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Title: A New and Improved Control of a Power Electronic Converter for Stabilizing a Variable Speed Generation System using an Embedded Microcontroller

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Roy C. Rathja

A new and improved stabilizer was developed for the variable speed generation (VSG) system. The VSG system exhibits periodic oscillations which sometimes leads to a loss of synchronism. After careful study, a simple but effective strategy to stabilize the system was implemented with real time digital feedback control.

The VSG system consists of an engine, which is the prime mover, driving a doubly fed machine (DFM), which is the generator. The stator of the DFM is directly connected to the grid while the rotor is connected to the grid through a power electronic converter. The converter used in this study is a series resonance converter (SRC), but the proposed method may also be applied to

other kinds of converters. The stabilizer senses the RPM of the engine, the feedback signal, and controls the rotor current amplitude and frequency of the doubly fed machine.

Control was implemented using the 80C196KB microcontroller. The software consists of a mix of "C" and assembly language. Speed being an important factor in the implementation, care was taken to minimize the control loop times. The important features of the hardware and software developed for the stabilizer are:

(1) 12 MHz controller board
(2) Real time digital band pass filter
(3) Instantaneous rotor speed measurement
(4) Interrupt driven measurement and control loops
(5) User defined setup parameters
(6) IBM PC based real time serial communication

The performance of the VSG system was studied with and without the stabilizer. A significant improvement in the stability of the system was noticed over the entire region of operation.

A New and Improved Control of a Power Electronic Converter for Stabilizing a Variable Speed Generation System Using an Embedded Microcontroller

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Redacted for Privacy

Head of the Department of Electrical and Computer Engineering

Redacted for Privacy

Dean of Graduate School

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A New and Improved Control of a Power Electronic Converter for Stabilizing a Variable Speed Generation System Using an Embedded Microcontroller

1. INTRODUCTION

A variable speed generation (VSG) system is able to generate electrical power at a set frequency and voltage from a prime mover which operates at variable speed. This is different from fixed speed generation where the prime mover is constrained to operate at fixed speed.

The VSG system under consideration is currently being developed at Electronic Power Conditioning Inc., it consists of an automobile engine driving a doubly fed machine (DFM), power is delivered to the grid from the stator of the DFM as well as the rotor. The rotor winding is connected to the series resonance converter (SRC), which converts the electrical power at slip frequency to the voltage and frequency of the grid.

During development it was noticed that the VSG system exhibited periodic oscillations. These oscillations, if uncontrolled, resulted in the system losing synchronism and it was imperative that these be controlled and the system stabilized.

A careful study of the possible causes for these oscillations was done. It was noted that the four stroke automotive engine was by its very nature delivering a pulsating torque. For a four cylinder engine there are two torque pulsations per revolution. Besides it was noticed that for a given throttle position the engine was not delivering uniform torque. It must be noted that these torque pulsations play an important role in affecting system stability.

The engine was driving a DFM operating in the synchronous mode. Concordia et al [1] have made a detailed study of the DFM, H.K.Lauw [2] in his report has made a detailed study of the characteristics of the DFM, Gish et al [3] and Liwschitz [4] have also studied the nature of the DFM. Lauw et al [5] have made a study of the control aspects of the brushless doubly fed machine and developed a strategy for stabilizing the machine. The DFM it must be noted does not have damper windings like a synchronous machine. Further the rotor winding of the doubly fed machine was connected to a converter which was not an ideal current source. For the system to exhibit a stable transition from one operating point to another it was required that the rotor be connected to an ideal current source.

Finally, the VSG system delivers power to the external grid. The grid is presumed to function like an infinite bus bar, but in reality the VSG system has to supply a varying load.

The VSG system behaves like a second order system. Each of the above mentioned causes can be correlated to a step input to the second order system. The system thus starts to oscillate with its natural frequency when it is subject to a disturbance. This also results in oscillations in other system variables such as power (real and reactive) and current.

In terms of control system theory, the instability in the VSG system can be correlated to a system which produces an unbounded output for a bounded input. The effect of the stabilizer is to change the system parameters such that the system exhibits bounded input bounded output (BIBO) stability.

We now outline the objectives of this dissertation:

(1) Choose an engineering problem that needs to be solved.

The problem chosen is the development of a stabilizer for the VSG system.

(2) Apply a knowledge of control system theory to develop an effective control strategy.

Feedback control to produce BIBO stability is used in this case.

(3) Solve the problem using the principles of computer engineering.

This dissertation is organized in to eight chapters. Chapter 1 is the introduction to the research. Chapter 2 is a detailed study of the VSG system. In chapter 3, a detailed study of the factors affecting the VSG system stability and variables available for controlling the system are discussed. Chapter 4 deals with the characteristics of the DFM. Chapter 5 deals with the analysis and design of the stabilizer. Various measures considered for stabilizing the system are discussed. Reasons for selecting the current method for implementation are also outlined. Chapter 6 is concerned with the implementation of the stabilizer. Here the hardware and software details regarding the implementation of the stabilizer are explained in detail. The experimental results and their significance constitute chapter 7. Finally a discussion of the improvement in system performance as a result of this stabilizer and scope for future research forms chapter 8.

2. THE VARIABLE SPEED GENERATION SYSTEM

The variable speed generation (VSG) system consists of the following three subsystems:

(1) The LSG-423 Ford Gasoline Engine

(2) The Series Resonance Converter

(3) The Doubly Fed Machine

(4) The VSG system controller

A study of the above subsystems, their interconnections and their characteristics gives us an understanding of the system and aids in the design of a simple but effective method of stabilizing the system.

A block diagram of the VSG system with its basic subsystems and their interconnections is given in Fig. 2.1. Lauw et al [14] have made a study of the operating modes of the VSG system using a doubly fed generator (DFM in the generating mode) and the series resonance converter.

2.1 The LSG-423 Ford Gasoline Engine

This is a four cylinder, 2.3 litre engine. It has a continuous gross output of 53.7 BHP and intermittent gross output of 63 BHP at 2800 RPM. It develops a peak torque of 119 Lbs-Ft and continuous torque of 101 Lbs-Ft at 2800 RPM.

The shaft of the engine is coupled to that of the doubly fed machine (DFM) which functions as the generator. Hence the engine functions as the prime mover. At this point it must be noted that this being a four cylinder engine there are two pulsations per revolution and that all the four cylinders complete their combustion cycle once every two revolutions. The power output from the engine is controlled by adjusting the throttle position. Since output power is a product of output torque and engine speed, variation of output power can result in the following modes of operation of the engine.

(a) Output torque remaining constant, a variation of output power results in a variation of engine speed.

(b) Engine speed being held constant, a variation of output power results in a variation of output torque.

(c) A variation of engine output power can result in a variation of both engine speed and output torque.

2.2 The Series Resonance Converter

This is a 25 KW, bidirectional 24 thyristor convertor. The input of the converter is connected to the grid and the output is connected to the rotor of the DFM.

The bidirectional nature of the converter is an important feature. It enables the converter to either deliver power into the rotor from the grid or extract power from the rotor and deliver it to the grid. Another important feature is that the converter is capable of running in the programmable current source mode. This feature is utilized in the development of the stabilizer. The

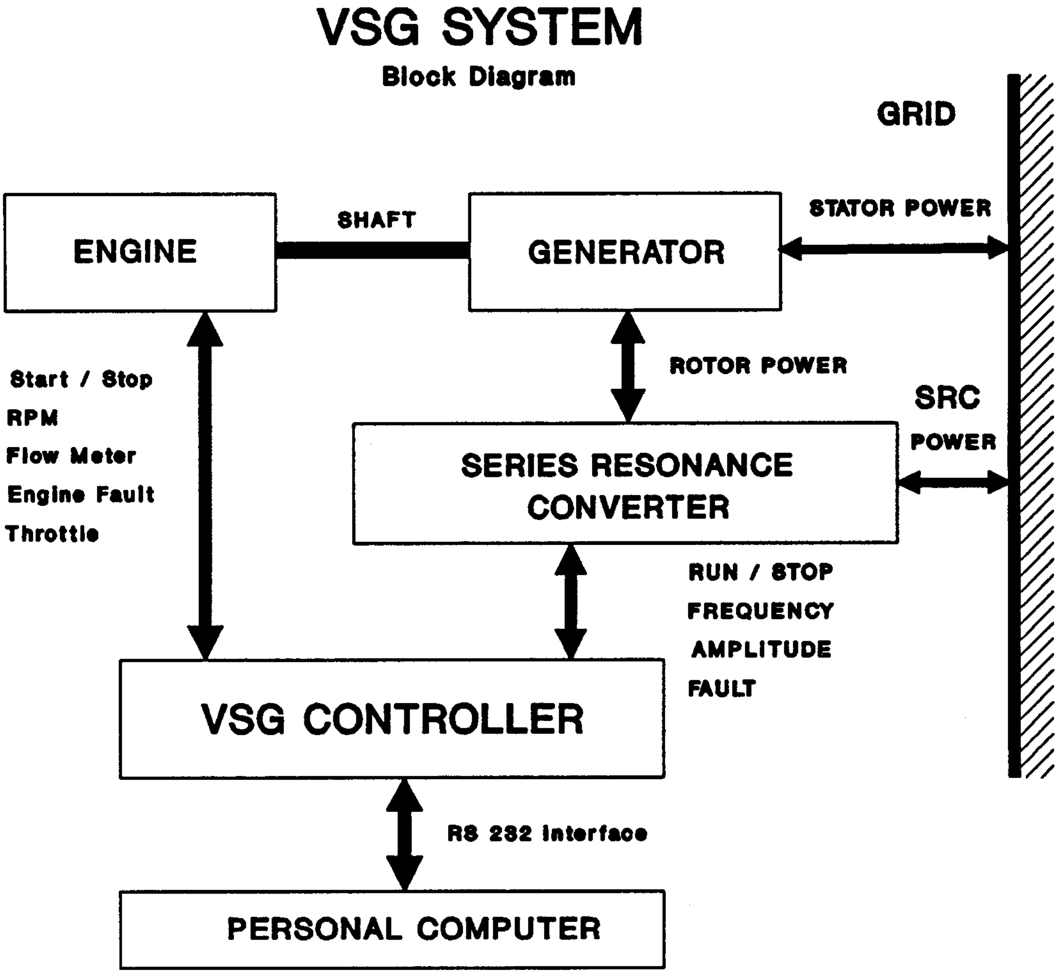


Fig. 2.1 VSG System Block Diagram

converter is also capable of V/F and voltage mode of operation.

In the VSG system the converter functions like a power transducer. It forms a link between the grid power, which is at 240 volts and at a frequency of 60 Hz, and the slip power of the DFM in the rotor, which is at the slip frequency of the machine and a voltage determined by the SRC output current and engine speed. The converter has external frequency and amplitude input signals which are used by the VSG system controller to control the converter output current magnitude and frequency.

2.3 The Doubly Fed Machine

This is the generator of the VSG system and was manufactured by Reuland. It is rated at 30HP on the stator and has a voltage rating of 240 volts and a current rating of 65 amperes on the rotor. It is essentially a slip ring induction machine with three phase windings on both the stator and the rotor.

H.K.Lauw has patented the use of the DFM in the doubly fed mode. In this mode the machine acts as a synchronous generator and is therefore capable of generating reactive power. However, the machine speed can be controlled independently from the machine's power factor which is not possible in the slip recovery mode. This mode of operation results in superior machine performance.

The DFM shaft is coupled to the engine shaft. The three phase windings of the rotor are connected to the output of the SRC. The DFM in the VSG system delivers power to the grid from both its stator winding, which is directly connected to the grid after synchronization, and its rotor winding, which is connected to the grid through the converter.

The VSG system controller controls the rotor current amplitude and frequency inputs to the DFM by means of the SRC, and is thus, for a given throttle setting of the engine, able to control the power output from the rotor as well as the stator and also the engine speed. In short, determines the system operating point.

Mounted on the shaft of the DFM is also the speed (in revolutions per minute (RPM)) sensor. It is an Avtron pulse tachometer with a resolution of 240 pulses per revolution. The output of the tachometer is sensed by interrupt driven software on the VSG system controller to measure the instantaneous RPM, which is defined as the average speed of the engine during the last revolution.

2.4 The VSG System Controller

It consists of hardware and software that controls the VSG system. A 12MHz controller board using the Intel 80C196 Embedded Microcontroller provides the measurement and control logic for the VSG system. Much of the software is written in the "C" language with assembly being used in time critical portions of the code. The Intel C96 compiler was used for program development using "C" and the Intel A96 assembler was used for assembly language programming.

Some of the characteristics of the VSG system controller software relevant to the implementation of the stabilizer are:

(a) Interrupt driven measurement of RPM using hardware timers

(b) Real time digital band pass filter for the RPM signal

(c) Interrupt driven control loops for precise control.

3. STUDY OF SYSTEM STABILITY

There are several factors that affect the stability of the VSG system. A detailed study of each of these factors gives us an insight into the nature of the system. This will help us design an optimal stabilizer for the system. The following factors have been identified as possible causes for system instability:

(1) Engine power output variation

(2) Engine torque pulsations

(3) Load variations

(4) Non-Ideal excitation current source

(5) Low damping characteristic of the DFM.

The function of the stabilizer is to maintain the system at a stable operating point when subject to the above inputs. We shall now study each of these factors, their possible causes and the methods that could be adopted to neutralize these disturbances.

Based on the above study, control variables which can keep the system stable in the face of these disturbances will be identified and their effect on system operation will be discussed.

3.1 Engine Power Output Variation

The engine should ideally deliver a steady torque for a given throttle setting. This is because a given throttle setting corresponds to a certain rate at which gasoline is being used by the engine to deliver power. But in practice the torque delivered by the engine is subject to variation.

These variations can be the result of:

(a) Engine not being properly tuned

(b) Engine not being properly balanced

(c) Fuel flow rate not being constant for a given throttle setting

In order to neutralize the effect of this disturbance the stabilizer must be able to transfer this energy to the external grid with out affecting system stability. This makes it necessary for the VSG system to sense these variations as they occur and suitably transform these variations into quantities in a manner that will maintain system stability.

3.2 Engine Torque Pulsations

A measure of the engine RPM is used as an indicator of system stability and as a feedback variable for control. Keeping in mind the pulsating nature of the torque developed, the engine requiring two revolutions to go through a cycle of operation and the inherent mismatch between the four cylinders, RPM needs to be measured. The nature of the control strategy also determines the type of RPM information needed.

This is mentioned here because it has been found that the average RPM when measured over two revolutions is fairly constant while the actual RPM exhibits large transitions (by as much as 200 RPM) over the mean because of the torque pulsations. For stabilization it is not these periodic momentary torque variations, which is characteristic of these engines, that are important, but the average engine speed which could be defined as the speed of the engine over two revolutions. An improper choice of RPM measurement will render the stabilizer ineffective.

3.3 Load Variations

The VSG system is theoretically assumed to be connected to an infinite bus, that is the grid. The grid is supposed to have a fixed voltage (230 volts) and frequency (60 Hz), whereas in reality, because of constant load changes the grid exhibits aperiodic changes in voltage and frequency. Hence the grid appears as a constantly varying load. Thus the system could be subject to sudden disturbances from the grid. These momentary disturbances can set the system oscillating at its natural frequency, and the stabilizer, by restoring the energy balance in the VSG system, can stabilize the system.

3.4 Non-Ideal Excitation Current Source

The power output from the VSG system can be controlled by varying both the engine speed and torque. Engine speed control is accomplished by varying the rotor current frequency and torque control by throttle position. The amplitude of the rotor current is to remain constant during these power output variations. But due to a variation in rotor impedance as the frequency of the current varies it is found that there is a variation of the rotor current amplitude delivered by the converter. If the excitation is not sufficient to keep the operating point of the doubly fed machine in the stable steady state region as the power output changes then the system is liable to lose synchronism.

This condition can be rectified by the stabilizer if it is able to keep the operating point of the DFM in the stable steady state region, while the system changes state, by varying the rotor current input command to the converter so as to maintain a constant current amplitude in the rotor.

3.5 Damping Characteristic of the DFM

The doubly fed machine has insufficient damping to keep the system from oscillating when it is subject to perturbations. The engine torque pulsations, which have been noted to occur twice for every revolution of the rotor, have an adverse affect on the VSG system stability. If the stabilizer is able to increase the damping of the system then the unwanted system oscillations could be suppressed.

3.6 Control Variables for Stabilization

The VSG system has essentially three variables which control its operation and hence determine its operating point. They are:

(a) Throttle Position Control:

This controls the torque output from the engine and hence the power output. The VSG system controller controls a stepper motor which controls the throttle position. Opening the throttle increases the fuel input to the engine and hence increases the engine torque, and closing the throttle likewise reduces this torque. A step change in throttle position corresponds to an average change of .25 KW in total power output.

(b) Rotor Current Frequency Control:

Changing the rotor current frequency results in a change of engine speed under synchronous operating condition as the grid forces the sum of the rotor frequency and the engine frequency to be equal to the grid frequency of 60 Hz.

Rotor current frequency can be varied in steps of 0.1 Hz without causing transients which result in a loss of synchronism. The frequency is varied by the VSG system controller by varying the frequency reference to the converter.

(c) Rotor Current Amplitude Control:

The excitation for the doubly fed machine is provided by the rotor current. Changing the rotor current amplitude results in a change of the reactive power output of the doubly fed machine.

Rotor current amplitude can be varied in steps of 0.6 amps. Rotor current amplitude is varied by the VSG controller by varying the amplitude input to the converter.

Thus we can see that there are three control variables available to affect stabilization. Of the three it has been found that the stepper motor control is relatively slower in affecting a change in system operation and not suitable for the fast control necessary for stabilizing the system. Hence we are left with the rotor current and frequency control variables.

The rotor current and frequency variables affect the operation of the doubly fed machine. By trying to stabilize the VSG system by controlling these variables we effectively control the operating point of the DFM. Hence it is necessary to study the characteristics of the DFM in detail at this point and the factors affecting its stability.

In the next chapter we shall study the characteristics of the DFM. In chapter 5 the development of the design and the analysis of the stabilizer using these variables is described.

4. CHARACTERISTICS OF THE DFM

A study of the factors affecting the stability of the VSG system in chapter 3 has shown that the system can be stabilized by controlling the doubly fed machine rotor current and frequency variables. We shall now study the basic equations governing the working of the DFM. H.K. Lauw [13] has made a detailed study of its characteristics and was also responsible for developing the DFM circle diagram.

4.1 Equivalent Circuit of the DFM

The equivalent circuit model per phase for a DFM can be represented as shown in Fig. 4.1. The voltages and currents vectors are sinusoidal waveforms. We define the various symbols used as follows:

V_1 = Stator voltage per phase (Connected to grid)

V_3 = Rotor voltage per phase (Connected to Converter)

R_1 = Stator resistance

X_1 = Stator leakage reactance

R_m = Resistance corresponding to core losses

X_m = Magnetizing reactance

I_o = Magnetizing current

E_1 = Excitation voltage

s = slip

R_2 = Rotor resistance

X_2 = Rotor leakage reactance

I_1 = Stator current

I_2 = Rotor current

We shall study the characteristics of the DFM by using the approximate per phase equivalent circuit given in Fig. 4.1. In this circuit the rotor quantities have been transferred to the stator and core losses are neglected.

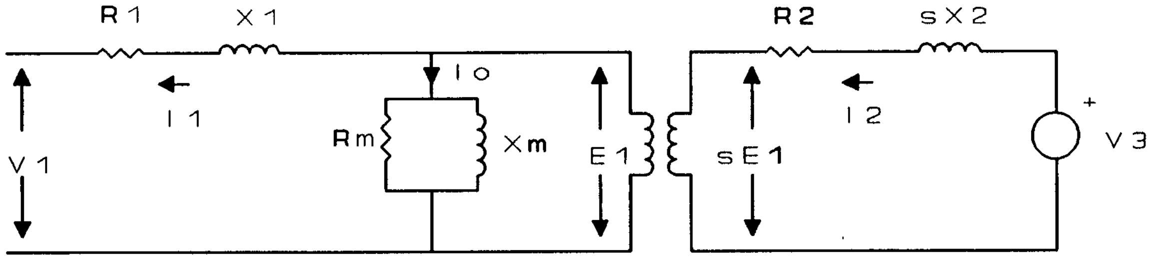
Writing the mesh equations we have:

$$V_1 = - I_1 R_1 - j I_1 (X_1 + X_m) + j I_2 X_m \qquad \textbf{(4.1)}$$

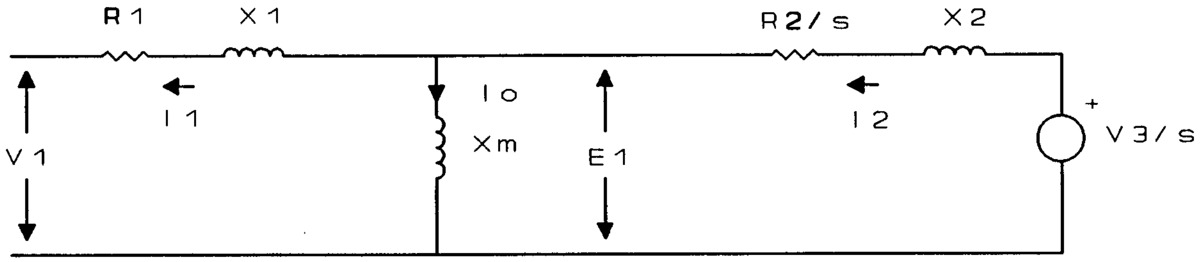
$$\frac{V_3}{s} = +I_2 \frac{R_2}{s} + j I_2 (X_2 + X_m) - j I_1 X_m \qquad \textbf{(4.2)}$$

Equation **4.1** can be written as shown in equation **4.3** to derive the circle diagram of the DFM, as shown in Fig. 4.2, for circles of constant rotor current amplitude.

From equation **4.3** the phasor I_1 and the terms on the right hand side can be used to draw the circle diagram. The center of the constant rotor current circles is at "N". The phasor I_2 with its base at N and its head at A represents the operating point of the doubly fed machine. Its magnitude is



EQUIVALENT CIRCUIT OF A DOUBLY FED MACHINE



APPROX. EQUIVALENT CIRCUIT OF A DOUBLY FED MACHINE

Fig. 4.1 DFM Equivalent Circuit

$$I_1 = \frac{V_1}{Z_{e1}}\, e^{j(\alpha_{e1}+\frac{\pi}{2})} + \frac{X_m}{Z_{e1}}\, I_2\, e^{j(\alpha_{e1}+\delta-\frac{\pi}{2})}$$

Where :

$$\alpha = \arctan \frac{(X_1+X_m)}{R_1} \qquad \textbf{(4.3)}$$

$$Z_{e1} = \sqrt{R_1^{\,2} + (X_1+X_m)^2}$$

$$\delta = \textit{Phase Angle of } E_2 \quad \textit{where} \quad E_2 = jX_{m2}I_2$$

given by the product of I_2 and X_{m2} / Z_{e1}. The ordinates of N are given by equation **4.4.**

$$X_N = \frac{V_1}{Z_{e1}} \sin(\alpha_{e1})$$

$$Y_N = \frac{V_1}{Z_{e1}} \cos(\alpha_{e1}) \qquad \textbf{(4.4)}$$

Where Z_{e1} and α_{e1} are defined in equation 4.3.

4.2 Circle Diagram of the DFM

A careful study of the circle diagram shown in Fig. 4.2, showing circles of constant rotor current will help us understand the steady state behavior of the DFM and hence the VSG system. It must be mentioned that the study of the circle diagram is valid for sinusoidal quantities, but it will be used in chapter

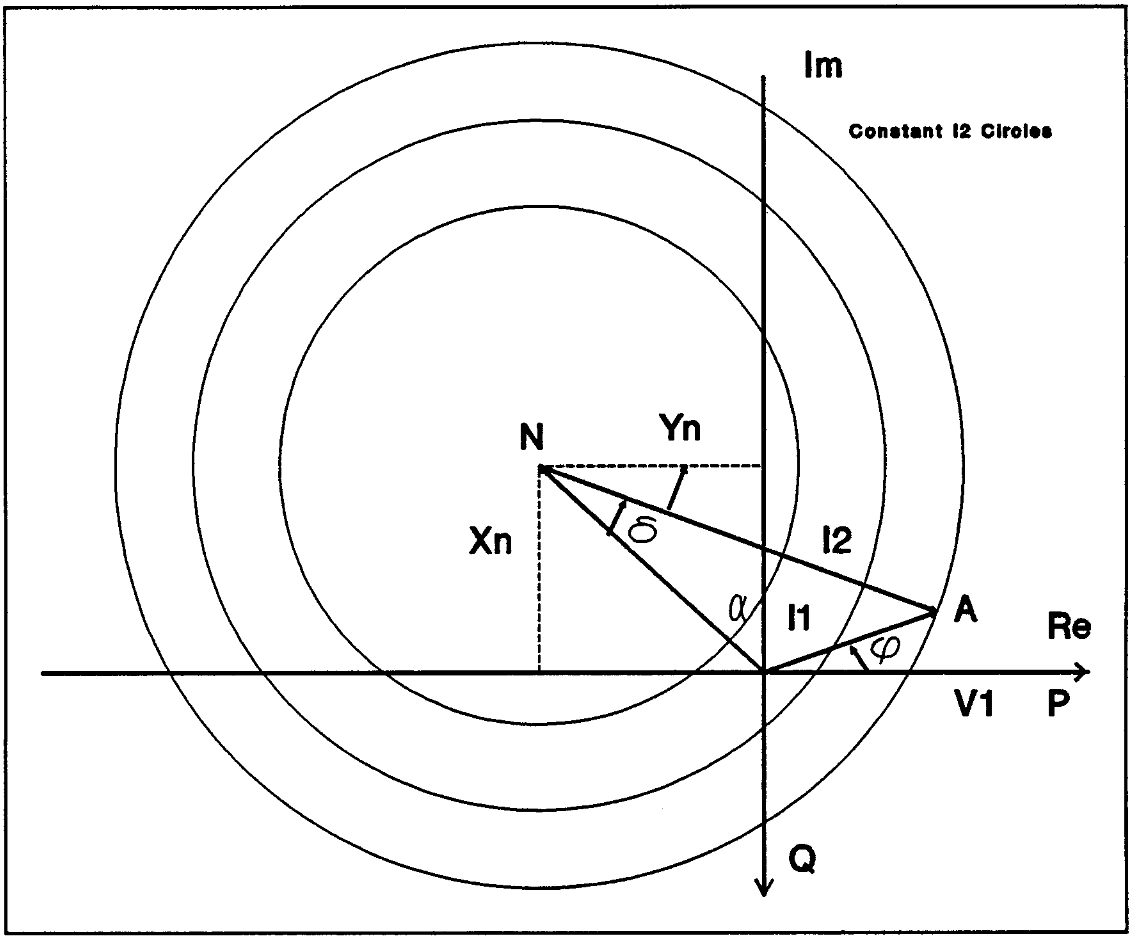


Fig. 4.2 Constant Rotor Current Circles

5 in order to gain an intuitive understanding of the VSG system behavior under transient conditions when the system variables are no longer sinusoidal.

On the circle diagram it will be noticed that the stator voltage is taken to be along the positive X_axis. The stator current I_1 is phase shifted by φ from V_1.

The projection of I_1 along the X_axis corresponds to the real power "P" developed by the stator and its projection along the Y_axis corresponds to the reactive power "Q".

It is important to note that the vector I_1 is determined by the magnitude of I_2 and the torque angle δ. In the VSG system changing the rotor current amplitude results in a change of I_2 and changing the rotor current frequency results in a change of torque angle δ.

In chapter 5 we shall study in detail the design and analysis of the stabilizer by the use of these two control quantities.

4.3 DFM Power Balance Relationship

In the VSG system the engine generates power. This mechanical power is distributed between the rotor and the stator. Assuming negligible losses in the system the total mechanical power developed is equal to the sum of the power output from the rotor and the stator. Developing the power balance equations, we have :

$$P_{em} = T_{em}\ \omega_{em} \tag{4.5}$$

Where:

P_{em} = Electromechanical power developed by the engine

T_{em} = Electromechanical torque developed by the engine

ω_m = Angular speed of the engine (radians/second)

ω_m = $2 \pi f_m$

f_m = Electrical frequency corresponding to engine speed

The slip "s" of the DFM is defined as:

$$s = \frac{\omega_s - \omega_m}{\omega_s} \tag{4.6}$$

ω_s = Angular speed corresponding to grid frequency

ω_s = $2 \pi f_s$

f_s = Electrical grid frequency

From equations 4.5 and 4.6 we have:

$$\begin{aligned} P_{em} &= T_{em}\, \omega_s\, (1-s) \\ P_{em} &= \omega_s\, T_{em} - s\, \omega_s\, T_{em} \end{aligned} \tag{4.7}$$

The first term in equation 4.7 corresponds to the power developed by the DFM on the stator and we note that it is a function only of the electromagnetic torque and independent of speed. The second term is a function of the slip "s" of the machine and hence dependent on the speed of the engine besides the electromagnetic torque.

From this equation we can see that if a momentary power imbalance occurs between the electromechanical power (P_{em}) that is developed by the engine and the power that is transferred to the grid, if the electromagnetic torque is kept constant, then the system will undergo a change in speed (slip). This can result in mechanical oscillations, which are difficult to control and can result in a loss of synchronization of the VSG system. Here the power imbalance results in a change in the kinetic energy of the system. If these power imbalances are sensed and instead transferred into an electromagnetic energy variation then the mechanical speed oscillations can be avoided. In the stabilizer these energy variations are transferred into electromagnetic torque variations and the system is found to be more stable. We shall study the design of the stabilizer in the next chapter.

5. DESIGN AND ANALYSIS OF THE STABILIZER

The design and analysis of the stabilizer for the VSG system will be covered in this chapter. Several methods were studied to build an optimal stabilizer for the VSG system. These methods will also be discussed, the requirements for their implementation will be described. Finally the method chosen will be discussed in detail. It will be seen that after a careful study of several methods the most effective method in terms of theory and simplicity of implementation is used to build the stabilizer.

As described in chapter 3 the stabilization of the VSG system is to be achieved by controlling the rotor current amplitude and frequency variables. By referring to Fig.5.1 it can be seen that in changing the rotor current and amplitude variables we are actually trying to change the rotor current vector. The rotor current vector being determined by the amplitude of I_r and the torque angle δ. It must be noted that by controlling the rotor current vector we also effect the stator current vector I_s. Thus we are effectively able to control the

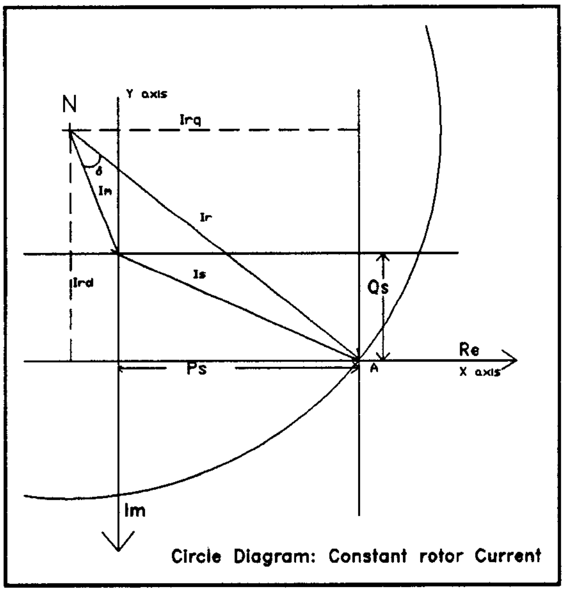


Fig. 5.1 Circle Diagram: Constant Rotor Current

electromagnetic torque generated by the DFM. From equation 4.7 it can be seen that we can control the power developed by the system. Thus the energy balance for the VSG system between the mechanical power developed by the engine and the electrical power developed by the DFM can be achieved.

5.1 Rotor Current Vector Control

From Fig. 5.1 it can be seen that the rotor current vector can be resolved along the X axis, I_{rq}, the component of rotor current responsible for real power and along the Y axis, I_{rd}, the component responsible for controlling reactive power generation. By maintaining I_{rd} constant we can keep the reactive stator power developed by the DFM constant and vary the output real power by varying I_{rq}. The DFM in the VSG system generates power while operating as an induction machine in the synchronous mode. Large torque angles (90 degrees) in synchronous machines lead to stability problems, similarly in the DFM stability problems arise when the torque angle is large, i.e., when reactive power is negative. A small disturbance results in the system oscillating with a large amplitude if the reactive power being developed is small and the possibility of the system losing synchronism is high.

Hence by means of vector control if I_{rd} is kept constant while varying I_{rq} to neutralize the effect of power imbalances in the VSG system, a system with greater stability would be obtained. In this case the electromagnetic torque generated by the system will be varied to neutralize momentary power imbalances and the system will not be subject to large mechanical oscillations to maintain the energy balance.

In order to implement vector control several methods were considered. Some of the methods were not used because of the impracticality of their implementation. Some were omitted because of the complexity of their measurement schemes or the fact that they were too expensive to implement. Some were omitted because of the complexity of the algorithm for vector control and the requirement of a special purpose high speed controller (both digital and analog) for their implementation. Finally, a method already in use is described and the new improved strategy is described. Both these methods it will be noticed are simple in both theory and implementation and of practical use in industrial control applications. Some of the methods considered are described below.

(a) Direct Air-gap Flux Measurement

In this method the air-gap flux is directly measured by mounting flux sensing coils or hall effect transducers on the stator of the machine. From the rotor flux vector and a knowledge of the measured stator current vector we can determine the component of the rotor current responsible for developing reactive power and the component responsible for active power. This information can be used to implement vector control on the DFM.

This method is not practical as it requires a special machine with additional wiring, and the signal detected may contain ripple components that will need to be filtered.

(b) Direct Measurement of Rotor and Stator Current Vectors

The stator current vector is measured in the synchronous reference frame. The rotor current vector is measured by transducers on the rotor windings and it is transposed to the stator reference frame. From a knowledge of these two vectors stabilizing control can be affected on the VSG system.

This method requires transducers on both the stator and rotor and is hence expensive and complex. Besides the equations for vector control are computation intensive and would require extensive digital and analog hardware for implementation.

(c) Rotor Position sensing

An optical encoder of high resolution is mounted on the shaft and can be used to indicate the instantaneous position of the rotor current vector. This can be used in coordination with the measured stator current vector for effecting vector control on the DFM.

This method involves an expensive encoder. Each system will have to be initialized with information regarding the position of the rotor windings with reference to the stator windings. This is additional complexity not desirable in an industrial environment. Besides, other problems associated with vector control as seen before persist.

(d) Use of machine parameters

From equation 4.3 and Fig. 5.1 we find that the rotor current I_r is a vectorial addition of I_s and I_m, the magnetizing current. The magnetizing current can be determined from a knowledge of machine parameters. The rotor current vector can be measured by one of the methods outlined above, simplest being to measure the rotor current. From a knowledge of the two we can determine the component of the rotor current responsible for reactive power and the component responsible for real power. By being able to control each component separately we can effect vector control and stabilize the system.

The main disadvantage with this system is that the machine parameters need to be known in advance and need to be programmed in to the control algorithm. The machine parameters are also temperature dependent. In an industrial environment each system will have to be separately programmed, an undesirable feature. Besides a relationship between rotor current and the relevant power components needs to be established directly or indirectly.

(e) Rotor Current Amplitude and Frequency Control

This is an indirect form of vector control. By control of the rotor current amplitude and frequency we are able to achieve the desired end, i.e., control of the rotor current vector to stabilize the system. In this method the speed of the system is sensed using a tachometer and changes in speed are related to changes in the torque angle. This information is used for control purposes.

This method is the simplest in terms of implementation and also in terms of hardware and software requirements. A speed transducer is the only necessity. This method was thus chosen for implementation and has been found to be effective in stabilizing the system. This method consists of two parts. One, the rotor current frequency is changed in relation to a change in speed, so as to bring about an effective change in torque angle. This was the old version of the stabilizer. Two, it was realized that better stabilizing could be obtained by also controlling the rotor current amplitude proportional to the speed change. This resulted in the improved stabilizer which is the topic of this thesis. We shall now discuss in detail the three forms of the stabilizer, placing emphasis on the improvement in the stabilizer obtained by the rotor current amplitude control.

The three different forms of the stabilizer are:

(1) Stabilizer with rotor current frequency control

(2) Stabilizer with rotor current amplitude control

(3) Stabilizer with both rotor current amplitude and frequency control

5.2 Effect Of Load Imbalance

Fig. 5.2 portrays the effect of a momentary energy imbalance in the system. The system is initially at an operating point A. Let it be subject to a small perturbation wherein, say there is a sudden increase of engine power output. This causes the engine to accelerate, causing the torque angle δ to increase until, at point B, there is a balance between the mechanical power generated and the electrical power delivered to the load. But the system cannot suddenly revert to its initial synchronous speed, so the load angle continues to increase while the system is subject to a retarding torque. This eventually results in the electrical power delivered by the system being larger than the mechanical power developed by the engine and the system begins to decelerate towards point B. Thus we have an oscillating system similar to that of a synchronous generating system.

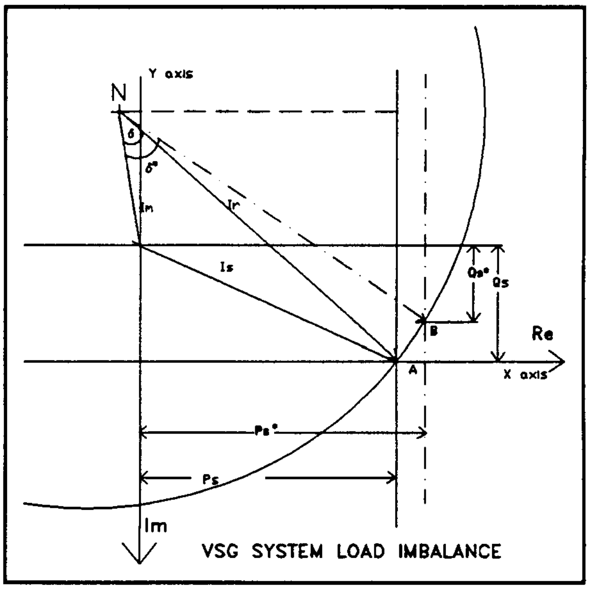


Fig. 5.2 Effect Of Load Imbalance

At point B, the stator power being delivered goes up from P_s to P_s^* and the load angle increases from δ to δ^*. The operating point of the system shifts from A to B momentarily. This is because the rotor current, which has not changed, moves along the constant rotor current circle to point B to deliver the new power required P_s^*. It is these perturbations, their causes having been discussed in chapter 3, that are to be sensed and controlled by the stabilizer.

In this case, we note that in the absence of external control, the system will start oscillating whenever there is a momentary perturbation and the oscillations will continue till the energy change is neutralized by means of losses and variation in electrical power output to the load. These oscillations are expressed in terms of speed changes and hence are mechanical in nature.

In the case of the VSG system the grid happens to be the load. This is convenient in the sense that if there are any perturbations in energy generation within the system, and if these perturbations are sensed and converted into variations in the electrical energy supplied to the grid then the mechanical oscillations can be avoided with the grid acting as a good sink of these power imbalances. This is the basic principle behind the stabilizer.

In section 5.3 we shall study the dissipation of this mechanical energy change by means of a variation of electrical energy output by changing the rotor current frequency or the slip frequency. While in section 5.4 the principle is applied to rotor current magnitude variation.

5.3 Stabilizer - Rotor Current Frequency Control

This was the method initially used to stabilize the VSG system. In this method of control the speed of the engine-generator system is sensed by a speed transducer. The resultant speed signal is filtered by means of a digital band pass filter. The frequency of the rotor current is then changed in a ratio proportional to the filtered frequency.

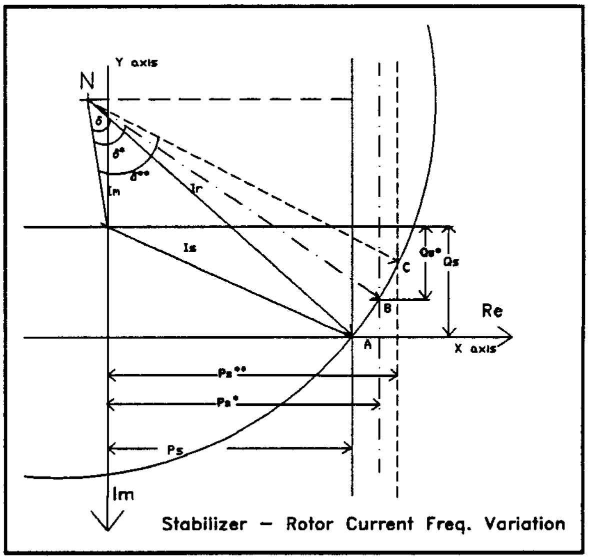


Fig. 5.3 Stabilizer - Rotor Frequency Control

In Fig. 5.3, let the operating point shift from point A to point B because of a momentary increase in engine power output. This is sensed by the speed transducer. In this case an increase in speed and hence an increase in torque angle is sensed. Using positive feedback the stabilizer further increases the resultant torque angle to δ^{**}, by increasing the rotor slip frequency. Hence the operating point is shifted to C. At this point the system develops stator power P^{**}, and the rotor power also increases as given by equation 4.7. Thus the excess mechanical power generated momentarily is quickly dissipated by increasing the power delivered to the grid. This has the effect of damping the system oscillations and the system is more stable.

5.4 Stabilizer - Rotor Current Amplitude Control

This was the improvement to the stabilizer described above and forms the basis of this dissertation. In this case the rotor current amplitude is varied proportional to the filtered speed signal.

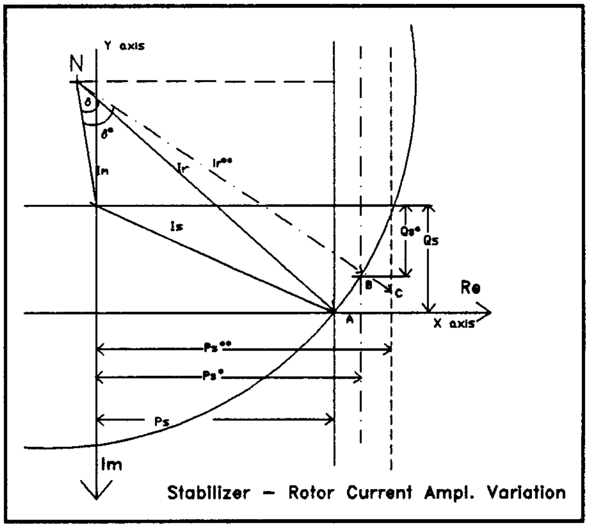


Fig. 5.4 Stabilizer - Rotor Current Amplitude

Consider Fig. 5.4. Let the initial operating point of the VSG system be at A. A momentary increase in the engine power output results in the operating point being shifted to point B, delivering a power output P^* with an increased torque angle δ^*. At this point the rotor current amplitude is increased by a ratio proportional to the filtered speed signal. From Fig. 5.4, we note that the operating point is shifted to C. The rotor current has been increased from I_r to Ir^{**} and the output power delivered has been increased to P^{**}.

Hence, sensing a change in mechanical power generated, the amplitude of the rotor current is changed so as to dissipate the excess power in terms of an electrical power output variation. This again results in reduced mechanical oscillations. It must be mentioned that this method is better suited for stabilization because the torque angle is not further increased as in the slip frequency method described in section 5.3. Further this method functionally increases the damping of the system. An additional advantage of this method of control is that the reactive power component Q_S varies by a smaller magnitude than in the previous method. This is of importance to power utilities which specify limits to the range of reactive power variation. We shall next study the combined effect of both the methods for stabilizing the system in section 5.5

5.5 Stabilizer - Rotor Current Vector Control

This is an indirect method for controlling the rotor current vector using the methods described above. In this method we control both the rotor current amplitude and the rotor current frequency in a ratio proportional to the filtered speed signal from the engine. We can call this an indirect method of vector control because by changing the rotor current amplitude and by momentarily changing the rotor current frequency we are changing the rotor current vector position as can be seen in Fig. 5.5. One of the basic principles of vector control in induction

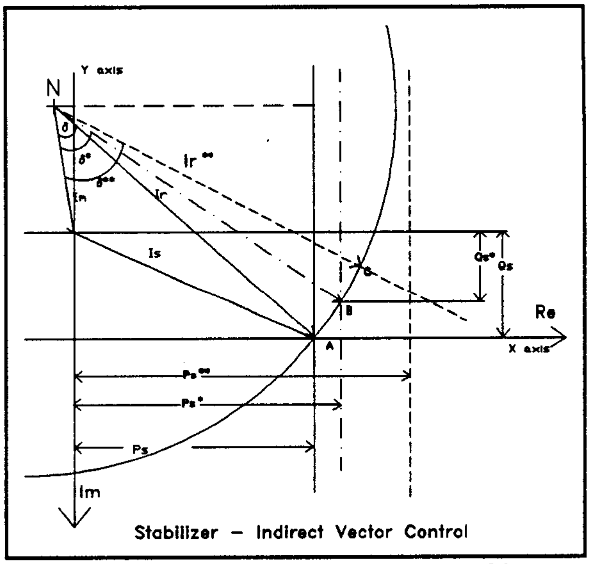


Fig. 5.5 Stabilizer - Indirect Vector Control

machines is the ability to control the torque and flux components of stator current independently. In this case, from Fig. 5.5, we can see that by controlling the rotor current vector we can keep the stator reactive power Q_s, corresponding to the projection of I_r on the Y - axis, constant and vary the real power output P_s according to energy perturbations in the system, which is similar to keeping the flux constant and varying the torque in general vector control of induction machines.

This method of control has experimentally yielded very good results as will be shown in the chapter pertaining to experimental results.

It must be noted that extensive work has been done on the vector control of squirrel cage induction machines [6]-[8]. These methods control the torque and flux related components of the stator current. In our approach we indirectly try to control the same using rotor current control instead.

5.6 Equations governing control of the rotor current vector

Consider the stability of a conventional synchronous machine. The torque equation is given by:

$$J\frac{d\ \Delta f_m}{dt} + \Delta Te = \Delta Tm \tag{5.1}$$

where

J = Rotational inertia of the system

Δf_m = Change in mechanical frequency

ΔT_e = Change in electrical torque

ΔT_m = Change in mechanical torque

We know:

$$\Delta f_m = \frac{d\,\Delta\delta}{dt} \tag{5.2}$$

$\Delta\delta$ = Change in torque angle

Substituting for ΔT_e we have:

$$\Delta T_e = \frac{1}{C}\,\Delta\delta \tag{5.3}$$

Thus a change in electrical torque is represented as a product of a constant and the change in torque angle. The constant being defined by the machine. Thus the torque equation for the synchronous machine can be rewritten as:

$$J\,\frac{d\,\Delta f_m}{dt} + \frac{1}{C}\int \Delta f_m\,dt = \Delta Tm \tag{5.4}$$

The above equation corresponds to an inductor capacitor resonant circuit which will oscillate with a natural frequency given by:

$$f_m = \frac{1}{\sqrt{J\,C}} \tag{5.5}$$

Here J corresponds to the inductance in the circuit and C corresponds to the capacitance.

For a doubly fed machine the change in torque angle is the sum of the change in mechanical frequency and rotor current frequency. i.e.

$$\Delta\, f_m + \Delta\, f_r = \frac{d\ \Delta\delta}{dt} \tag{5.6}$$

Hence the torque equation for the DFM operating in the synchronous mode can be written as:

$$J\,\frac{d\ \Delta f_m}{dt} + \frac{1}{C}\int (\ \Delta f_m + \Delta f_r\ )\ dt = \Delta Tm \tag{5.7}$$

Now, the effect of the stabilizer is to increase the damping in the system. This is achieved if the rotor current frequency is controlled according to the equation:

$$\Delta\, f_r = K_f\,\frac{d\ \Delta f_m}{dt} \tag{5.8}$$

That is, the change in rotor current frequency is proportional to the rate of change of mechanical frequency. K_f is the gain corresponding to the change in rotor current frequency.

The capacitance "C" as used in the regular synchronous machine example can be expressed as a function of the stator and rotor currents of a DFM:

$$\frac{1}{C} = K_T \, i_s \, i_r \qquad \textbf{(5.9)}$$

K_T being a constant and i_s and i_r being the stator and rotor currents of the DFM. Consider the change in rotor current amplitude proportional to the rate of change of mechanical frequency

i.e. $i_r \rightarrow i_r + \Delta i_r$, this gives us the equation:

$$\Delta \, i_r = K_i \frac{d \, \Delta f_m}{dt} \qquad \textbf{(5.10)}$$

where

K_i = Gain of rotor current amplitude change

Substituting the above equations (**5.8** to **5.10**) in the torque equation of the DFM (**5.7**) we get the following equation:

$$J \frac{d\,\Delta f_m}{dt} + \left[\frac{1}{C} + \frac{K_i}{C\,i_r} \frac{d\,\Delta f_m}{dt} \right] \int \Delta f_m \, dt + \left[\frac{K_f}{C} + \frac{K_i}{C\,i_r} \frac{d\,\Delta f_m}{dt} \right] \Delta\, f_m = \Delta Tm \qquad \textbf{(5.11)}$$

In this equation we find that there is a damping term, represented by the presence of Δf_m. Consider the above equation with gains K_i and K_f set to zero. We get the following:

$$J \frac{d\,\Delta f_m}{dt} + \left[\frac{1}{C} \right] \int \Delta f_m \, dt = \Delta Tm \qquad \textbf{(5.12)}$$

This is the equation for a synchronous machine we have seen before. Thus the DFM is effectively a synchronous machine in the absence of a stabilizer. Its low damping may lead to unstable operation for severely fluctuating torques.

Consider the introduction of frequency control of the rotor current vector (K_i being zero in our DFM torque equation). This results in:

$$J \frac{d\,\Delta f_m}{dt} + \left[\frac{1}{C} \right] \int \Delta f_m \, dt + \left[\frac{K_f}{C} \right] \Delta\, f_m = \Delta Tm \qquad \textbf{(5.13)}$$

Here we see that the introduction of rotor current frequency control has resulted in the addition of a damping factor which provides the damping for the DFM. We note that the natural frequency of oscillation, a function of the first two terms, "J" and "C", of the system is not affected.

The same torque equation can be studied for the presence of only rotor current amplitude control:

$$J \frac{d\,\Delta f_m}{dt} + \left[\frac{1}{C} + \frac{K_i}{C\,i_r} \frac{d\,\Delta f_m}{dt} \right] \int \Delta f_m \, dt + \left[\frac{K_i}{C\,i_r} \frac{d\,\Delta f_m}{dt} \right] \Delta\, f_m = \Delta Tm \tag{5.14}$$

In this case we note that the natural frequency of the system is subject to change and also the damping depending on the rate of change of mechanical frequency or engine speed. We note that the change in natural frequency, assuming a small rate of change in frequency, does not adversely affect our control. This is because the corner frequency of the bandpass filter is set at 20Hz, whereas the natural oscillation frequency of the VSG system will vary a little about the 2Hz normal system oscillation frequency .

We can also see that the damping can be positive or negative with rotor current amplitude control. If the rate of change of speed is positive the damping increases, thus preventing large oscillations. If the rate of change of speed is negative the damping decreases, but this has practically not been found to be detrimental to the operation of the stabilizer.

Thus from the above equations we can conclude that rotor current frequency control introduces a constant damping in the system whenever there is a change in system speed whereas rotor current amplitude control introduces a damping and a change in system natural frequency of oscillation only when the system is undergoing a change in speed.

These conclusions can clearly be seen in the experimental results obtained in the next chapter.

5.7 Digital Band Pass Filter Design

This is required to filter the input speed signal from the engine-generator set. The band pass filter removes all frequencies above and below the system oscillation frequency.The system has been found to oscillate with a frequency of about two hertz. For control implementation it was theoretically found that in order to produce the required damping effect the rotor current amplitude and frequency need to vary proportional to the rate of change of the engine speed. This being a differential term calls for the filter to also incorporate a 90 degree lead in to the filtered signal. In order to incorporate this phase change besides filtering the unwanted frequencies the corner point of the bandpass filter was set at 20Hz. That is a decade above the system oscillation corner frequency of 2Hz. And hence the filter is also able to provide a phase shift.

The band pass filter was designed as a combination of a high pass filter and a low pass filter. The band pass filter transfer function is given in Fig. 5.6. It can be seen that the filter consists of two blocks. The first block corresponds to the low pass filter section and has a corner frequency of f_1 Hertz. The next block corresponds to the high pass filter section and

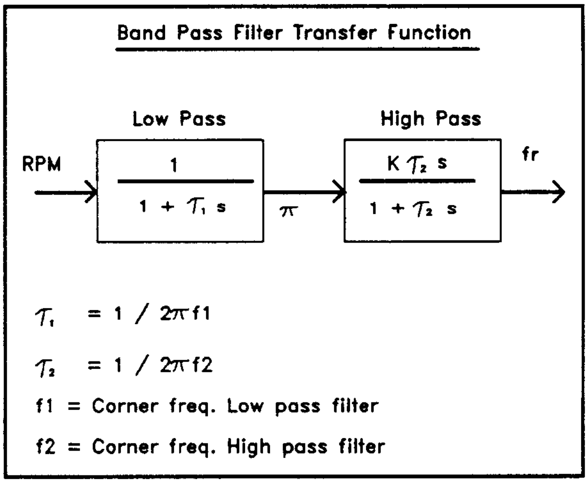


Fig. 5.6 Filter - Transfer Function

corresponds to a corner frequency f_2 Hertz. In order for the filter to function as a band pass filter f_1 must be greater than f_2. The magnitude and phase logarithmic plots corresponding to this transfer function is given in Fig. 5.7. We notice that the low pass filter gives rise to a phase shift of -90 degrees for frequencies much larger than f_1 and the high pass filter gives rise to a phase shift of +90 degrees for frequencies much smaller than f2. As a result at our frequency of interest, that is the oscillation frequency of the system f_{osc} (2Hz), the filter introduces the required phase shift of 90 degrees when f_1 and f_2 are maintained at the same corner frequency of 20Hz. One of the disadvantages of using the band pass filter to introduce the phase shift is that the gain of the filter is reduced near the frequency of oscillation of the system. But this is rectified by increasing the filter gain so that an appreciable error signal occurs at the oscillation frequency of the system. Since the high frequency signals to be filtered are much larger than 20Hz the maximum gain that will occur at that point is not detrimental to the stabilizer. This method has been adopted because of the simplicity of its digital implementation.

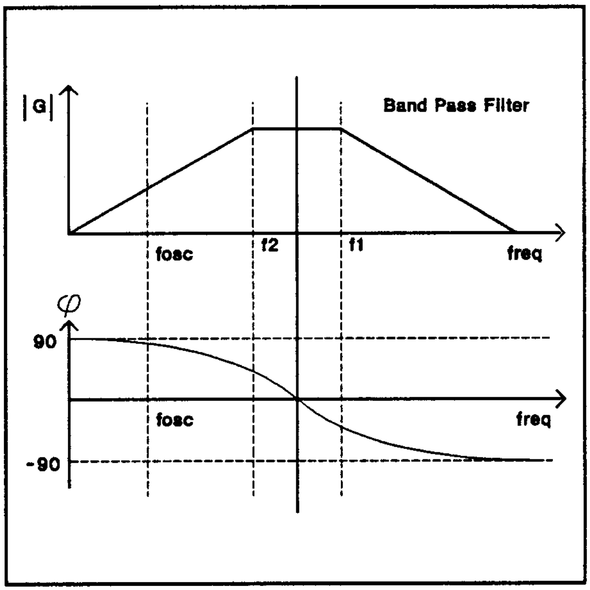


Fig. 5.7 Filter - Magnitude Phase Plot

The derivation of equations used for the implementation of the filter transfer function is given below:

If x(s) is the input and y(s) is the output of the band filter then the transfer function of the filter is given by:

$$y(s) = \left(\frac{1}{1 + \tau_1 s} \right) \left(\frac{k\, \tau_2 s}{1 + \tau_2 s} \right) x(s) \qquad \textbf{(5.15)}$$

let:

$$y_1(s) = \left(\frac{1}{1 + \tau_1 s} \right) x(s)$$

$$y_2(s) = \left(\frac{k\, \tau_2 s}{1 + \tau_2 s} \right) y_1(s) \qquad \textbf{(5.16)}$$

$$y(s) = y_2(s)$$

or:

$$y_1(\,t\,) + \tau_1 \frac{dy_1(\,t\,)}{dt} = x$$

$$y_2(\,t\,) + \tau_2 \frac{dy_2(\,t\,)}{dt} = k\, \tau_2 \frac{dy_2(\,t\,)}{dt} \qquad \textbf{(5.17)}$$

It can be shown that a discrete representation of:

$$x = \frac{dy}{dt} \qquad \textbf{(5.18)}$$

is:

$$x_n + x_{n-1} = \frac{2}{\Delta T} (y_n - y_{n-1}) \qquad \textbf{(5.19)}$$

Therefore substituting for x, y_1 and y_2 in equation **5.17** the relevant discrete terms we get the following equations:

$$y_{1n} = \frac{(x_{1n} + x_{1n-1})}{1 + \frac{2\,\tau_1}{\Delta T}} - y_{1n-1} \left(\frac{1 - \frac{2\,\tau_1}{\Delta T}}{1 + \frac{2\tau_1}{\Delta T}} \right) \qquad \textbf{(5.20)}$$

$$y_{2n} = (y_{1n} - y_{1n-1}) \left(\frac{k \frac{2\,\tau_2}{\Delta T}}{1 + \frac{2\,\tau_2}{\Delta T}} \right) - y_{2n-1} \left(\frac{1 - \frac{2\,\tau_2}{\Delta T}}{1 + \frac{2\tau_2}{\Delta T}} \right) \qquad \textbf{(5.21)}$$

The above equations represent the final form of the filter representation in digital terms. The time period of each filter loop is given by ΔT, this should be chosen to be sufficiently small compared to the time constants τ_1 and τ_2 for the filter to effective. The gain of the band pass filter is determined by k.

The above filter has been digitally implemented in real time and is found to work satisfactorily with τ_1 and τ_2 set to 8 milliseconds, (i.e. both corner frequencies set to 20Hz.) with the time period ΔT of the filtering loop at 5 milliseconds.

6. IMPLEMENTATION OF THE STABILIZER

The development of the hardware and software required for implementing the stabilizer is discussed in this chapter. Given the complexity of the hardware and software it will only be possible to give a brief overview of the overall system implementation. We shall note some of the critical features of the software used to implement the controller of the VSG system. Besides the actual control the system needed the development of hardware and software for protection and diagnostics in case of system faults. Some of the important features incorporated for the purpose will be outlined. Several miscellaneous features which enable the safe and reliable operation of the system have been included in the controller program and they will be listed.

A brief overview of the software structure, software characteristics and the hardware implementation of the controller is also described with reference to the stabilizer.

6.1 VSG System Control Features

We have discussed in detail the stability of the VSG system. The stabilizer developed actually forms a small part of the overall VSG control system. Some of the important control features that are incorporated in this fairly complex system will be discussed in this section.

(a) Digital filter implementation:

The measured RPM signal is filtered to remove noise using a bandpass filter. The bandpass filter is a combination of a low pass and a high pass filter. The filter has user definable corner frequencies and gain. The filter output is used by the stabilizer for rotor current amplitude and frequency control. The filter is implemented in a 5 millisecond software timer interrupt driven control loop. As described in chapter 5 this is necessary to keep the sample time of the filter constant. The gain and time constants of the filter can be set using the display keypad or by means of a personal computer.

(b) RPM measurement:

A pulse tachometer mounted on the DFM shaft is used for measuring RPM. It has a resolution of 240 pulses per revolution of the engine shaft. The 80C196 microcontroller has a high speed input (HSI) port and a free running 16 bit timer which increments every 1.6 microseconds. The HSI port was programmed to record the timer value when a pulse occurred and generate a software interrupt. The timer values are then used to calculate the RPM of the engine. The system has a measurement accuracy of +/- 0.013 % at 6000 RPM.

This measured RPM signal is used for stabilizing the system, for overspeed protection in case the system loses synchronism and also displayed on the user interface.

(c) Automatic startup:

The VSG system controller has the capability for automatic startup and synchronization with the grid. When the RUN command is given it carries out a series of tests to check the system hardware. It next starts the engine if it is not running. It then closes the series resonant converter input and the DFM rotor (SRC output) contactors. The controller, by varying the rotor current amplitude, increases the output stator voltage of the DFM to match the grid voltage in magnitude. It also sets the rotor current frequency to a preset value. The engine speed is then changed by controlling the throttle position so that the frequency of the voltage in the stator matches the grid frequency. We note that the frequency of the stator voltage is the algebraic sum of the rotor current frequency and the frequency corresponding to engine speed. There is a synchronizer board that gives a "SYNC" signal when the stator and grid voltages have the same magnitude, frequency and phase. After sensing this the stator contactor is closed. The system is thus synchronized to the grid and automatic startup is complete.

(d) Real power - P control

The total power output from the VSG system is the sum of the power output from the DFM (stator power) and the converter (rotor power). The reference value of the total power to be generated by the system is set by the user. The system has also to develop a set stator power. Keeping the reactive power developed by the DFM constant (by varying the rotor current) the controller first varies the throttle position by activating the stepper motor to develop the set stator power. Next the required reference total output power is developed by varying the engine speed (by varying the rotor current frequency). Closed loop feedback of total power output and stator power is used to maintain the reference values.

(e) Reactive power - Q control

The system has to develop a set reactive power. The reactive power to be developed by the DFM is set by the user. As noticed by studying the circle diagram for constant rotor current in chapter 4, the reactive power can be kept constant by varying the rotor current amplitude as stator real power output varies.

Stator reactive power is directly sensed by a power transducer and closed loop control is used to maintain the reference value.

(f) Rotor current amplitude and frequency control:

The rotor current amplitude is a seven bit analog (0-10v) signal sent by the VSG controller to the SRC external amplitude input terminal. The frequency signal has a resolution of 10 bits. A seven bit analog signal combined with a 3 bit digital signal. This was necessary because it is difficult to transfer a 10 bit analog signal accuracy. Incorporated in the software are rotor current amplitude and frequency gain parameters which control the magnitude and phase change of the rotor current vector.

6.2 VSG System Protection Features

Several fault detection, diagnostics and protection features have been incorporated into the VSG system. Most of these are in software and a few in hardware. The engine and the DFM form the moving parts of the system. The engine can operate upto speeds of 3600 RPM during power generation. A loss of synchronism at this speed can occur. This will result in dangerous overspeeding.

Damage to both the engine and the DFM is probable. Measures have been taken to detect loss of synchronism or overspeeding of the system in advance. An appropriate safe and orderly shutdown of the system for different kinds of faults has been incorporated into the system software and hardware.

VSG SYSTEM PROTECTION FEATURES	
FAULT CONDITION	**DESCRIPTION**
Engine Fault	This refers to unsafe engine conditions such as engine over temperature.
Engine Overspeed	This is to protect the system in case of engine overspeed resulting from, say, loss of synchronization with the grid.
Throttle Control Failure (Stepper Motor)	In case the throttle of the engine does not respond to a control signal.

Rotor / Stator Contactor Failure	These contactors are controlled by software, if they fail to respond during the startup, runtime, protection or shutdown process of the VSG system.
Power Supply Under / Over Voltage	The Controller System Power Supply has to be maintained within certain limits. This protection has been incorporated both in hardware and software. (+5volt, +/- 12 volt)
Grid Under / Over Voltage	The system needs to be protected during grid under voltage and over voltage conditions and a safe shutdown is necessary.
System Overload (Over Current Limit)	In case the rated system currents are exceeded.
Battery Backup Memory Failure	Several of the system settings such as gain parameters, preset operating points etc. are stored in static RAM. Corrupt data could damage the system.
Controller Hardware Failure	A failure of the controller hardware should not damage the system. A method of determining hardware failure and then to shutdown the system in an orderly fashion was incorporated.
Controller Software Failure	A watchdog timer is used to detect a bug in the software which may cause the system to "hang". Under this situation the system undergoes an orderly shutdown.

6.3 Miscellaneous Features

The user interface to the VSG system has been made quite versatile. The user can study the variation of system variables on the displays while it is running. Changes to system parameters can be made at runtime. This enables the fine tuning of the system for better performance. User default parameters can be stored in static RAM for later reference. These and other helpful features are listed in the table below.

VSG CONTROLLER - Miscellaneous Features	
FEATURE	**DESCRIPTION**
Fault Diagnosis with Fault History	A history of the sequence of fault occurrence can give a clue as to the cause of a system shutdown.
Power Supply Self Calibration for Protection	The system control electronic power supply is critical. The system has the capability to self calibrate its power supply and then protect itself under over and under voltage conditions.
User Calibration of System Variables at Runtime	The system variables such as power, current, voltage, RPM etc. need to be calibrated for an accurate display of measured values and also for control purposes. This can be done during runtime.
User Definable Default Values for System Variables	These values are stored in static RAM. Operating points for automatic system startup, filter corner frequencies and gain are some of the parameters that can be user defined.
Recallable Factory Default Settings	Preset factory values used for system operation.
Password Protection for System Variables	A system of protection for system variables so that unauthorized or unqualified personnel are not able to access and change critical system parameters.
User Definable Analog Inputs	(0-5v, 0-10v, 0-20ma) Analog Inputs. System control from a remote source is possible.
Maximum and Minimum Limits for System Variables	Factory defined, these contain maximum and minimum limits for system variables for system safety purposes.
RPM Ramp Control	Controlled change in system speed because of inertia considerations.

6.4 VSG System Software Structure

The software for the VSG system can be organized into specific functional blocks. Upon power up or reset the system performs initialization functions. The controller runs a selftest on the digital hardware as well as the VSG system hardware. When the RUN command is given the system performs automatic startup and synchronizes to the grid. In the run mode, after synchronization, the stabilizer, P - Control and Q - Control become activated. On the STOP command the system performs a normal shutdown. The fault detection, measurement, RS232 communication, keypad and display monitoring functions of the system are functional at all times. In case a fault is detected the system takes action as warranted by the fault. The system software structure is outlined below. Fig. 6.1 represents the flowchart of the system software program. **Table I** shows the software development environment for the VSG controller.

SOFTWARE STRUCTURE

INITIALIZATION FUNCTIONS

- Microcontroller Initialization
- Hardware / Software Selftest
- VSG System Selftest
- VSG System Initialization

STARTUP FUNCTIONS

- Automatic Startup
- Automatic Grid Synchronization
- Fault Diagnosis / Protection

STOP MODE FUNCTIONS

- Display / Keyboard Monitoring
- Fault Diagnosis / Protection
- Measurement
- RS232 Communication
- Series Resonance Converter Control

RUN MODE FUNCTIONS

- CONTROL
    1. Series Resonance Converter Control
    2. Stabilizer (Rotor Current Frequency and Amplitude)
    3. Q - Control (Rotor Current Amplitude)
    4. P - Control (Throttle Position)
    5. Efficiency Maximization
- Display / Keyboard Monitoring
- Fault Diagnosis / Protection
- Measurement

- RS232 Communication

SHUTDOWN FUNCTIONS

- Normal System Shutdown
- Emergency Shutdown
- Display of System Status
- Fault Diagnosis

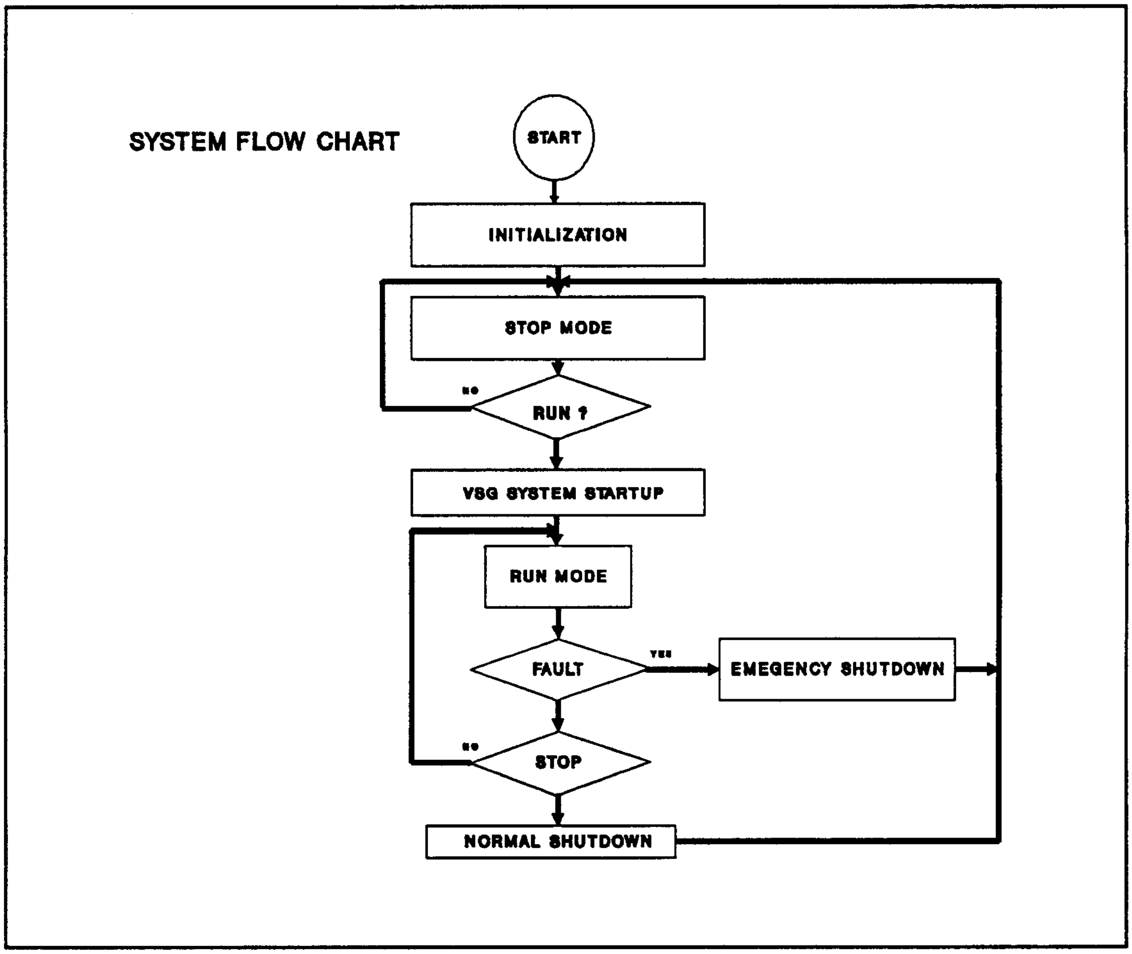


Fig. 6.1 VSG System Flowchart

Table I SOFTWARE DEVELOPMENT ENVIRONMENT

PROGRAMMING LANGUAGES USED

- 'C'
- ASSEMBLY LANGUAGE

OPERATING SYSTEM

- DEVELOPED AT E.P.C.

DEVELOPMENT ENVIRONMENT

- INTEL 80C196KB EMBEDDED CONTROLLER IN CIRCUIT EMULATOR
- iPLDSII INTEL PROGRAMMABLE LOGIC DEVELOPMENT SYSTEM
- INTEL 80196 C COMPILER
- INTEL 80196 ASM ASSEMBLER
- TURBO C FOR PC BASED APPLICATIONS
- TURBO ASM ASSEMBLER
- TURBO DEBUGGER

6.5 VSG System Controller Hardware Structure

The controller hardware architecture is as shown in Fig. 6.2. It consists of the supervisory (SPV) board which contains the 80C196 microcontroller. This is linked to the personal computer through an RS232 serial port and the keyboard and display. These form the user interface to the controller. The SPV board connects to the application controller (APC) board. The APC board is linked to the voltage and current sensing (VCS) board. The VCS board gets the stator voltage and current signals. The APC board is also linked to the VSG signal processing board which communicates with the converter and the external VSG system. The SPV board also directly interfaces with the contactors and servers as an input point for fault signals. A detailed explanation of the function of each of these boards is given below. **Table II** lists the hardware resources available in the VSG controller.

(a) Supervisory (SPV) board:

The SPV board is the heart of the VSG controller. It has the 80C196 microcontroller. It is driven by a 12MHz crystal and operates on an 8Bit bus. It has 32K of EPROM memory and 8K of static RAM. The 24K controller program is burned into the EPROM. It has a RS232 serial port for communication with an IBM PC AT computer. The microcontroller communicates with external I/O devices through memory mapped I/O. It has six digital inputs, four open collector digital outputs, four user programmable analog inputs (0-5V, 0-10V and 0-20mA) and a variety of special purpose inputs and outputs. All inputs and outputs are protected by MOV's, diodes and fuses. Besides this the I/O capability of the SPV board can be increased by means of the APC board. The Keyboard and display interfaces to the SPV board. The 80C196 microcontroller has provisions for four high speed inputs which are used to detect fault conditions and also for sensing the RPM input pulses.

(b) Keyboard and Display:

This is a direct interface to the VSG system. User input to the controller is by means of twelve keys present on this board. Besides there are three liquid crystal displays. Two of these are 0.5" seven segment four digit LCD's and the third is a 16 digit character LCD. The seven segment LCD's are used to set the reference values of total power output and stator reactive power. The character LCD is used to display measured values and for setting system parameters.

(c) Application Controller (APC) Board:

The application board has a 16 channel analog multiplexer. This is used to multiplex the processed stator voltage and current signals coming in from the VCS board. It has an 8 bit output and an 8 bit input port. It also has an 8 channel digital to analog converter (DAC). The digital I/O ports and the DAC communicate with the VSG signal processing board. The APC board thus forms an extended interface between the SPV board and the external VSG system.

(d) Voltage and Current Sensing (VCS) Board:

The VCS board gets high voltage signals and current transducer outputs from the DFM stator. These signals are processed in the board and 0-10v signals are sent to the APC board. There is provision for seven high voltage inputs and six current inputs on the VCS board.

(e) VSG Signal Processing Board:

This board communicates with the converter by means of the 10 bit frequency signal, 7 bit analog signal, Run/Stop and Forward/Reverse signals. All the signals are buffered on this board. It also converts the 0-1mA current corresponding to the stator reactive and total power output signals to a 0-10V proportional signal for use by the SPV board for measurement. Both inputs are buffered. The stepper motor controller for the throttle control is mounted on this board. It also serves as an input point for RPM pulses, flowmeter pulses, DFM overtemperature, system "SYNC" and stepper motor limit switch signals.

Table II VSG SYSTEM HARDWARE RESOURCES

80C196KB MICROCONTROLLER

16 BIT ADDRESS BUS / 8 BIT DATA BUS

12 MHz CLOCK

8K RAM WITH ON CHIP BATTERY AND REAL TIME CLOCK

32K EPROM (EXPANDABLE TO 128K WITH MEMORY PAGING)

4 HIGH SPEED INPUT LINES LINKED TO INTERRUPT DRIVEN SOFTWARE

28 INTERRUPT SOURCES

10 BIT A/D CONVERTER WITH 26 ANALOG INPUT CHANNELS

4 GENERAL ANALOG INPUT LINES (0-5V, 0-10V, 4-20MA USER SELECTABLE)

40 DIGITAL INPUTS (16 PROTECTED WITH MOV'S & FUSES)

14 DIGITAL OUTPUT LINES (4 PROTECTED WITH MOV'S-FUSES)

WATCHDOG TIMER FOR SOFTWARE FAILURE PROTECTION

RS 232 SERIAL I/O (TESTED TO 19200 BAUD)

HARDWARE CIRCUIT FOR AUTOMATIC SYSTEM SHUTDOWN

POWER SUPPLY UNDER / OVER VOLTAGE DETECTION CIRCUIT

6.6 Stabilizer Hardware and Software Specifics

There are certain characteristics of the VSG system specific to the implementation of the stabilizer and these are detailed below:

(a) The system sends the rotor current amplitude control signal to the converter by means of a 10V analog signal which is interpreted after A/D conversion to 7 bits of accuracy.

This means that the amplitude signal has a resolution of 1 in 128, or in current amplitude terms, 0.7 amperes per bit.

(b) The frequency signal transmitted to the converter to control the rotor current frequency has a total accuracy of 10 bits. Of these the lower 7 bits are transmitted as a 10V analog signal and the top 3 bits are transmitted as digital signals. This is because in industrial environments, because of noise, it is not practical to transmit analog signals which are able to give greater than 8 bits of accuracy. This gives a frequency resolution of 1 in 1096. With a frequency range of 0 to 94 hertz this corresponds to a resolution of 0.1Hz per bit.

(c) The filter loop, though it is executed once every 5 ms, has an actual execution time of 2ms. The remaining time is utilized in processing other tasks by the microcontroller.

(d) RPM is measured by measuring the time periods of the pulses given by the pulse tachometer. Using interrupt driven measurement logic an accuracy better than 0.013% in the 100 RPM to 6000 RPM range can be obtained. Time periods of these pulses can be measured to an accuracy of 1.333 μs.

(e) For maximum control speed, part of the stabilizer logic has been implemented in the interrupt driven loop and the rest in a slower outer loop.

(f)In order to take care of torque pulsations due to the four stroke automobile engine the average RPM is measured once every two revolutions, wherein all the four cylinders have undergone one complete cycle of operation.

(g) In order to operate the intel 80C196KB embedded microcontroller at its maximum capacity the system board was modified to execute the software with zero wait state for memory access.

7. EXPERIMENTAL RESULTS

The stabilizer was incorporated into the VSG system and tested. The theoretical nature of the stabilizer and its hardware implementation have been covered in previous chapters. The various results obtained and a discussion about their implications are covered in this chapter. The results obtained are shown in the form of photographs taken from a digital storage oscilloscope which recorded the waveforms while the system was under operation. Various modes of operation of the system have been recorded and a description plus the relevant photographs are given in the sections below.

7.1 System settings for experimental results

The following system settings were maintained while the experimental results were obtained:

1.	RPM	1520
2.	Stator Power Output	18 KW
3.	Total Output Power	11 KW
4.	Stator Reactive Power	3 KVAR
5.	RPM Filter Corner Frequency	20 Hz
6.	Stabilizer Amplitude Gain	3.00
7.	Stabilizer Frequency Gain	3.00

7.2 Loss of Stability

In the absence of a stabilizer the system habitually loses synchronism with the grid. It is the task of the stabilizer not only to prevent this occurrence but also to prevent large system oscillations, both mechanical and electrical. Fig. 7.1 and Fig. 7.2 show the loss of synchronism in the system.

In Fig. 7.1 the stabilizer is removed at the beginning of the RPM (speed variation of the system) waveform. We see that the system oscillations begin. In Fig. 7.2 these oscillations continue to increase in magnitude till the system loses synchronism. We thus note the need for a stabilizer.

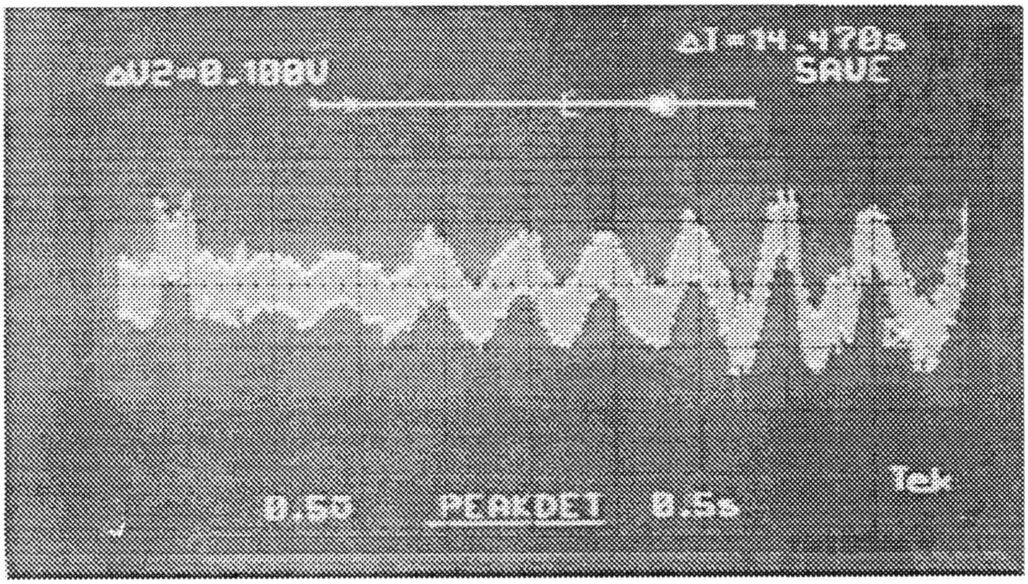


Fig. 7.1 Loss of Stability, Part 1

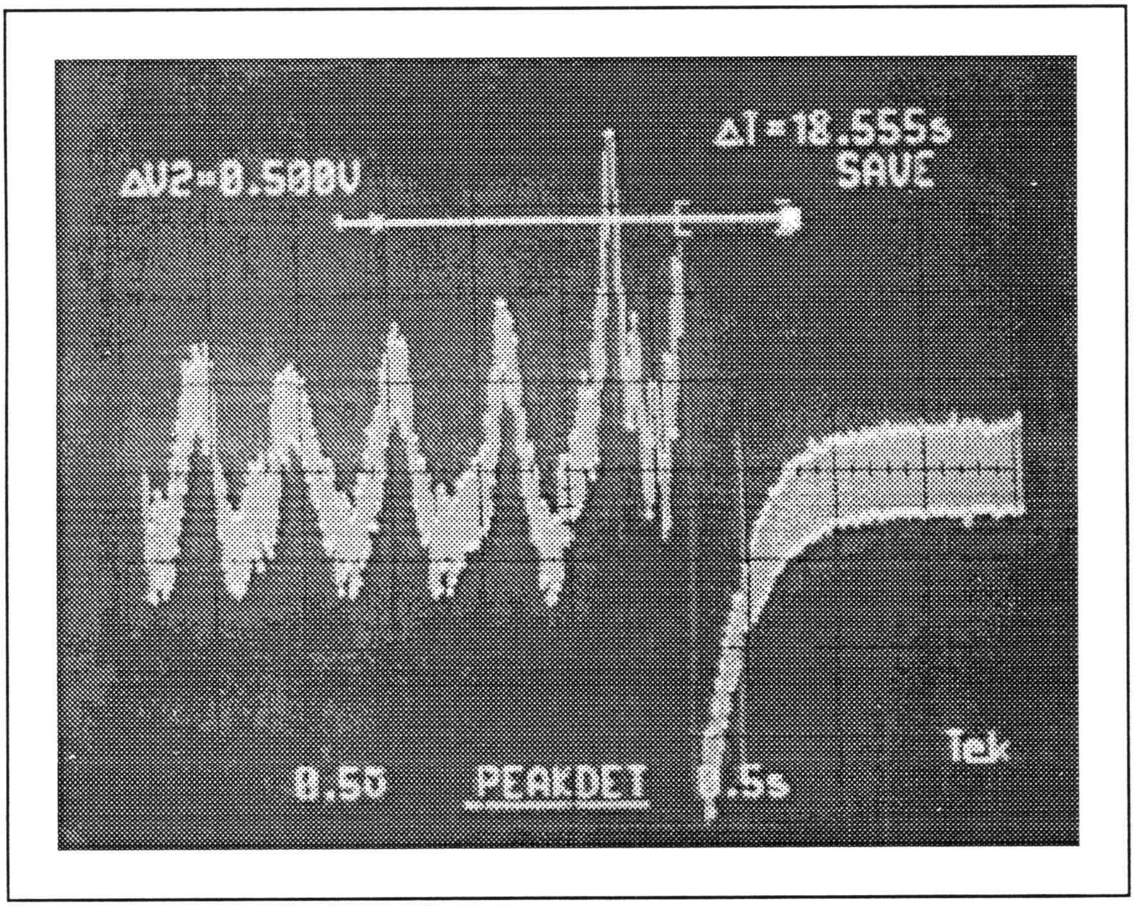


Fig. 7.2 Loss of Stability, Part 2

7.3 Effect of the Digital Filter

The digital band pass filter has to introduce a phase shift of 90 degrees on the measured RPM signal. In the Fig. 7.3, the input RPM signal is displayed in the top trace and the filtered signal with a phase shift of approximately 90 degrees is shown in the bottom.

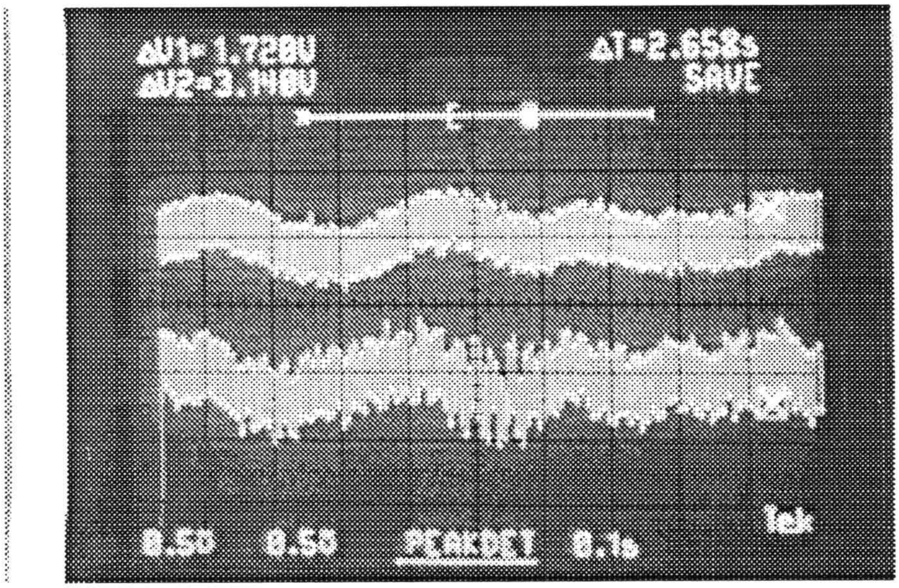


Fig. 7.3 Effect of the RPM Digital Filter

7.4 Effect of the Stabilizer on the VSG system

The effect of the stabilizer on the following VSG system variables is considered:

(a) Engine RPM

(b) Stator Reactive Power

(c) Stator Real Power

The effect of the stabilizer on the VSG system is considered under the following three modes of operation:

(1) Stabilizer with rotor current frequency control (Original Stabilizer)

(2) Stabilizer with rotor current amplitude control (New Addition)

(3) Stabilizer with rotor current amplitude and frequency control

Photographs of each of the above VSG system variables in the three modes of operation of the stabilizer were taken and will be the subject of discussion in the following sections.

7.5 Effect of the Stabilizer on Engine Speed

In Figures 7.4a, 7.4b and 7.4c we see the effect of the stabilizer on engine RPM (mechanical speed) oscillations. All three figures contain the original oscillatory waveform, without the stabilizer, on the top and the waveform with the stabilizer at the bottom of picture.

Fig. 7.4a displays damped oscillations because of rotor current frequency control. In Fig. 7.4b we see the effect of rotor current amplitude on the RPM. The oscillations are damped and the system is oscillating with a smaller natural frequency compared to the original waveform on the top. This confirms our theoretical expectations. Fig. 7.4c shows the effect of both frequency and amplitude control of the rotor current vector. This shows a very stable RPM signal waveform. Thus we see that the addition of rotor current amplitude control has resulted in a very stable system and an improved stabilizer.

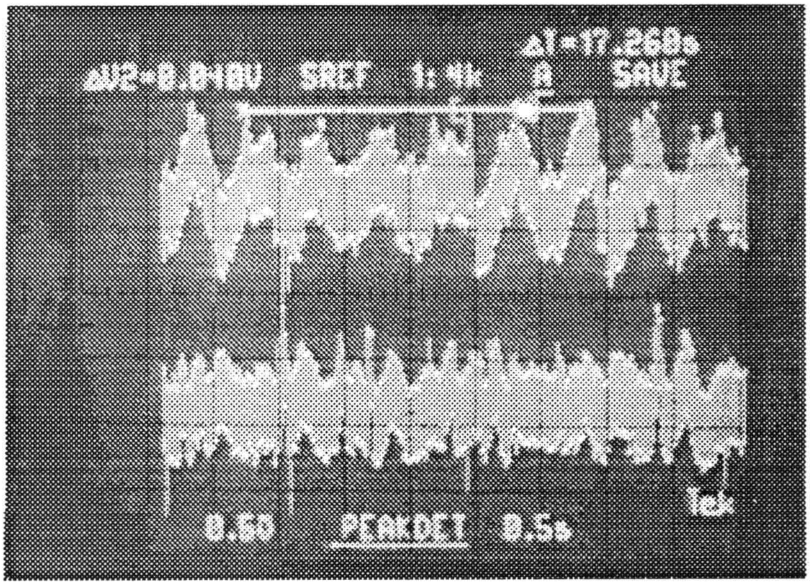


Fig. 7.4a Effect of Rotor Current Frequency Control on Engine RPM

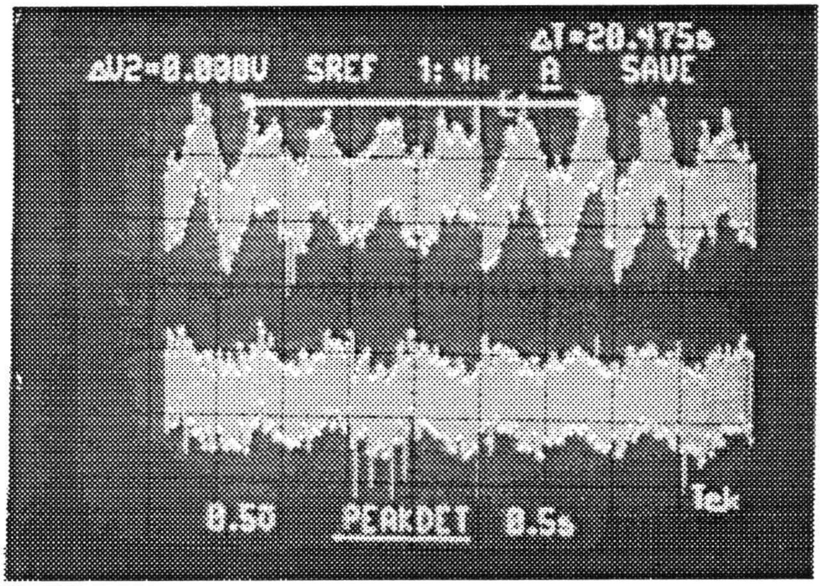


Fig. 7.4b Effect of Rotor Current Amplitude Control on Engine RPM

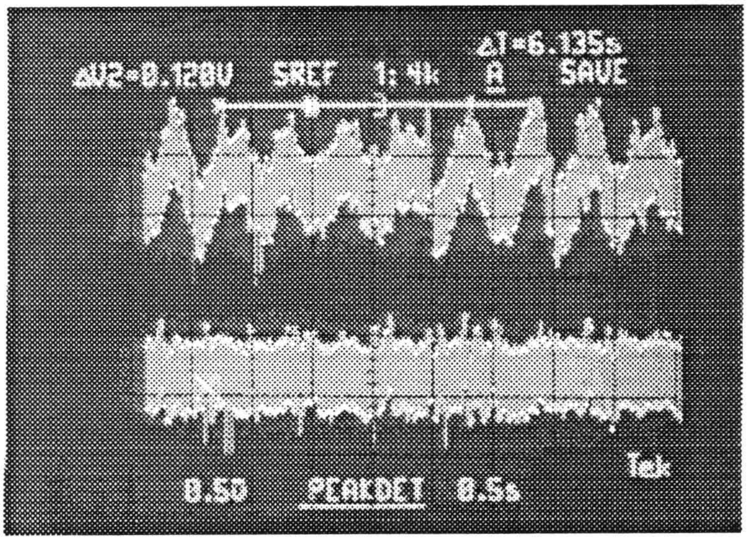


Fig. 7.4c Effect of Rotor Current Amplitude and Frequency Control on Engine RPM

7.6 Effect of the Stabilizer on Stator Reactive Power

In figures 7.5a, 7.5b and 7.5c we see the effect of the stabilizer on stator reactive power oscillations. All three figures contain the original oscillatory waveform, without the stabilizer, on the top and the waveform with the stabilizer at the bottom of picture. We note that the magnitude of oscillations of the original waveform is increasing and finally this would result in a loss of synchronism.

Fig. 7.5a displays damped oscillations because of rotor current frequency control. In Fig. 7.5b we see the effect of rotor current amplitude on the stator reactive

power. The oscillations are damped and the system is oscillating with a smaller natural frequency compared to the original waveform on the top. Fig. 7.5c shows the effect of both frequency and amplitude control of the rotor current vector. This shows a fairly stable reactive power signal waveform. Thus we see that the addition of rotor current amplitude control has again resulted in a very stable system and an improved response for reactive power control.

It must be noted that the control of stator reactive power is of particular importance because as the reactive power decreases (becomes negative) the torque angle increases and the system becomes unstable.

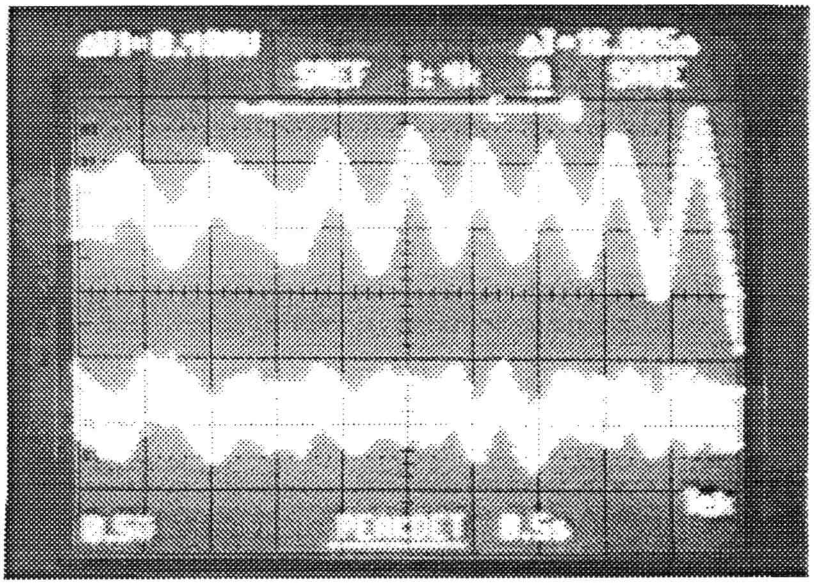


Fig. 7.5a Effect of Rotor Current Frequency Control on Stator Reactive Power

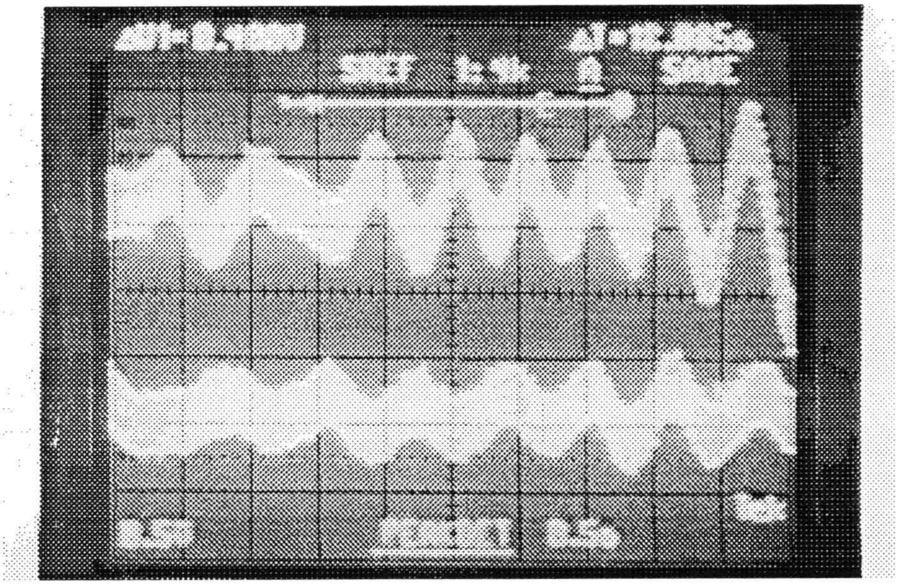


Fig. 7.5b Effect of Rotor Current Amplitude Control on Stator Reactive Power

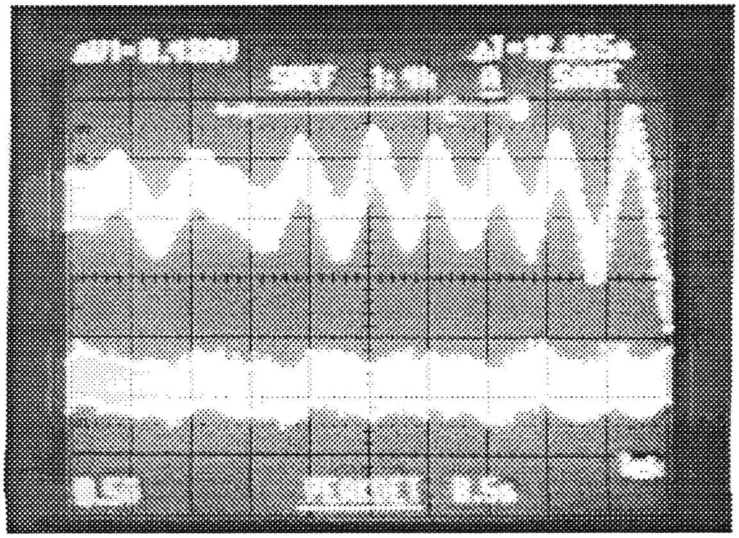


Fig. 7.5c Effect of Rotor Current Amplitude and Frequency Control on Stator Reactive Power

7.7 Effect of the Stabilizer on Stator Real Power

In figures 7.6a, 7.6b and 7.6c we see the effect of the stabilizer on stator real power oscillations. All three figures contain the original oscillatory power output waveform, without the stabilizer, on the top and the waveform with the stabilizer at the bottom of picture.

Fig. 7.6a displays damped oscillations because of rotor current frequency control. In Fig. 7.6b we see the effect of rotor current amplitude on stator real power. The oscillations are again damped. Fig. 7.6c shows the effect of both frequency and amplitude control of the rotor current vector. This shows a very stable real power output signal waveform. Thus we see that the addition of rotor current amplitude control has resulted in a very stable system and an improved stabilizer.

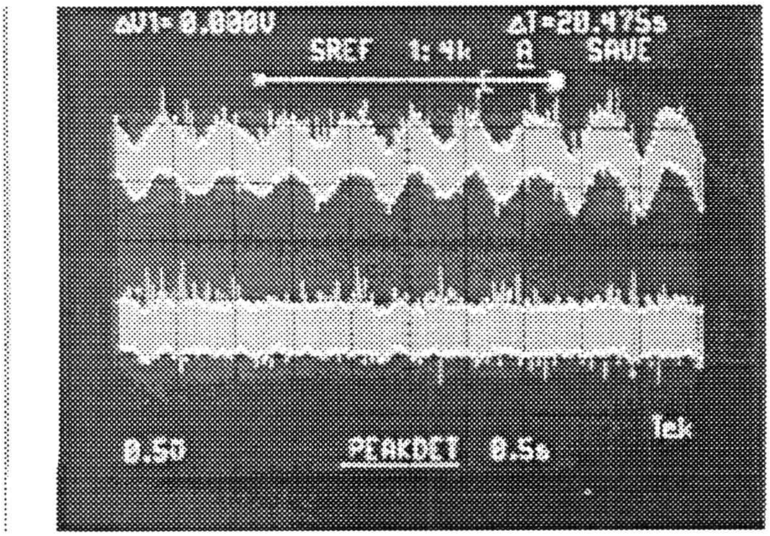


Fig. 7.6a Effect of Rotor Current Frequency Control on Stator Real Power

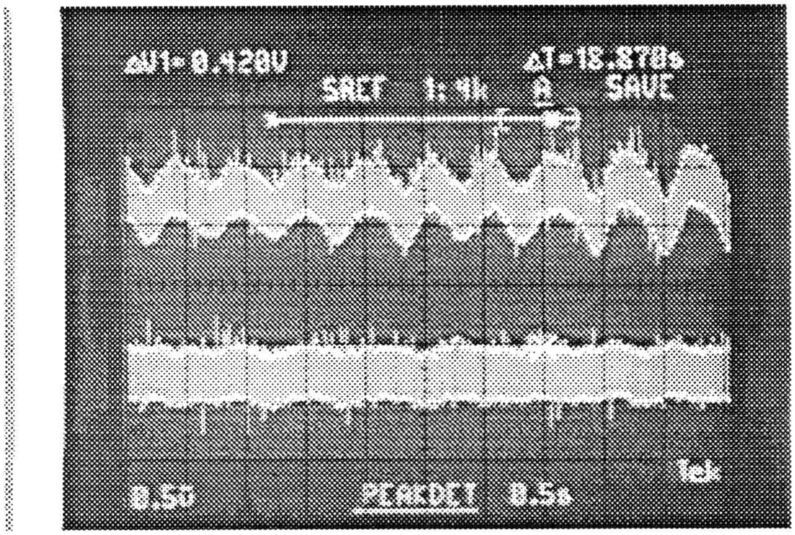


Fig. 7.6b Effect of Rotor Current Amplitude Control on Stator Real Power

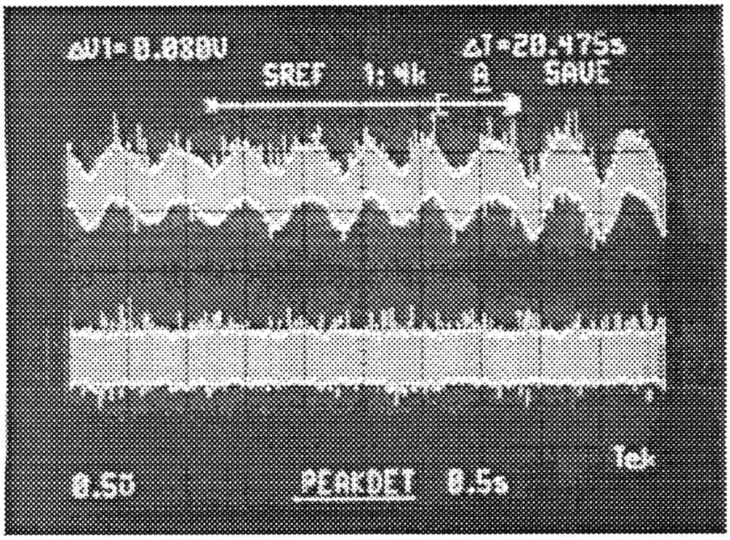


Fig. 7.6c Effect of Rotor Current Amplitude and Frequency Control on Stator Real Power

7.8 Effect of Rotor Current Amplitude Variation on Stator Current

It has been noted in previous chapters that if any variation in the energy balance of the VSG system is converted to a variation in electrical power then the need for the system to go into mechanical oscillations in order to maintain the balance by means of kinetic energy variations is removed. This naturally results in a system with little or no mechanical oscillations. The concept of rotor current amplitude control effectively performs this task. In Fig. 7.7a and Fig. 7.7b the top waveform is an indication of the variation in stator current without the stabilizer as the system finally loses synchronism. We see increasing oscillations until after losing synchronism the amplitude falls to zero.

The bottom waveforms are stator current waveforms with the rotor current amplitude control of the stabilizer. Fig. 7.7a shows the stator current envelope which is fairly stable. The point where the cursor is placed in Fig.7.7a on the stator current has been expanded in Fig. 7.7b to see the actual stator current waveform. We see that the stator current waveform is varying in magnitude at times and hence as per our expectation, maintaining the energy balance by electrical energy transfer.

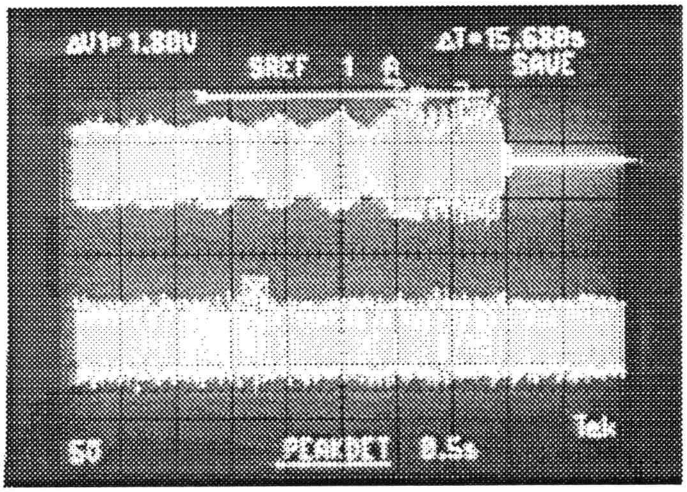


Fig. 7.7a Stator Current with Rotor Current Amplitude Control

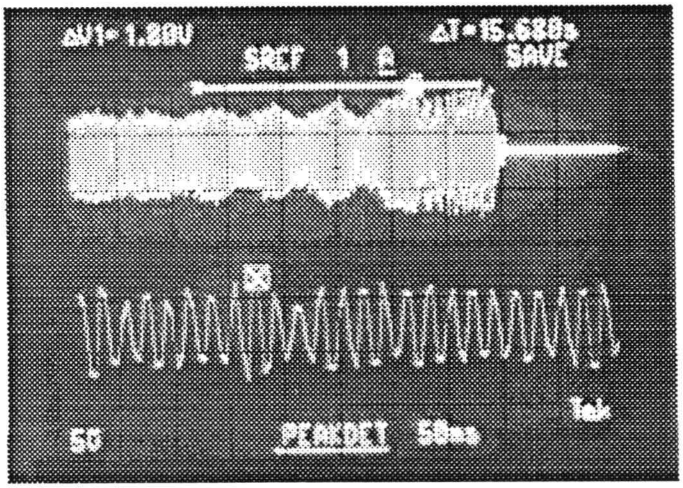


Fig. 7.7b Rotor Current Amplitude Control, Stator Current Variation

In conclusion it can be said that the experimental results agree with the theoretical predictions regarding the performance of the stabilizer. Our intuitive expectation that the variation of rotor current amplitude would result in a better stabilizer has also been proved to be right. The system now produces a bounded output for a bounded input.

The combined use of both frequency and amplitude control of the rotor current vector has yielded better results. The variable speed generation system is now stable through the operating range (1200 RPM to 3600 RPM). This stabilizer can thus be used on similar VSG systems to improve their bounded input bounded output (BIBO) stability. The corner frequency of the bandpass filter, the rotor current amplitude and frequency gains may have to be changed.

8. CONCLUSIONS

In this dissertation a conscious attempt has been to apply the principles of electrical engineering to solve a practical problem. The variable speed generation system had problems of stability which was resulting in loss of synchronism. This problem had to be solved if the system was to be of any practical use in industry.

After careful observation the reasons for the stability problem were deduced. Once the causes were clearly understood the various system components were studied along with their characteristics so as to adopt a viable strategy for stabilizing the system.

The generator, a doubly fed machine, was noted to be the critical component. By control of this component the system could be stabilized. Given a clear understanding of the nature and causes of system oscillations, it was determined that the system could be stabilized by controlling the rotor current vector.

There was, thus, the need to build a suitable stabilizer to do the job. The engine speed signal was used as the feedback variable since this characterized the system oscillations. Given the hardware and software limitations of the controller, a simple but effective means for controlling the rotor current vector was developed. After a careful study of several direct and indirect vector control schemes an innovative method for indirect vector control of the rotor current vector was implemented. Initially the phase of the rotor current vector was controlled. As part of the improved stabilizer the rotor current amplitude was also controlled.

This procedure has resulted in an effective stabilizer for the variable speed generation system. As can be seen in the results of the previous chapter, significant reduction in the magnitude of the system oscillations has resulted. The problem of the system losing synchronization has been solved. The system exhibits stable operation over the entire operating range. The system is bounded input bounded output (BIBO) stable.

The objectives of this dissertation have been met. We note that an intuitive understanding of the engineering problem has helped in the development of a simple original idea for solving the problem.

8.1 Scope for Future Improvement

During the development of the current stabilizer several critical factors were noted and these are listed below. Improvement in stabilizer performance will be obtained if these factors are kept in mind for future designs.

(a) The filter operates on a 5 millisecond control loop. As the time period of the control loop is reduced the performance of the filter improves. A faster control loop would enhance stabilizer performance.

(b) 16 bit integer computations have been used. 32 bit integer or floating point computation would improve the control.

(c) The rotor amplitude signal is controlled with an analog signal with an effective resolution of 7 bits. This could be increased to 10 bits for better resolution.

(d) A well balanced engine should inherently lead to a more stable system.

(e) A strategy for automatic variation of stabilizer gains so as to give an optimal stabilizer at all operating points would further improve stabilizer performance.

(f) Some of the vector control strategies discussed yield direct methods of controlling the rotor current vector. But it is to be expected that, while the performance may be better, these methods are much more cumbersome and expensive to implement.

BIBLIOGRAPHY

[1] C. Concordia, S.B. Crary and C.Kron: "The Doubly Fed Machine", AIEE Transactions, Vol. 61, p. 286, 1942.

[2] H.K.Lauw: "Characteristics of the Doubly Fed Machine in a Hydro Variable Speed Generation System", Final Report, USDOE Bonneville Power Administration Contract No. 79-85BP24332, June 1986.

[3] W.B. Gish, J.R.Schurz, B. Milano and F.R. Schleif: "An Adjustable Speed Synchronous Machine for Hydroelectric Power Applications", IEEE Transactions on PAS, Vol. PAS-100, p. 2171, May 1981.

[4] M.M. Liwschitz: "Damping and Synchronous Torque of the Doubly Fed Asynchronous Machine", AIEE Transactions, Vol. 60, p. 923, 1941.

[5] H.K. Lauw and Sheela Krishnan: "Control Aspects of the Brushless Doubly Fed Machine", Final Report, USDOE Bonneville Power Administration Contract No. 79-85BP24332, MOD-6, Sept. 1990.

[6] R. Gabriel, W. Leonhard and C.J. Nordby: "Field Oriented Control of a Standard AC Motor Using Microprocessors", IEEE Transactions on Industrial Applications, Vol. IA-16, No. 2, pp 186-192, 1980.

[7] S.Sathiakumar and Joseph Vithayathil: "Digital Simulation of Field Oriented Control of Induction Motor", IEEE Transactions on Industrial Electronics, Vol. IE-31, No. 2, pp 141-148, 1984.

[8] R.Krishnan and Frank C. Doran: "Study of Parameter Sensitivity in High-Performance Inverter-Fed Induction Motor Drive Systems", IEEE Transactions on Industrial Applications, Vol. IA-23, No. 4, pp 623-635, 1987.

[9] Philip L. Alger: "The Nature of Polyphase Induction Machines", John Wiley & Sons Inc., 1951.

[10] John Hindmarsh: "Electrical Machines and their Applications", Pergamon Press, 1984.

[11] Irving L. Kosow: "Control of Electric Machines", Prentice Hall, 1973.

[12] Intel: "16-Bit Embedded Controller Handbook", Reference Manual by Intel Corporation, 1989.

[13] H.K. Lauw: "Doubly Fed Generator Variable Speed Generation Control System", U.S. Patent No. 4,994,684.

[14] H.K. Lauw, J. Ben Klaassens, Nicholas G. Butler and Douglas B. Seely: "Variable Speed Generation with the Series Resonance Converter", IEEE Transactions on Energy Conversion, Vol. 3, No. 4, pp 755-764, Dec. 1988.