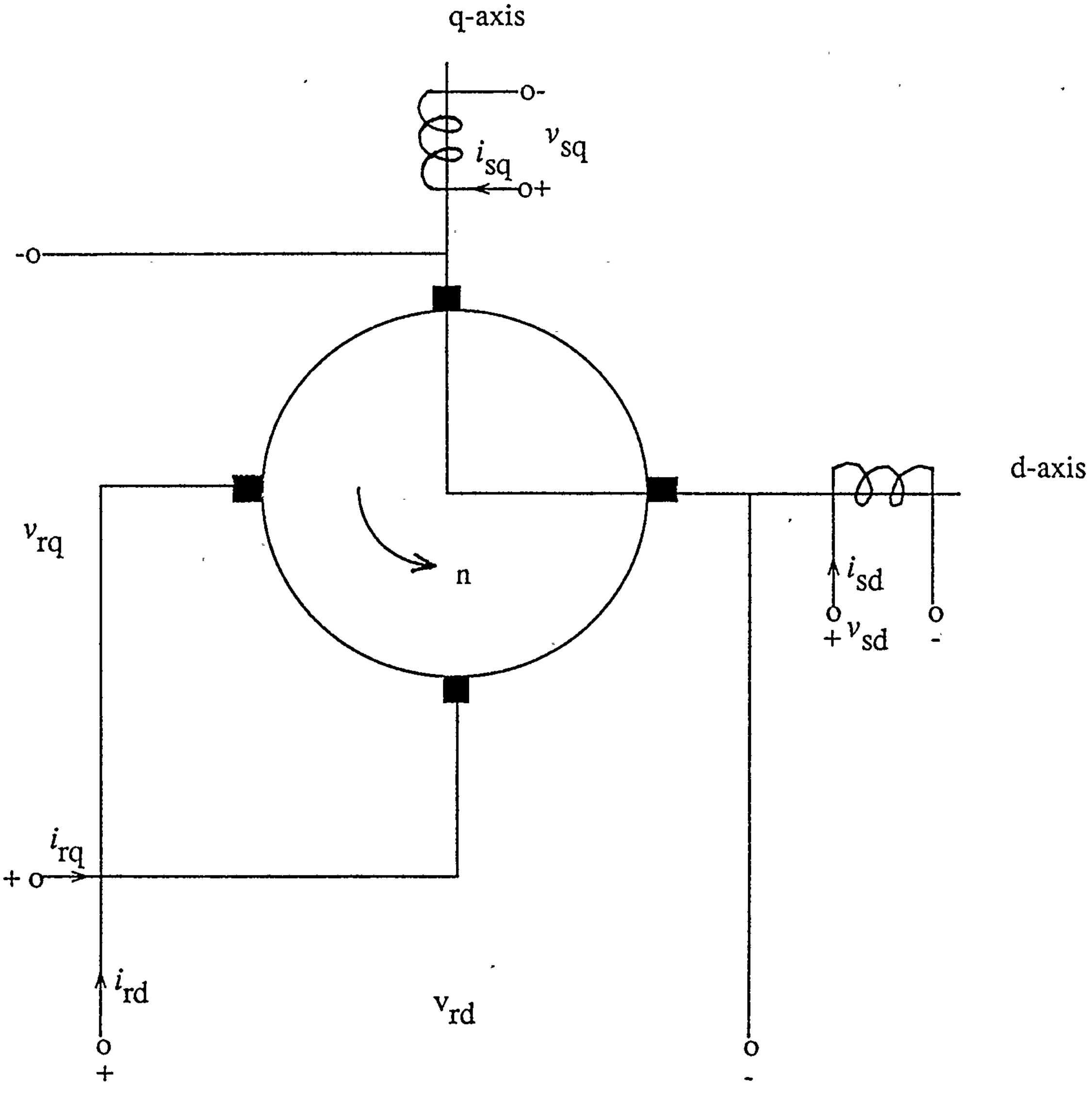


FIG. 4.2 SCHEMATIC REPRESENTATION OF THE TWO-PHASE COMMUTATOR MACHINE

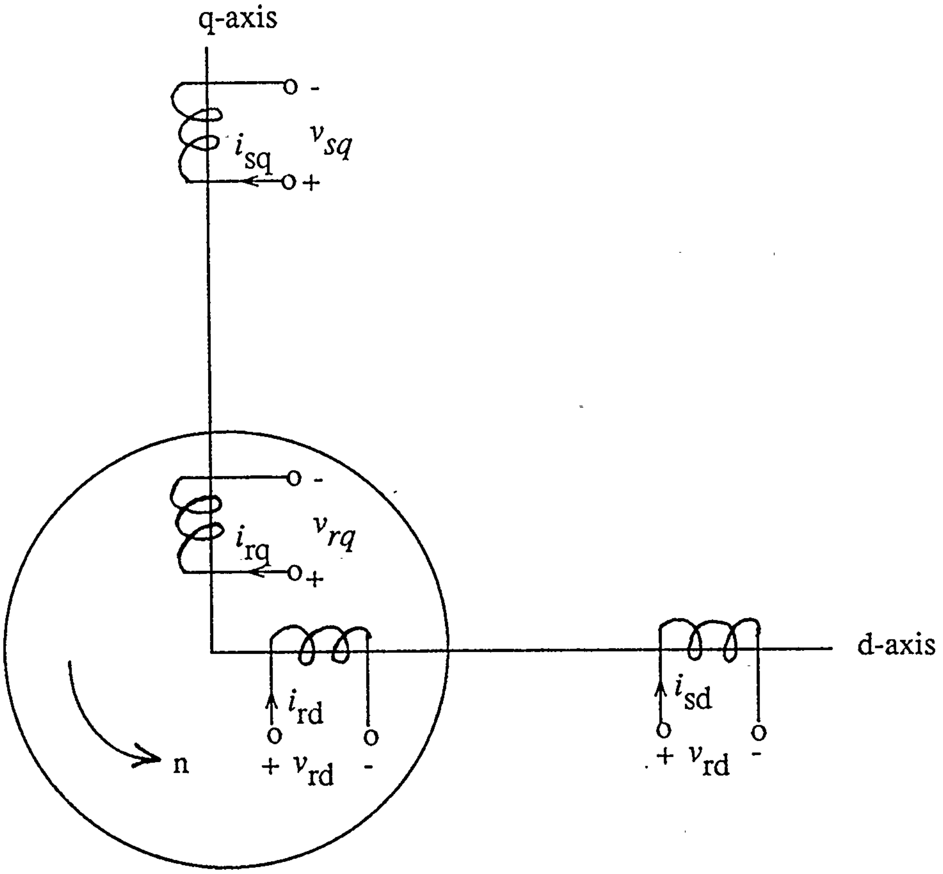


FIG. 4.3 THE PRIMITIVE MACHINE

As the machine is symmetrical and under balanced conditions, the zero the sequence current, i_0, is neglected in the subsequent analysis because it arises only under special conditions [17].

The second transformation converts the 2-phase to a d-q system as follows:

$$i^{dq} = C_2\, i^{\alpha\beta} \tag{4.3}$$

where C_2, the required transformation matrix from 2-phase to d-q system, is given by

$$C_2 = \begin{array}{c c} & \begin{array}{cc} \alpha & \beta \end{array} \\ \begin{array}{c} d \\ \\ q \end{array} & \begin{bmatrix} \cos\theta & \sin\theta \\ & \\ \sin\theta & -\cos\theta \end{bmatrix} \end{array} \tag{4.4}$$

The C_2 matrix has the interesting and useful characteristic that

$$C_2^{-1} = C_{2_t} = C_2 \tag{4.5}$$

The relationship between 3-phase to a d-q system is given by

$$i^{dq} = C\ i^{ABC} \tag{4.6}$$

where

$$C = C_1 . C_2$$

For impedance

$$Z^{dq} = C_t . Z_{ABC} . C \tag{4.7}$$

4.2.1. Mathematical Model Of The ACCM

The voltage equations for the primitive machine, Fig. 4.3, describing its mathematical model can be written as [18]:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & Mp & 0 \\ 0 & R_s + L_s p & 0 & Mp \\ Mp & nM & R_r + L_r p & nL_r \\ -nM & Mp & -nL_r & R_r + L_r p \end{bmatrix} = \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \tag{4.8}$$

where

$$n = \frac{d\theta}{dt}$$

Equation (4.8) is written for the primitive machine using the two-axis theory and gives the transformer and rotational voltages due to sinusoidally distributed air gap flux on the two axes, each flux being measured by the corresponding flux linkage. It is obvious from equation (4.8) that the armature voltage depends on the speed of the armature and the flux linkage due to the current in the field winding.

The work in this dissertation is oriented towards variable speed and hence, no mechanical mechanism is applied to control the shaft speed and thereby the terminal voltage of the ACCM. By regulating the excitation voltage which in turn controls main field flux, the terminal voltage of the ACCM can be held within limits while its frequency must be the same as the excitation supply. The frequency of the inverter output which supplies one of the stator (excitation) windings can be adjusted to the desired value (60 Hz in this case) without encountering any difficulty, as discussed in Sec. 4.3.

V_{rd} and V_{rq} are the rotor voltages which are sinusoidal in themselves but in-quadrature with each other. The resultant rotor voltage vector V_t at any instance (say at time 't') must be rotating at the same speed as established by the excitation frequency. The resultant voltage V_t can be expressed in the following form:

$$\vec{V_t} = V_t \; e^{j\omega_s t} \qquad (4.9)$$

where ω_s - is the excitation supply frequency.

Further

$$\begin{aligned} \vec{V_t} &= V_t \; [\; \cos(\omega_{st}) \; + j\sin(\omega_{st}) \;] \\ &= V_t \; \cos(\omega_{st}) + j \; V_t \; \sin(\omega_{st}) \\ &= V_{rd} + j \; V_{rq} \qquad (4.10) \end{aligned}$$

$$V_t = \sqrt{V_{rd}^2 + V_{rq}^2} \qquad (4.11)$$

Similarly, the resultant stator voltage can be expressed as:

$$V_s = \sqrt{V_{sd}^2 + V_{sq}^2} \qquad (4.12)$$

4.3. EXCITATION CONTROL TO MAINTAIN TERMINAL VOLTAGE

The aim of the proposed variable speed wind energy conversion scheme is to generate power at constant voltage and constant frequency. The simplified model is used to develop a control strategy which aims to maintain generator terminal voltage and frequency constant in case of variations in the wind speed.

The frequency of the output power must be the same as of the excitation supply (refer to Chapter 3). The supply to the field winding (excitation) of the generator is the output of the inverter employed in the control system which is discussed in the next section. The frequency of the output of the inverter is controlled by the thyristor firing circuit. Further, the desired single value of the frequency (60 Hz in this case) can be obtained by using a fixed frequency sine wave inverter where the extra cost can be justified on account of the reduction in size of the output filter [19]. Therefore only one variable (i.e. terminal voltage) needs to be controlled, which is discussed in the next section.

The present study concerns only the investigation of the operating conditions and the control of the output variables when the machine is subjected to rapid transients due to gusting wind conditions. The control problem, of keeping the output terminal voltage constant in case of wind speed variations, is solved by closed-loop excitation control in the system. The effect of the control loop on the system performance is investigated and the results are presented in the next chapter.

4.3.1. Description Of The Excitation System

The study involves the analysis of the overall system when the machine and the excitation control system are in operation. The excitation control system maintains the terminal voltage of the generator within a suitable tolerance limit by adjusting the field voltage. A block diagram showing the input and the output of the various elements of the excitation system is given in Fig. 4.4. The excitation control system responds quickly to voltage deviations under disturbance conditions through the feedback circuit as shown in Fig 5.2 through 5.5.

A basic control system for the studies reported in this dissertation consists of a bridge rectifier, a smoothing filter for the terminal voltage signal feedback, a regulator, a pulse generator, an inverter, and a second smoothing filter which filters any unwanted ripple in the output of the inverter to produce a smooth AC supply for the field circuit. The regulator compares the terminal voltage of the generator with the desired reference voltage and determines the voltage error signal. This small voltage error signal is added to the constant DC voltage signal and the resultant is the input to the pulse generator whose function is to generate pulses proportional to this input. The pulse modulation form can either be pulse amplitude modulation (PAM) or pulse width modulation (PWM) depending on the technique adopted. The output of the pulse generator, which is of course in the form of pulses, serves as a gate signal to the inverter. The gate signal to the inverter determines its firing angle (i.e. when the thyristor is to be fired). By

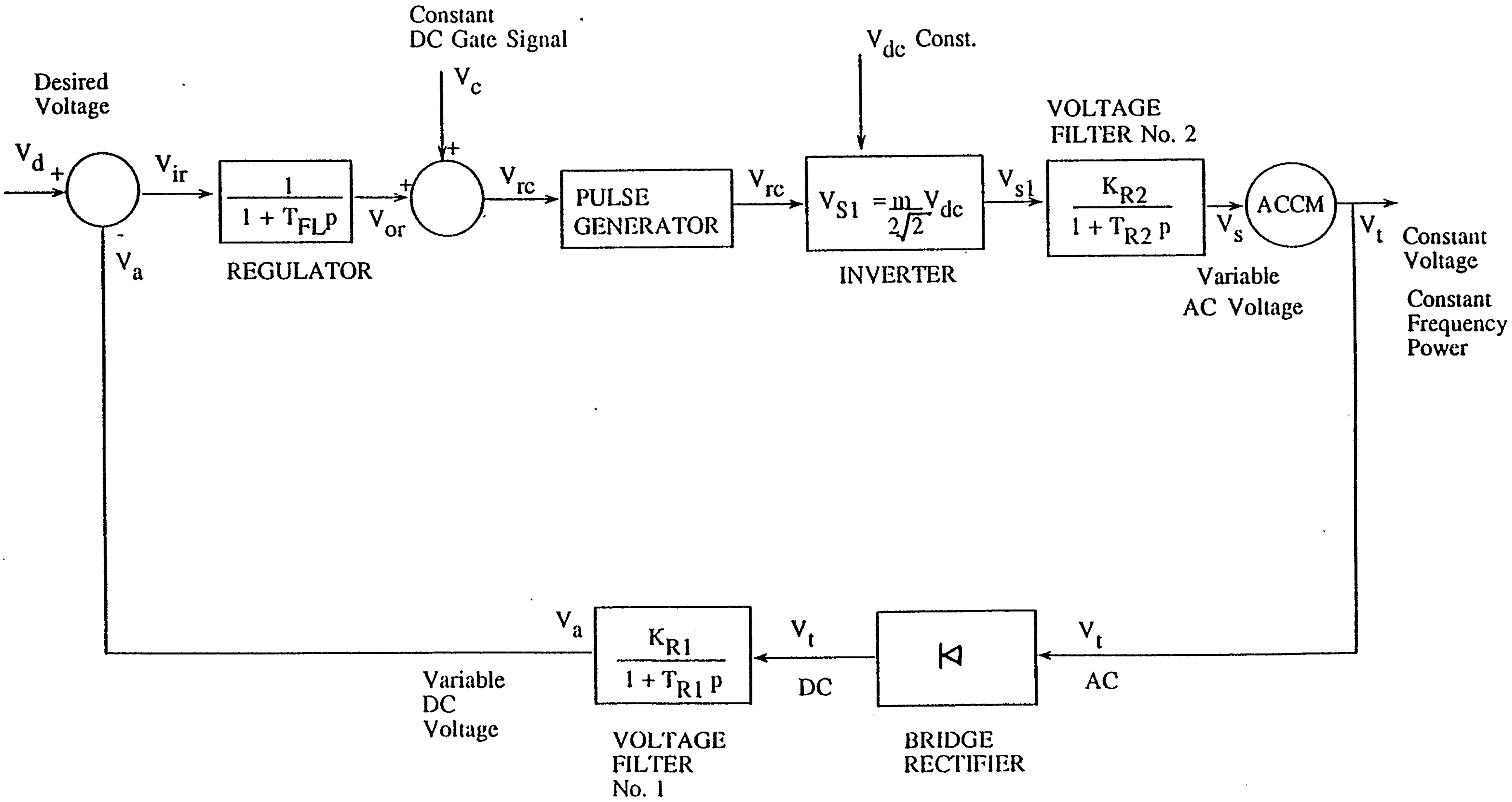


FIG. 4.4 BLOCK DIAGRAM OF THE COMPLETE CONTROL SYSTEM

controlling the firing angle, the magnitude of the effective output voltage of the inverter is controlled.

The circuit complexity is in the firing logic of the inverter stage. It is feasible, therefore, to expand this firing circuitry to permit voltage control by the inverter. The switching of the inverter thyristors, which is determined by the gate signal, controls the excitation voltage to produce a rotating magnetic field for operation [20]. The frequency of the output of the inverter is held constant at the desired value (60 Hz in this case) as explained in Section 4.2, and full details are available in the literature [21-22]. This variable output of the inverter is further filtered to clean all the unwanted ripples and hence produce a smooth AC supply for the excitation of the AC commutator generator.

4.3.2. Mathematical Model Of The Excitation System

The representation given here is in block diagram format, each minor block representing, in quasi-physical fashion, the transfer function of a major component of the excitation system. The block diagram depicting the transfer functions of the elements of an excitation system constitutes a mathematical model of the physical system. Models provide a means of evaluating the excitation system performance. If the model exhibits the same gain, phase and time delay characteristics as the actual equipment, it is adequate [23].

To analyze the transient performance of the automatic control system, it is necessary to set up the differential equation describing the behavior of the system.

The solution to this equation is a function of time during a transient. The input and the output variables of the closed loop excitation control system, described in Fig. 4.4, are related by differential equations and are summarized below [24].

1. Voltage Filter No. 1.

This component filters the output of the bridge rectifier and its transfer function is given by

$$\frac{V_a}{V_t} = \frac{K_{R1}}{1 + T_{R1}\, p} \tag{4.13}$$

where $p = d/dt$, derivative operator

Re-arranging eqn (4.13) yields

$$pV_a = \frac{1}{T_{R1}} \left[V_t \, K_{R1} - V_a \right] \tag{4.14}$$

where

K_{R1} - gain of the filter

T_{R1} - time constant of the filter

Generally, the values of T_{R1} and K_{R1} are nearly zero and one respectively which reduces equation (4.14) to

$$V_a = V_t$$

2. Regulator

$$\text{Input} = V_{ir} = V_d - V_a$$

$$\text{Output} = V_{or}$$

Therefore

$$\frac{V_{or}}{V_{ir}} = \frac{1}{1 + T_{FL}\, p} \qquad (4.15)$$

where

T_{FL} - time constant of the regulator

V_d - desired voltage at the machine terminals

$$pV_{or} = \frac{1}{T_{FL}} \left[V_{ir} - V_{or} \right] \qquad (4.16)$$

$$pV_{or} = \frac{1}{T_{FL}} \left[V_d - V_a - V_{or} \right] \qquad (4.17)$$

The intermediate variable V_{or} is the output of the regulator which under steady state conditions is zero. This shows that V_c is the steady state gate signal to the inverter.

3. Inverter

The well established relation for the inverter is given by [25]

$$V_{s1} = \frac{m}{2\sqrt{2}}\, V_{dc} \qquad (4.18)$$

where

V_{dc} - constant d.c. input to the inverter

V_{s1} - output of the inverter

m - modulation index which is the ratio of the

amplitude of the terminal voltage to that of the reference voltage.

Therefore

$$m = \frac{V_t}{V_{ref}} \tag{4.19}$$

V_{s1} increases linearly with m, until m=1. But for m > 1, the relation does not hold linearity. From the block diagram in Fig 4.4, it can be seen that

$$V_d - V_a = V_{ir} \tag{4.20}$$

Adding V_c, the constant d.c. signal for auxillary commutation as a gate signal under steady state, on both sides, gives

$$V_d - V_a + V_c = V_{ir} + V_c \tag{4.21}$$

$$V_{ref} - V_a = V_{rc} \tag{4.22}$$

$V_{ref} = V_d + V_c$ and also under steady state $V_{ir} = 0$, therefore

$$V_c = V_{rc}$$

Further, dividing equation (4.22) by V_{ref} yields

$$1 - \frac{V_a}{V_{ref}} = \frac{V_{rc}}{V_{ref}}$$

or

$$1 - m = \frac{V_{rc}}{V_{ref}}$$

$$m = 1 - \frac{V_{rc}}{V_{ref}} \tag{4.23}$$

Using this value of m in equation (4.18), gives

$$V_{s1} = \frac{1}{2\sqrt{2}} \left[1 - \frac{V_{rc}}{V_{ref}} \right] V_{dc} \tag{4.24}$$

4. Voltage Filter No. 2.

This component filters, V_{s1}, the output of the inverter to produce smooth A.C. supply for the excitation and its transfer function is given by

$$\frac{V_s}{V_{s1}} = \frac{K_{R2}}{1 + T_{R2}\,p} \tag{4.25}$$

where V_s is the excitation voltage.

Re-arranging equation (4.25), yields

$$pV_s = \frac{1}{T_{R2}} \left[K_{R2}\, V_{s1} - V_s \right] \tag{4.26}$$

Equations (4.14), (4.17), (4.24) and (4.26) form the mathematical model of the excitation system and are summarized below:

$$pV_a = \frac{1}{T_{R1}}\left[V_t\ K_{R1} - V_a\right]$$

$$pV_{or} = \frac{1}{T_{FL}}\left[V_d - V_a - V_{or}\right]$$

$$V_{s1} = \frac{1}{2\sqrt{2}}\left[1 - \frac{V_{rc}}{V_{ref}}\right]V_{dc} \qquad (4.27)$$

$$pV_s = \frac{1}{T_{R2}}\left[K_{R2}\,V_{s1} - V_s\right]$$

The numerical values for the parameters are given in the appendix.

4.4. ANALYSIS OF THE ACCM

Four basic differential equations (eqn. 4.8) describing the machine are obtained in a synchronously revolving d-q frame and are given below in the matrix form.

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & Mp & 0 \\ 0 & R_s + L_s p & 0 & Mp \\ Mp & nM & R_r + L_r p & nL_r \\ -nM & Mp & -nL_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \qquad (4.28)$$

where $n = \frac{d\theta}{dt}$

Equation (4.28) can be written in the form

$$[V] = [Z]\,[I] \tag{4.29}$$

where

$$[Z] = [L]p + [R] + [G] \tag{4.30}$$

$$[L] = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix}$$

$$[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix}$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & nM & 0 & L_r \\ -nM & 0 & -nL_r & 0 \end{bmatrix}$$

Therefore

$$[V] = \{[L]p + [R] + [G]\}[I]$$

$$= \{[L]p[I] + [R][I] + [G][I] \qquad (4.31)$$

Re-arranging equation (4.31), gives

$$[L]\,[pI] = [V]-[R][I] - [G][I]$$

$$[pI] = [L]^{-1}\,[V] - [L]^{-1}\,[R][I] - [L]^{-1}\,[G][I] \qquad (4.32)$$

The inverse of $[L]$,$[L]^{-1}$, is obtained by a matrix inversion subroutine to the main program. Equation (4.32) is the standard state-space form for a system which is quite helpful in analyzing transient behavior of the system. It yields 4-basic differential equations:

$$\begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \\ \frac{di_{rd}}{dt} \\ \frac{di_{rq}}{dt} \end{bmatrix} = [L]^{-1} \begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} - [L]^{-1}\,[R] \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} - [L]^{-1}\,[G] \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \qquad (4.33)$$

As

$$Z_L = R_L + jX_L \tag{4.34}$$

From equation 4.10

$$V_t = V_{rd} + jV_{rq}$$

$$I_t = I_{rd} + jI_{rq}$$

Also

$$\begin{aligned} V_t &= Z_L\ I_t \\ &= (R_L + jX_L)\ (I_{rd} + jI_{rq}) \qquad (4.35) \\ &= (R_L\ I_{rd} - X_L\ I_{rq}) + j\,(X_L\ I_{rd} + R_L\ I_{rq}) \end{aligned}$$

Therefore

$$V_{rd} = R_L\ I_{rd} - X_L\ I_{rq} \tag{4.36}$$

$$V_{rq} = X_L\ I_{rd} + R_L\ I_{rq} \tag{4.37}$$

In the present study, the driving torque to the ACCM is supplied by a turbine devoid of pitch control. Therefore, the input torque changes to different levels are relatively fast. The torque input T_m from the turbine can be represented as [26]

$$T_m = K\,(n)^2 \tag{4.38}$$

where n, the speed of the generator in radians per second, is related to the wind speed, and K is a constant which takes into account the gear ratio, power coefficient, diameter of the turbine and atmospheric density.

An expression for electrical torque is given by

$$T_e = \frac{n}{2} [\psi_d \, i_q - \psi_q \, i_d] \tag{4.39}$$

Neglecting the rotational losses, the accelerating torque is given by

$$T_a = J\frac{dn}{dt} \tag{4.40}$$

Also

$$T_m = T_e + T_a$$

Therefore

$$T_a = J\frac{dn}{dt} = (T_m - T_e) \tag{4.41}$$

Also, the electrical power output of the machine is given by

$$P_e = (v_d \, i_d + v_q \, i_q) \tag{4.42}$$

The average electrical output power, P_e, converted from the mechanical to electrical form, including both phases, is computed from the terminal voltage and the current when the machine is connected to the load. The results are presented and discussed in the next chapter.

CHAPTER 5

SIMULATION RESULTS

In this Chapter, the results of simulation studies with the proposed scheme are described. The AC commutator machine with controlled excitation is simulated. The performance of the complete system is described under steady state as well as transient conditions. Parameters of the AC commutator machine and the excitation control system, used in this study, are given in appendix A.

5.1. OPERATING REGION

As the rotor speed increases starting from rest, the magnitude of the voltage decreases in direct proportion to the slip. The voltage becomes zero when the machine is running at synchronous speed because the rotor rotates at the same speed as the flux in the excitation winding i.e. no relative motion. Any further increase in the speed of the rotor will result in a reversal of the sign of the voltage [15]. The change in speed from sub-synchronous ($n < \omega$) to super synchronous ($n > \omega$), or vice versa, causes the phase sequence reversal which is not tolerable under any circumstances. Also below synchronous speed, the output of the machine decreases with an increase in rotor speed. Because the speed of the machine below or at synchronous speed is not acceptable, for the reasons explained above, a mechanism must be incorporated so that the synchronous system always runs above synchronous speed. If the speed of the machine happens to be below or at synchronous speed, this mechanism will disconnect the machine from the turbine and shut the complete system down.

The number of poles in the sample machine is assumed to be four and at a gear ratio of 20, the practical slip range was found to be 0.316 to -0.624 in wind power applications where negative slip implies super-synchronous speed [10]. For the reasons explained above, the proposed scheme is required to be run at super-synchronous speed, and the magnitude of the negative slip assures that the amount of speed variation available could be wide. Gear ratio must be selected in such a way that most of the power can be extracted from the wind by letting the turbine run in the most available wind speed range.

The synchronous speed of the machine, i.e. 1800 rpm, is taken as 1.0 p.u.. The steady state speed of the machine under consideration is set at 1.1 p.u. for analysis purposes. Simulation studies will be carried out in the super-synchronous region by varying the speed of the machine.

5.2. ESTABLISHMENT OF INITIAL CONDITIONS

To analyze the transient process in an automatic control system, it is necessary to set up the differential equations describing the behavior of the system (Sec. 4.2.2.). These equations are determined on the basis of the known quantities for each individual element of the system. The solution of these equations gives the regulated variable as a function of time during a transient.

The program developed solves such equations for the entire system. The Runge-Kutta method is well suited to solve first-order differential equations [27].

To establish initial conditions for the Runge-Kutta method used to solve the differential equations it is assumed that balanced steady state conditions exist such that all the fluxes, currents and voltages are sinusoidal with the angular frequency $\omega=2\pi f$ and can conveniently be represented as phasors as follows:

Replacing $'p'$ by $'j\omega'$, the voltage equation (4.8) yields

$$\vec{V}_{sd} = R_s\vec{I}_{sd} + j\ X_s\vec{I}_{sd} + jM\ \vec{I}_{rd} \tag{5.1}$$

$$\vec{V}_{sq} = R_s\vec{I}_{sq} + jX_s\vec{I}_{sq} + jM\vec{I}_{rq} \tag{5.2}$$

$$\vec{V}_{rd} = jM\vec{I}_{sd} + nM\vec{I}_{sq} + R_r\vec{I}_{rd} + jX_r\vec{I}_{rd} + nL_r\ \vec{I}_{rq} \tag{5.3}$$

$$\vec{V}_{rq} = -nM\vec{I}_{sd} + jM\vec{I}_{sq} - nL_r\vec{I}_{rd} + R_r\vec{I}_{rq} + jX_r\ \vec{I}_{rq} \tag{5.4}$$

Because the system is balanced, one can write [17]:

$$\vec{V}_{sd} = j\vec{V}_{sq} \tag{5.5}$$

$$\vec{V}_{rd} = j\vec{V}_{rq} \tag{5.6}$$

$$\vec{I}_{sd} = j\vec{I}_{sq} \tag{5.7}$$

$$\vec{I}_{rd} = j\vec{I}_{rq} \tag{5.8}$$

thus, it is possible to concentrate on one phase for the purpose of initial conditions.

The equations (5.1) and (5.3) for V_{sd} and V_{rd} contain four variables i.e. V_{sd}, V_{rd}, I_{sd}, and I_{rd} . Fixing two of these variables by the boundary conditions relating to the particular conditions under consideration, enables the equations to be solved and the behavior of the machine to be determined under steady state conditions. These steady state values are the initial values for the variables to be solved under transient process. In this study, boundary conditions mean that certain variables have certain numerical values under given conditions.

5.3. POWER/TORQUE/SPEED CHARACTERISTICS

The power generated by a wind turbine varies as the cube of its rotor speed. Thus there is a large variation in the power output over the full speed operating range. Because of the absence of independent mechanical blade pitch control mechanism in a variable speed wind turbine, the input torque changes to different levels are relatively fast. The power output P_m, torque T_m from the turbine are related to the wind speed and the relation, for maximum power transfer, can be expressed as [26]:

$$T_m = K(n)^2 \tag{5.9}$$

$$P_m = n.T_m = K(n)^3 \tag{5.10}$$

The relationship between power, torque and speed is shown in Fig. 5.1. This figure describes how fast the power and torque is affected with speed variations.

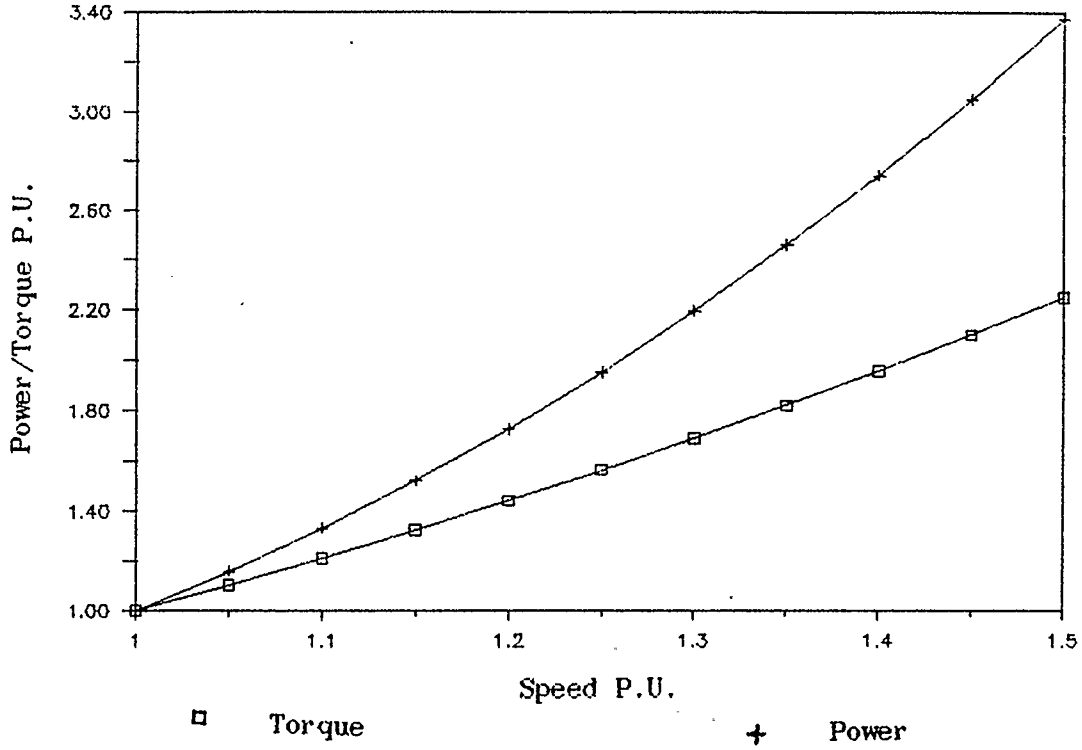


Fig. 5.1 Power/Torque Versus Speed Characteristics

5.4. STEADY STATE CONDITIONS

Equations (5.1) through (5.4) are the voltage equations of the machine in the steady state and can be re-written as follows:

$$\vec{V}_{sd} = (R_s \vec{I}_{sd}) + j(X_s \vec{I}_{sd} + M\vec{I}_{rd}) \tag{5.11}$$

$$\vec{V}_{sq} = (R_s \vec{I}_{sq}) + j(X_s \vec{I}_{sq} + M\vec{I}_{rq}) \tag{5.12}$$

$$\vec{V}_{rd} = (nM\vec{I}_{sq} + R_r \vec{I}_{rd} + nL_r \vec{I}_{rq}) + j(M\vec{I}_{sd} + X_r \vec{I}_{rd}) \tag{5.13}$$

$$\vec{V}_{rq} = (-nM\vec{I}_{sd} - nL_r \vec{I}_{rd} + R_r \vec{I}_{rq}) + j(M\vec{I}_{sq} + X_r \vec{I}_{rq}) \tag{5.14}$$

It has been explained in Sec. 5.2. that when the system is balanced and steady state conditions exist, it is possible to concentrate on one phase for the purpose of analysis.

steady state speed = 1.1 p.u.

During steady state analysis i.e. when the magnitude of the terminal output voltage is equal to the magnitude of the desired voltage,

$$V_{ir} = V_{or} = 0 \text{ and } m = 1 \tag{5.15}$$

Therefore, $V_{rc} = V_c$ is the constant signal to the gate of the inverter. Also the steady state output of the inverter is equal to $\dfrac{V_{dc}}{2\sqrt{2}}$

The first 0.5 s. in Figs. 5.2 through 5.4 show the power output, terminal voltage and excitation voltage during steady state.

5.5. TRANSIENT CONDITIONS

The performance of the excitation control scheme and the AC commutator machine is evaluated by subjecting the system to step changes in machine speed. The fluctuations in speed are a result of varying wind speed and subsequent input torque changes. The effect of speed variations on power output of the turbine and torque input to the machine are shown in Fig. 5.1.

The mathematical models of the machine and the excitation control system are described by eqn. (4.8) and eqn. (4.27) respectively. Eqns. (4.8) and (4.27) are solved simultaneously to provide complete information about the system under various perturbations.

The value of the desired voltage, V_d, is selected as 1.0 p.u.. Numerical values of the various parameters, used in this analysis, are given in the appendix. The system is running under steady state and balanced conditions for 0.5 s. before any disturbance in speed is applied. The transient performance of the proposed scheme with a step change in machine speed is shown in Figs. 5.2 through 5.4 for the following cases respectively:

(i) decrease in speed from 1.1 p.u. to 1.05 p.u.:

Fig. 5.2 shows the variations in the excitation voltage, terminal voltage and power output of the machine against step decrease in the machine speed. It is clear that in order to maintain the terminal voltage within tolerable limits, the excitation voltage has increased but the power output has dropped correspondingly because of the decrease in speed.

(ii) increase in speed from 1.1 p.u. to 1.15 p.u.:

Fig. 5.3 shows the performance for this case. Again, in order to maintain the terminal voltage, the excitation voltage has decreased but power output has increased correspondingly because of the increase in speed.

(iii) increase in speed from 1.15 p.u. to 1.2 p.u.:

Fig. 5.4 shows the performance when the speed is further stepped up. The excitation voltage has dropped down but the power output has increased considerably because of the increase in speed.

In order to illustrate the concept of the proposed scheme, the simulation studies under steady state as well as transient conditions are carried out and the following observations are made from the results of the computer simulation for the above cases.

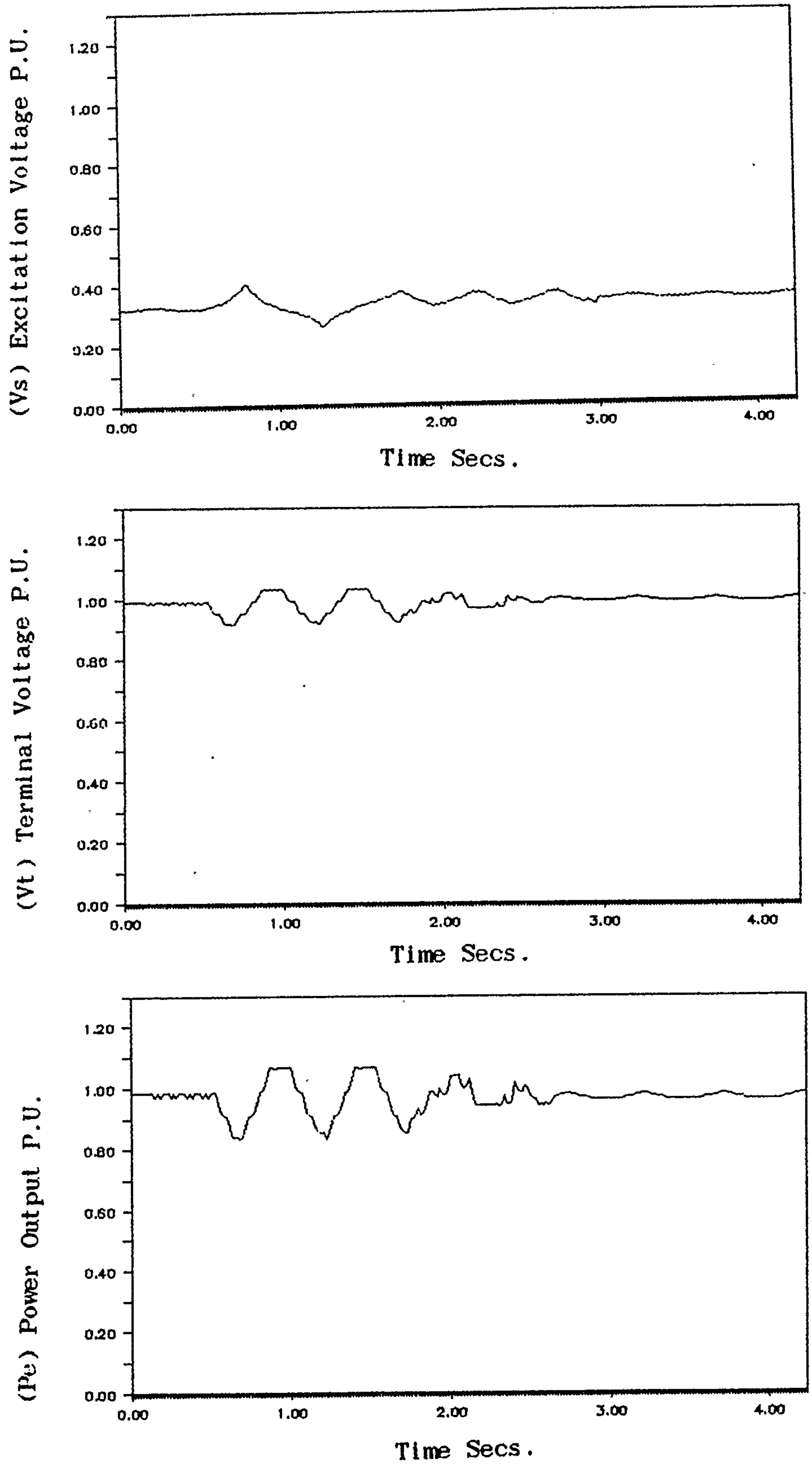


Fig. 5.2 Variations in Excitation Voltage, Terminal Voltage and Power Output With Step Decrease in Speed From 1.1 p.u. to 1.05 p.u.

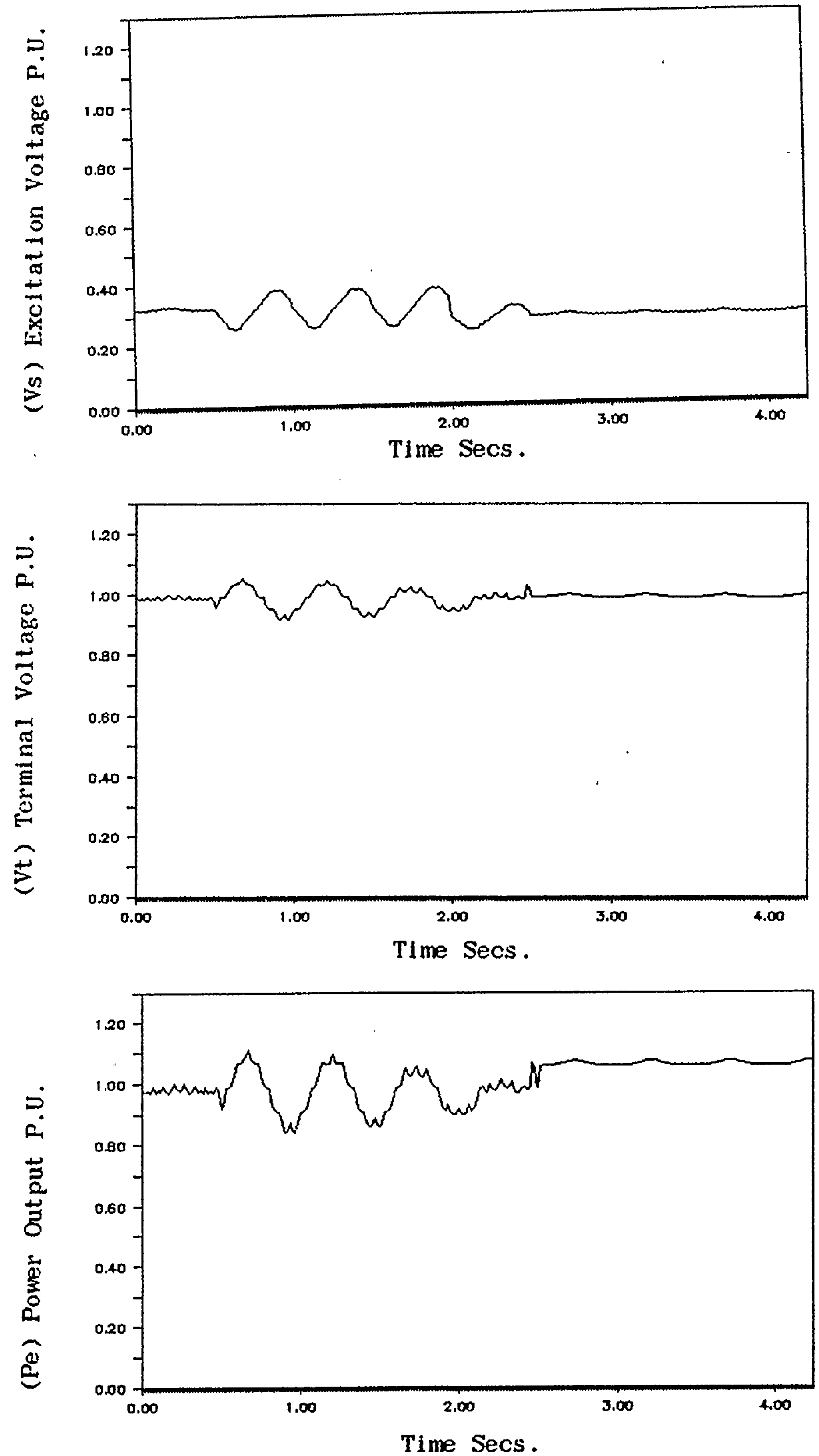


Fig. 5.3 Variations in Excitation Voltage, Terminal Voltage and Power Output With Step Increase in Speed From 1.1 p.u. to 1.15 p.u.

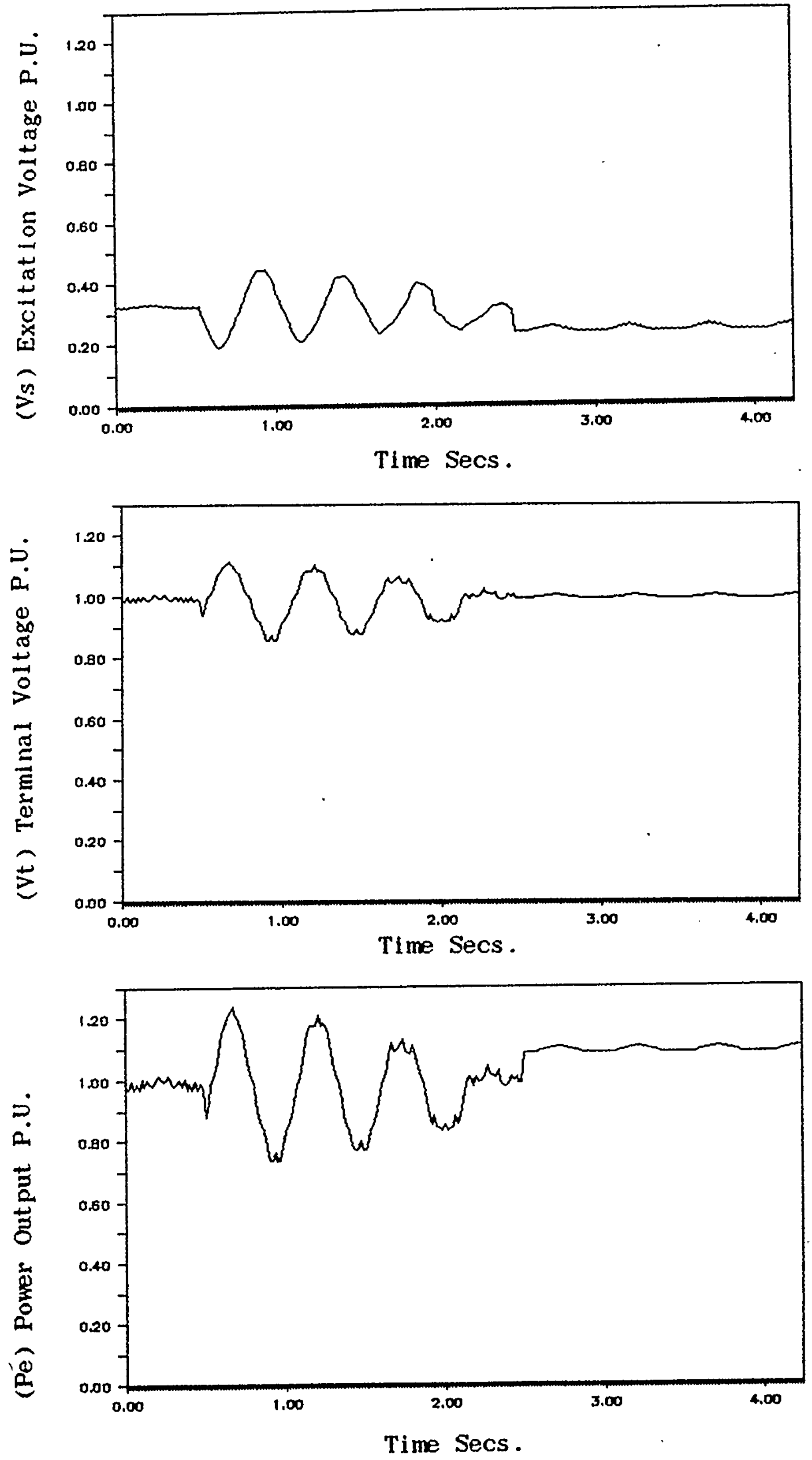


Fig. 5.4 **Variations in Excitation Voltage, Terminal Voltage and Power Output With Step Increase in Speed From 1.1 p.u. to 1.20 p.u.**

(i) The surges in the power output, terminal voltage and excitation voltage are settling down to steady state values and time taken is in the range of 2 to 3 secs.

(ii) No excessive overshoot occurs except at the start of the disturbance.

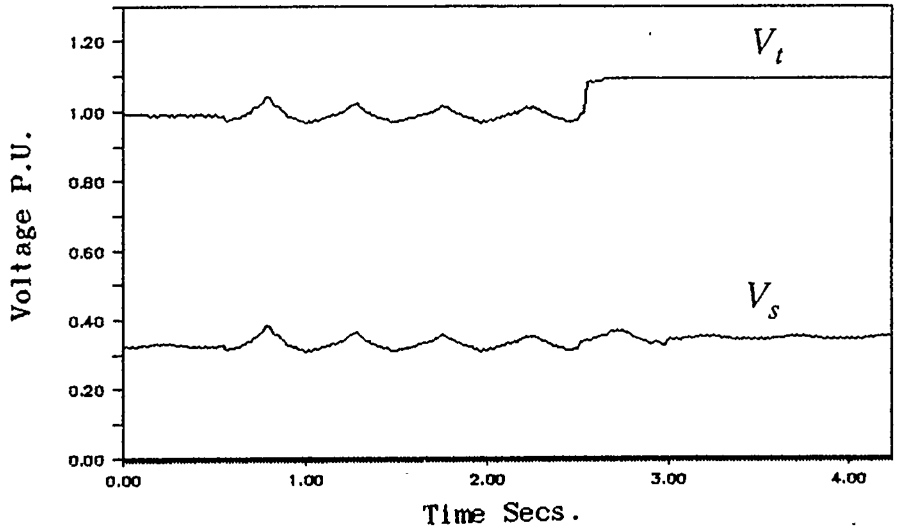
(iii) The control system maintains the terminal voltage within a suitable tolerance limit by adjusting the field voltage.

5.6. CASE STUDIES

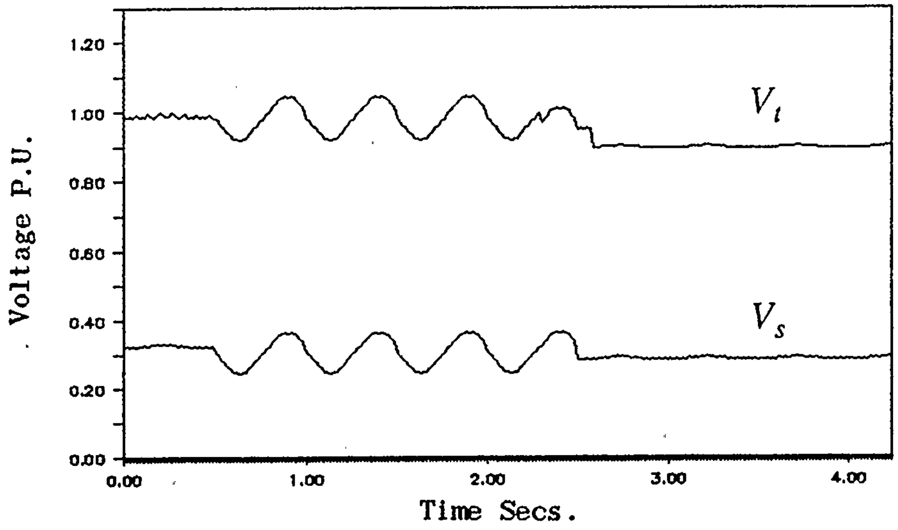
The analysis can be extended further by evaluating the performance of the system by varying the reference voltage and the load separately. These studies show that the control scheme is capable of maintaining the steady state conditions when the system is subjected to the above variations.

5.6.1. Effect of Reference Voltage Variation

The purpose of the feedback loop is, of course, to permit the system to maintain the output voltage at, or close to, the desired value. Normally the value remains fixed and the output voltage fluctuations would be caused by changes in speed or load. But, if required, the desired value can be varied. Usually it is done slowly and the system has no trouble following the variation [28]. Cases where rapid changes in desired voltage occur are rare. Here the study is carried out by increasing and decreasing the desired voltage by 0.1 p.u. in steps. The prime mover driving the machine is assumed to rotate at constant speed.



(a) Step increase in reference voltage from 1.0 p.u. to 1.1. p.u.



(b) Step decrease in reference voltage from 1.0 p.u. to 0.9 p.u.

Fig. 5.5 Variations in Terminal Voltage and Excitation Voltage With Step Change in Reference Voltage

(i) step increase in the reference voltage by 0.1 p.u. from 1.0 p.u.:

Fig. 5.5(a) shows the performance of the system when the reference voltage is stepped up by 0.1 p.u. to 1.1 p.u. at 2.5 s. The terminal voltage has increased corresponding to the desired voltage and to accommodate this change, the excitation voltage, eventually, has gone up too.

(ii) step decrease in the reference voltage by 0.1 p.u. from 1.0 p.u.:

Fig. 5.5(b) shows the performance of the system when the reference voltage is stepped down by 0.1 p.u. to 0.9 p.u. at 2.5 s. The terminal voltage has decreased correspondingly to the desired voltage and, again, to accommodate this change, the excitation voltage also decreases.

Fig. 5.5 shows that, for any step change in reference voltage, within the range investigated, the system settles down to the desired value in a very short time, without any high surge in any of the system variables.

5.6.2. Effect of Load Variation

In section 5.5, the terminal voltage variation due to speed change has been presented. In addition, the output voltage of the machine varies not only with varying speed but also with varying load even at one constant speed. The way in which the terminal voltage varies with load depends on the load current, the internal impedance and the load power factor. The change of voltage from no-load to full-load current at any particular power factor is termed regulation. The voltage variation due to load change is undesirable and should be kept small.

The Kirchhoff's voltage law yields a basic equation for the machine circuit as follows:

$$V = E - I_L\ Z_s \tag{5.16}$$

where

V - the terminal voltage with load current I_L

E - no-load voltage

$Z_s = R_r + jX_s$ where $X_s = X_r + X_m$

By simulating equation (5.16) and eqns. 4.34 through 4.37, the behavior of the terminal voltage as load varies can easily be determined.

Usually a generator terminal voltage is maintained constant by controlling the field current manually or by using a voltage regulator (proposed in this scheme), which senses the departure of the terminal voltage from a desired value and applies a correction to the field voltage. Beside the load variation, the voltage varies with the type of load (inductive/capacitive) connected to the terminals. Typical curves

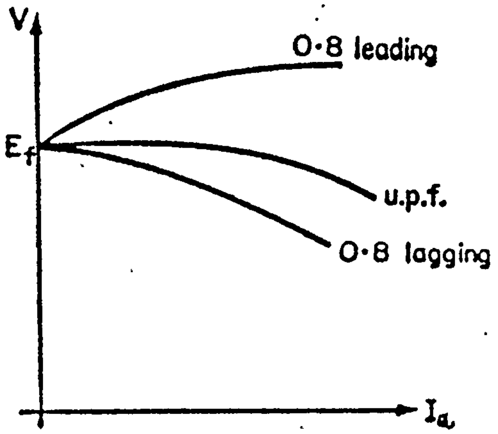


Fig. 5.6 Generator External Characteristics

are shown in Fig. 5.6. The voltage falls on lagging power-factors and rises on leading power-factors, though in practice undue increases would be limited by saturation.

Again, the purpose of the feedback loop is, of course, to permit the system to maintain the output voltage at, or close to, the desired value. The prime mover driving the generator is assumed to rotate at constant speed.

If the load is changed suddenly by an amount ΔI_L, the terminal voltage V_t is obviously changed suddenly too by $\Delta V_t = \Delta I_L Z_s$. If there was no feedback loop (i.e. for open-loop operation) this change would also be the steady-state condition because an open-loop system has no mechanism that permits it to correct for this change. With feedback there is a correction, and the steady-state condition can be determined.

When the load is increased or decreased in steps, its effect on the control system is the same as for the increase or decrease in steps in the reference voltage which has been studied in Sec. 5.6.1. The basic nature of the transient response to a disturbance in load is exactly the same as the transient response to a change in reference voltage, (Fig 5.5).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

The objective of the dissertation as outlined in Chapter 1 was to investigate and analyze the application of an AC commutator machine in the field of wind power generation. The control strategy in the field winding of the AC commutator machine was developed and simulated to justify its ability to maintain the output voltage of the machine terminals after being disturbed by the transients in the wind speed. The work presented in this dissertation centers around a variable speed wind-turbine driven AC commutator machines.

Among the several schemes described in the literature, VSCF systems using AC commutator machines seemed to be less complicated and less costly because the main aim was to maintain only one variable, i.e. voltage, as compared to other wind generation schemes.

The performance of an AC commutator machine powered by a variable speed wind-turbine has been described. The analysis of the proposed scheme shows that it is feasible to avoid the use of variable pitch turbines because of the reasonable effective cost of solid state devices used in the scheme. The study also shows that the speed range could be wide enough to accommodate most of the practical wind speed range. Also the simplified model is general in the sense that wind-turbine can be replaced by any variable speed source.

The AC commutator machine has mainly been restricted to constant speed power generation. Its application in the variable speed generation mode has been discussed particularly in the realm of wind energy conversion.

6.2. RECOMMENDATIONS FOR FURTHER RESEARCH

Following are some areas worth investigation, even if they are not relevant to this work, but would be of advantage to the area of wind energy generating systems in general.

(i) The class of machines called asynchronized synchronous machines have all the advantages of conventional synchronous machines and are capable of running with slip at any speed and still generate power at constant frequency if both field windings are excited by alternating voltages. Also conventional uniaxial synchronous machines cannot be used for transmission of electrical energy over long distances of the order of 1000 km. or so. This is because the angle δ attains a value $\geq 90^o$ and the machine becomes unstable. High level excitation regulation depending on the angle δ may increase the stability of operation considerably [29]. By a proper choice of the control strategy, such machines may be operated as wind power driven generators. This machine choice does not seem to have been tried in wind power applications and is worth investigating.

(ii) The synchronous-flux generator whose output frequency, phase angle and torque angle are independent of the shaft speed [30]. The generator is automatically in synchronism with the system voltage. The voltage control strategy might prove useful in wind power applications and should be considered for investigation.

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APPENDIX - A

A.C. Commutator Machine and Excitation System Parameters

(i) The A.C. Commutator Machine

The machine used for simulation studies was 4-pole, 3-phase, 30 kVA, 220V, 60 Hz [8]. The base quantities for the machine are chosen as below:

kVA base = 30 kVA

Voltage base = $220 / \sqrt{3}$

= 127.01V

Current base = 78.73 amps

Impedance base = $V_B \; / \; I_B$

= 1.6133 Ω

Synchronous speed = 1800 rpm

= 1.0 P.U.

Steady state speed = 1.1 P.U.

Parameters:

Stator resistance = 0.071 Ω

= 0.044 P.U.

Stator reactance = 0.133 Ω

= 0.08244 P.U.

Stator impedance = 0.09345 P.U.

Rotor resistance = 0.071 Ω

= 0.044 P.U.

Rotor reactance = 0.152 Ω

= 0.099216 P.U.

Rotor impedance = 0.10398 P.U.

Mutual reactance = 0.3905 P.U.

(ii) The Excitation Control System

T_{FL} = 1.0 s.

T_{RI} = 0.0 s.

T_{R2} = 0.0 s.

$K_{RI} = 1.0$

$K_{R2} = 1.0$

Steady state inverter output voltage = 0.32 P.U.

Steady state inverter gate signal = 0.03 P.U.