AN ABSTRACT OF THE THESIS OF

Sheela Krishnan for the degree of Master of Science in Electrical and Computer Engineering presented on October 1, 1990.

Title: Digital Stabilizer For Brushless Doubly-fed Machine.

Abstract approved: Redacted for Privacy

Roy Rathja

The exceptional feature of the brushless doubly-fed machine is the lack of need for frequent replacement of brushes. The inherent instability of this machine has to be overcome for its application in adjustable speed drives and variable speed generation systems.

Specific objectives were:

- to study the characteristics of the machine pertinent to its application in adjustable speed drives and variable speed generation systems.
- to develop a stabilizer depending on the nature of the instability.

The brushless doubly-fed machine was found to be unstable over much of the useful operating range. A digital feedback control was implemented using a combination of hardware and software elements, to stabilize the machine. The feedback

system was a band pass filter. The software was developed with a processing time fast enough to match the speed of response required by the stabilizer to overcome the unstable oscillations.

The performance of the machine was compared with and without the stabilizer to test its effectiveness. Stable operation was achieved over the entire operating region.

Digital Stabilizer
for Brushless Doubly-fed Machine

by

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A THESIS

submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of
Master of Science

Completed October 1, 1990
Commencement June 1991

APPROVED:

Redacted for Privacy

Associate Professor of Electrical and Computer Engineering in charge of major

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Date thesis is presented October 1, 1990

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ACKNOWLEDGEMENTS

I wish to express my gratitude and appreciation to my professors Dr. Hian K. Lauw and Dr. Roy Rathja for their guidance and encouragement. I would also like to thank my committee members Dr. David Griffiths and Dr. Patrick Lenders for their advice and comments.

I appreciate all the help and support given by my friends and the faculty and staff of the Department of Electrical and Computer Engineering at Oregon State University. I would like to express my appreciation to my husband, Rajeev for his help and encouragement. Lastly, I wish to dedicate this work to my dearest father, Late P. N. P. Pillai.

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CHAPTER 1

INTRODUCTION

The design of a brushless doubly-fed machine is based on the configuration of the single frame cascade induction machine invented by J. L. Hunt [1] in 1907. The rotor of the machine is of the squirrel cage type and does not require windings or slip rings. This is an outstanding feature resulting in low maintenance requirements as well as low manufacturing cost. The stator windings are configured as two three-phase systems. The same windings are used for the two systems. This is another exceptional feature.

The brushless doubly-fed machine exhibits two modes of operation: the induction mode and the synchronous mode. Unlike other machines, the loss of the synchronous mode causes the brushless doubly-fed machine to enter the induction mode. Since machine efficiency in the synchronous mode is higher than that in the induction mode, this research was confined to synchronous mode only.

To operate in the synchronous mode one of the three-phase systems is directly connected to the electric power grid. The other three-phase system is connected to a power electronic convertor for the purpose of controlling the shaft speed. The machine is severely underdamped or completely unstable over much of the potentially useful speed range in this configuration.

Cook and Smith [2] proved that feedback control of a converter's output current will stabilize the operation of two induction machines connected on the same shaft when their rotors are connected to each other in opposite phase polarity. It can be expected that the single-frame doubly-fed machine studied in this thesis will exhibit similar characteristics.

1.0 Objectives

The objectives of this research are to study the nature of instability of the brushless doubly-fed machine and implement a digital feedback control to stabilize its operation. The digital feedback control system was used because of its flexibility of implementation and easy access to the parameters.

This dissertation is organized in six chapters. Chapter I is an introduction to the thesis. Chapter II introduces the design and control strategy of the brushless doubly-fed system. It also includes a review of work done by previous researchers in this area. In Chapter III the structure of the stabilizer for the brushless doubly-fed machine is discussed. The actual implementation of the control system, details of the hardware involved and the software developed are discussed in Chapter IV. The effectiveness of the stabilizer is verified in Chapter V. A summary of the research and suggestions for future work are presented in Chapter VI.

CHAPTER 2

CHARACTERISTICS OF BRUSHLESS DOUBLY-FED MACHINES

2.0 Introduction

The brushless doubly-fed machine exhibits characteristics different from those of conventional doubly-fed machines. These differences are due to the way in which excitation is applied to the machine. This chapter provides a brief overview of some characteristics of the brushless doubly-fed machine.

2.1 Design Aspects

The design of the brushless doubly-fed machine is based on the configuration of the single frame cascade induction machine invented by J. L. Hunt [1] in 1907. Hunt's work [1] was discussed in more detail and presented more comprehensively by Creedy [3] in 1924. Improvements on the design of the rotor were proposed by Broadway et al [4] in 1970.

Work on control strategies for the machine with emphasis on the doubly-fed operation was carried out at Oregon State University by H. K. Lauw [5]. A 15 HP brushless doubly-fed machine was built as a result of Lauw's work. This machine, controlled by a series resonant converter [6], was used for experiments required to develop this thesis.

Design and implementation of a proper stabilizer was the main challenge.

2.1.1 Stator Winding Design

The wiring diagram for the stator windings of the brushless doubly-fed machine is shown in figure 2.1. The stator of the machine is wound such that it can be configured as two three-phase systems using a common set of windings. The electric power grid can be connected to one three-phase system and an electronic power converter to the second three-phase system in order to control the shaft speed of the machine. It is possible to vary the shaft speed by varying the frequency or amplitude of the converter output current.

It can be seen from figure 2.1 that common windings are used for the two three-phase systems. Each coil of the stator windings carries two current components originating from the two three-phase systems to which the machine is connected. These two component currents are of different frequencies and flowing in different paths of the same coil. Complete separation of the individual frequencies exist at the lines of the two connecting three phase systems.

The machine used in this study is six-pole as viewed from the A, B, C terminals and two-pole as viewed from the a, b, c terminals. The six-pole system takes care of the

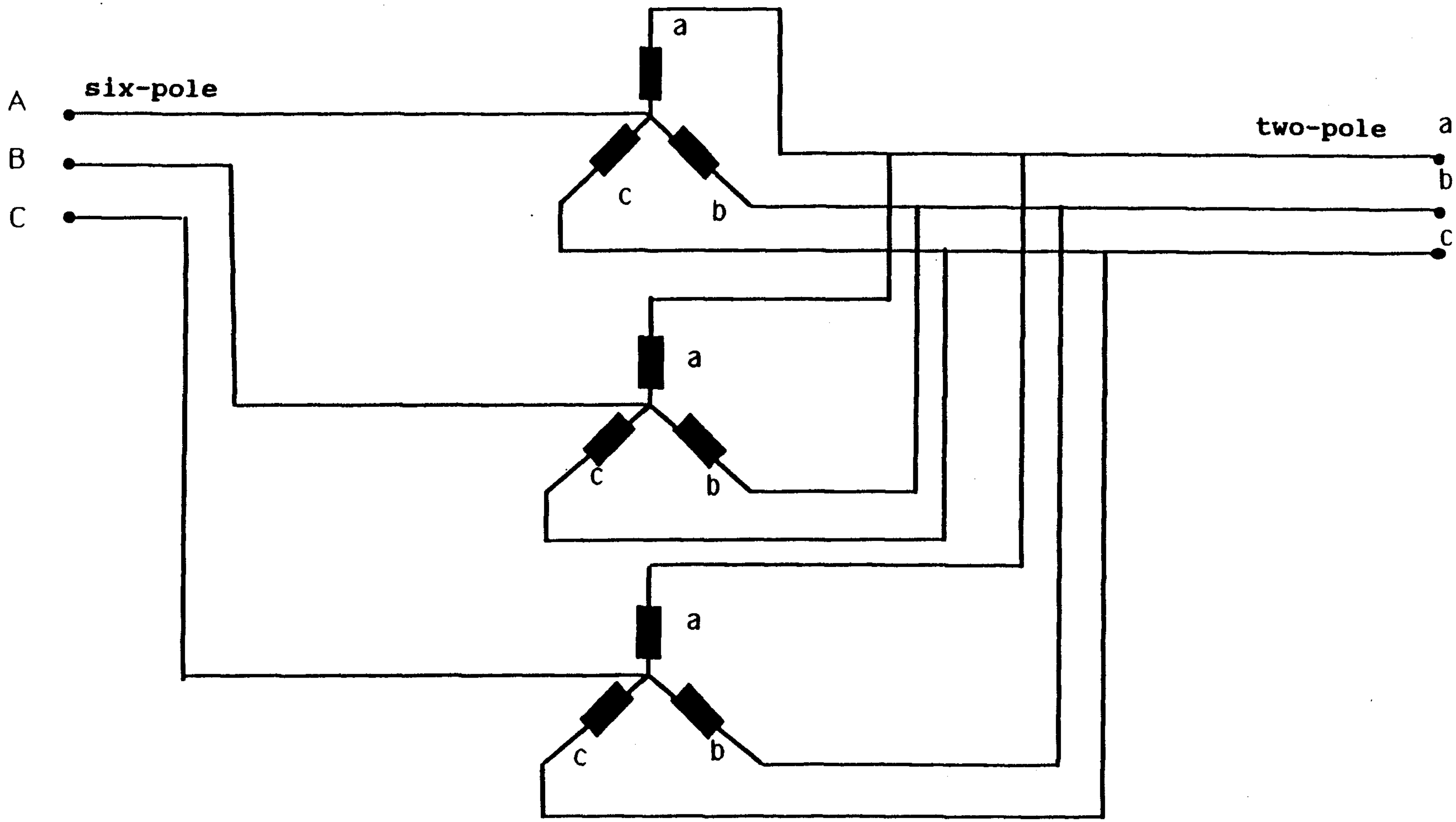


Fig 2.1 Circuit Diagram of Brushless Doubly-fed Machine Stator

bulk energy transfer and its terminals are connected directly to the electric power grid. The terminals of the two-pole system are connected to the power electronic converter to satisfy the excitation requirements.

2.1.2 Rotor Design

The design of the rotor of the brushless doubly-fed machine is based on the work done by Broadway et al [3]. This design has the advantages of being robust and low cost.

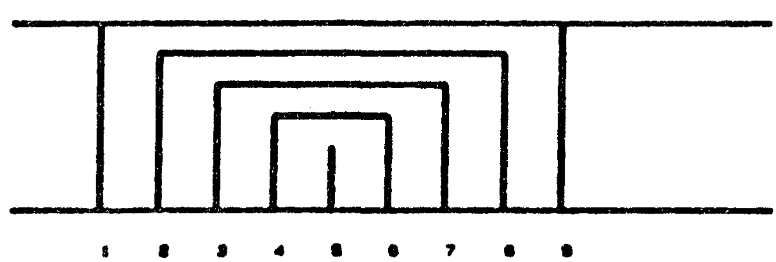


Fig 2.2 Brushless Doubly-fed Machine Rotor

Figure 2.2 shows the nested type rotor of the brushless doubly-fed machine. This rotor looks similar to the squirrel cage rotor of a conventional induction machine, with modifications on one side of the end rings.

2.2 Modes of Operation

From experiments conducted on the 15 HP brushless doubly-fed machine, it was observed that this machine is capable of exhibiting synchronous as well as induction modes of operation. Synchronous operation is preferred for efficiency and speed control. Hence, understanding constraints of the machine in the synchronous mode is necessary.

Shaft speed of the brushless doubly-fed machine under steady state and synchronous operating conditions satisfies the following relationship

$$RPM = 60 * (fs_1 - fs_2) / (N_1 + N_2), \qquad 2.1$$

where,

fs_1 = frequency of six-pole system,

fs_2 = frequency of two-pole system,

n_1 = number of pole-pairs of six-pole system,

n_2 = number of pole pairs of two-pole system.

The brushless doubly-fed machine requires synchronization efforts. We use the DC synchronization method. The two-pole current is set to DC by the power electronic converter. Prior to turning on the converter, the machine runs at 1200 RPM by connecting the six-pole system to the 60-HZ power grid. Gradual increase of the two-pole DC current decreases the RPM until a sudden lock at 900 RPM occurs. This RPM value follows the relationship expressed in equation 2.1 for DC and 60-HZ frequency supply to the two-pole and the six-pole systems respectively. Further increase in the 2-pole DC current leaves the machine speed locked at

900 RPM in the event that the synchronous mode of operation is established. However synchronous mode of operation is lost when the two-pole current exceeds a certain limit. Once synchronized in DC, an increase in frequency to vary the speed requires an increase in two-pole current, in order to maintain the synchronous mode.

The series resonant-converter used to energize the two-pole system has three different modes of operation. It can be operated as a constant current source (I-mode), constant voltage source (V-mode) as well as a voltage source such that the voltage over frequency ratio can be kept constant (V/f mode). The V/f mode was found to be the best suited for the brushless doubly fed machine in the synchronous mode. An increase in frequency in this case results in a corresponding increase in amplitude of the two-pole current. Hence automatic adjustment of the amplitude of the two-pole current to maintain synchronism can be achieved by a proper choice of the voltage over frequency ratio. Constraints on the synchronous mode of operation for this machine are discussed in section 2.5.

2.3 Frequency Separation

The two sets of three-phase systems on the stator of the machine have common windings and yet these two sets have different numbers of poles. This peculiar feature of the design of the brushless doubly fed machine was tested and complete frequency separation at the terminals of the two systems was ensured. By connecting the six-pole system to the 60 HZ power grid and the two-pole system to a 10 HZ power supply, no 60-HZ component was detected on the voltages and currents at the terminals of the two pole system . Also, no 10-HZ component in the currents and voltages at the terminals of the six-pole system were detected. A deviation from this characteristic will be discussed in section 2.5 later in this chapter.

2.4 Speed Control

The capability to vary the shaft speed by electrical means is an essential feature of variable-speed generation systems. With conventional doubly-fed machines, the shaft speed is varied by varying the rotor current frequency. The rotor current amplitude does not have any effect on the shaft speed as long as the machine does not pull out of synchronism. However, the shaft speed of the brushless doubly-fed machine was observed to be dependant on both amplitude and frequency of the two-pole current, during stable operation. As long as the two-pole current is maintained within certain limits, it is possible to vary the shaft speed by varying the supply frequency to the two-pole system. Nevertheless, this statement is true only for a limited range of frequencies. This will be explained in section 2.5.

2.5 Constraints to Synchronous Mode

The characteristics of the brushless doubly-fed machine mentioned above are true only for a limited frequency range of operation. From the experiments carried out in the laboratory on the 15 HP machine, it was observed that the machine cannot be operated in the synchronous mode for certain frequency values. Hence equation 2.1 no longer holds at these frequencies and continuous speed control over the entire frequency range is impossible to achieve without a stabilizer. The unstable region of operation for the tested machine was found to be in the range of 15 to 25 HZ. This observation agrees with the instability phenomenon analyzed by Cook & Smith (1979) [2] for two induction machines connected in cascade. In such a system, the rotors are electrically connected to each other with opposite phase sequence. In their experiments with the stator of one machine connected to a fixed voltage and frequency source and the stator of the other machine supplied with variable frequency, it was found that the machine was unstable over the majority of the operating range, when operated in the synchronous mode. A theoretical explanation for this behavior based on eigen-value analysis and a possible solution to the problem for a doubly-fed single frame cascade connected induction machine was presented by Cook &

Smith [2] and is given as follows:

A balanced three-phase induction motor transferred to a two phase set with reference to d-q axes rotating at $p\theta_c$ with respect to a fixed reference is given by

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s+L_sp & -L_sp\theta_c & Mp & -Mp\theta_c \\ L_sp\theta_c & R_s+L_sp & Mp\theta_c & Mp \\ Mp & -Mp(\theta_c-\theta_r) & R_r+L_rp & -L_r(\theta_c-\theta_r) \\ Mp(\theta_c-\theta_r) & Mp & L_rp(\theta_c-\theta_r) & R_r+L_rp \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad 2.2$$

where,

subscripts d, q = quantities referred to d-q axes

subscripts s, r = stator and rotor quantities

subscripts 1, 2 = separate machine sections

subscript 0 = steady-state value

p = operator d/dt

J = moment of inertia

L, M = per phase self and mutual inductance

P, Q = pole pair members of each machine section

P_m = total mechanical power out

R = per phase resistance

S = slip

V_{s1}, V_{s2} = per phase stator supply voltages

δ_1, δ_2 = phase of stator voltages with respect to d-q axes

θ_c = reference angle for d-q axes

θ_r = reference angle for rotor position

w_r = rotor angular velocity

w_s = angular frequency of rotor currents

w_1, w_2 = angular frequency of stator quantities

In terms of d-q variables, the constraints due to the connection of rotor windings of the two induction machines become

$$v_{dr1} = -v_{dr2}; \quad v_{qr1} = v_{qr2};$$
$$i_{dr1} = i_{dr2}; \quad i_{qr1} = -i_{qr2}. \qquad 2.3$$

The two set of equations associated with the two machines can be combined to give a set of six equations represented by

$$[V] = [Z][I]. \qquad 2.4$$

Since all d-q voltages and currents are constant for steady state operation, this result can be rewritten as:

$$\begin{bmatrix} v_{s10}\cos\delta_1 \\ v_{s10}\sin\delta_1 \\ 0 \\ 0 \\ v_{s20}\cos\delta 2 \\ -v_{s20}\sin\delta 2 \end{bmatrix} = \begin{bmatrix} R_{s1} & -L_{s1}w_1 & 0 & -M_1w_1 & 0 & 0 \\ L_{s1}w_1 & Rs_1 & -M_1w_1 & 0 & 0 & 0 \\ 0 & -M_1w_s & R_r & -L_rw_s & 0 & -M_2w_s \\ M_1w_s 0 & -L_rw_sn & R_r & M_2w_s & 0 & 0 \\ 0 & 0 & 0 & -M_2w_2 & R_{s2} & -L_{s2}w_2 \\ 0 & 0 & M_2w_2 & 0 & -L_{s2}w_2 & R_{s2} \end{bmatrix} \begin{bmatrix} i_{ds10} \\ i_{qs10} \\ i_{dr10} \\ i_{qr10} \\ i_{ds20} \\ i_{qs20} \end{bmatrix} \qquad 2.5$$

From equation 2.2 , the steady state currents are found and substituted into

$$T_e = PM_1(i_{qs1}i_{dr1}-i_{ds1}i_{qr1}) + QM_2(i_{qs2}i_{dr2} - i_{ds2}i_{dr2}) \quad 2.6$$

to give the steady-state torque. Equation 2.4 can be combined with

$$T_e-T_m = Jp^2\theta_r \quad 2.7$$

to give

$$[V_D] = [Z_D] [I_D]. \quad 2.8$$

Giving a small perturbation about a steady state value and separating coefficients,

$$[p\Delta I_D] = [B]^{-1}[\Delta V_D] - [B]^{-1}[A] [\Delta I_D], \quad 2.9$$

where [A] is given by 2.10, [B] by 2.11, $[\Delta V_D]$ by 2.12 and $[\Delta I_D]$ by 2.13.

The stability at any operating point of the system is determined by examining the eigen-values of [B] [A]. The eigen-values comprise four complex conjugate pairs over most of the operating range. One of these has the frequency of a second order underdamped system which results from speed and position-dependant torques acting on the system inertia. Other than in the vicinity of a slip value given by Q/(P+Q), this eigen value dominates the response which leads to

$$[A] =$$

$$\begin{bmatrix}
R_{s1} & -L_{s1}\omega_1 & 0 & -M_1\omega_1 & 0 & 0 & P(-L_{s10}i_{qs10} - M_1 i_{qr10}) & P\sqrt{\tfrac{3}{2}}V_{s10}\sin\delta_1 \\
L_{s1}\omega_1 & R_{s1} & M_1\omega_1 & 0 & 0 & 0 & P(L_{s1}i_{ds10} + M_1 i_{dr10}) & P\sqrt{\tfrac{3}{2}}V_{s10}\cos\delta_1 \\
0 & -M_1(\omega_1 - \omega_{r1}) & R_R & -L_{r1}(\omega_1 - \omega_{r1}) + L_{r2}(\omega_2 - \omega_{r2}) & 0 & -M_2(\omega_2 - \omega_{r2}) & 0 & 0 \\
M_1(\omega_1 - \omega_{r1}) & 0 & L_{r1}(\omega_1 - \omega_{r1}) - L_{r2}(\omega_2 - \omega_{r2}) & R_R & -M_2(\omega_2 - \omega_{r2}) & 0 & 0 & 0 \\
0 & 0 & 0 & M_2\omega_2 & R_{s2} & -L_{s2}\omega_2 & Q(-L_{s2}i_{qs20} + M_2 i_{qr10}) & Q\sqrt{\tfrac{3}{2}}V_{s20}\sin\delta_2 \\
0 & 0 & M_2\omega_2 & 0 & L_{s2}\omega_2 & R_{s2} & Q(L_{s2}i_{ds20} + M_2 i_{dr10}) & Q\sqrt{\tfrac{3}{2}}V_{s20}\cos\delta_2 \\
-M_1 P i_{qr10} & M_1 P i_{dr10} & M_1 P i_{qs10} + M_2 Q i_{qs20} & -M_1 P i_{ds10} + M_2 Q i_{ds20} & M_2 Q i_{qr10} & M_2 Q i_{qr10} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0
\end{bmatrix}$$

where $\omega_{r1} = P\omega_r$ and $\omega_{r2} = Q\omega_r$

2.10

$$[B] = \begin{bmatrix} L_{s1} & 0 & M_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_{s1} & 0 & M_1 & 0 & 0 & 0 & 0 \\ M_1 & 0 & L_R & 0 & M_2 & 0 & 0 & 0 \\ 0 & M_1 & 0 & L_R & 0 & -M_2 & 0 & 0 \\ 0 & 0 & M_2 & 0 & L_{s2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -M_2 & 0 & L_{s2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -J & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad 2.11$$

$$[\Delta V_D] = \begin{bmatrix} \sqrt{\tfrac{3}{2}}\Delta V_{s1}\cos\delta_1 + \sqrt{\tfrac{3}{2}}V_{s10}\sin\delta_1\Delta\theta_1 \\ -\sqrt{\tfrac{3}{2}}\Delta V_{s1}\sin\delta_1 + \sqrt{\tfrac{3}{2}}V_{s10}\cos\delta_1\Delta\theta_1 \\ 0 \\ 0 \\ \sqrt{\tfrac{3}{2}}\Delta V_{s2}\cos\delta_2 + \sqrt{\tfrac{3}{2}}V_{s20}\sin\delta_2\Delta\theta_2 \\ -\sqrt{\tfrac{3}{2}}\Delta V_{s2}\sin\delta_2 + \sqrt{\tfrac{3}{2}}V_{s20}\cos\delta_2\Delta\theta_2 \\ \Delta T_m \\ 0 \end{bmatrix} \qquad 2.12$$

$$[\Delta I_D] = \begin{bmatrix} \Delta i_{ds1} \\ \Delta i_{qs1} \\ \Delta i_{dr1} \\ \Delta i_{qr1} \\ \Delta i_{ds2} \\ \Delta i_{qs2} \\ \Delta\dot{\theta}_r \\ \Delta\theta_r \end{bmatrix} \qquad 2.13$$

instability.

Well-damped stable operation over the whole operating range is obtained by current feedback. Power balance in a lossless invertor is given by

$$V_{DC}(-I_{DC}) = v_{ds2}i_{ds2} + v_{qs2}i_{qs2}. \qquad 2.14$$

For constant V_{DC},

$$\Delta I_{DC} = -1/V_{DC}\ (v_{ds20}\Delta i_{ds2} + i_{ds20}\Delta v_{ds2} + v_{qs20}\Delta i_{qs2} + i_{qs20}\Delta v_{qs2}). \qquad 2.15$$

The perturbations Δv_{ds2} and Δv_{qs2} are functions of θ_r and θ_2 for constant amplitude of the second stator voltage of the second machine. Equation 2.15 can be substituted into the original system equation to give:

$$p\Delta\theta_2 = K_a v_{ds20}\Delta i_{ds2} + K_a v_{qs20}\Delta i_{qs2} + K_b\Delta\theta_r + K_c\Delta\theta_2. \qquad 2.16$$

This equation adds a ninth row and column to matrices [A] and [B], producing an additional eigen-value which lies on the real axes. Appropriate choice of parameters enables the eigen-value responsible for the instability to be shifted sufficiently far into the left hand-plane so that an over-damped response results.

It has been shown that the machine can be stabilized over a considerable part of its operating range and control over its dynamic response is possible using feed back.

2.6 Stabilizer for Brushless Doubly-fed Machine

A system model for a brushless doubly-fed machine is not available at this point. Since the principle of operation of the brushless doubly-fed machine is in many aspects, similar to that of two induction machines connected in cascade, it is felt reasonable to apply the feed-back control as presented by Cook and Smith [2] to stabilize the brushless doubly-fed machine.

CHAPTER 3

STABILIZER FOR BRUSHLESS DOUBLY-FED MACHINE

3.0 Introduction

As mentioned in the previous chapter, the brushless doubly-fed machine is inherently unstable at certain ranges of the shaft speed. This chapter covers the structure of the stabilizer used to eliminate the unstable region. The objective was to achieve continuous speed control over the entire range of shaft speed. The stabilizer used is a digital feedback controller. It controls the output frequency of a power electronic converter connected to the two-pole stator of the machine. The feedback control is described.

3.1 Feedback Control

The feedback strategy undertaken is to use the amplitude of the output current of the converter to modify its frequency. The feedback transfer function is of the form $T_1s/((1+T_1s)(1+T_2s))$. T_1 and T_2 are given by $1/2\pi f_1$ and $1/2\pi f_2$ respectively, where f_1 and f_2 are the corner frequencies of the band pass filter shown in figure 3.1. In the previous chapter, it was explained that this feedback could result in eigen-values responsible for the instability to be shifted to the left-half plane of the complex domain.

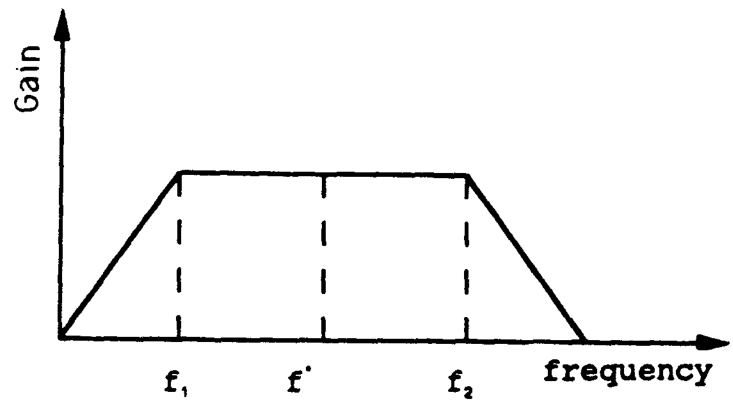


Fig 3.1. Feedback Transfer Function

Figure 3.2 shows the block diagram for the control. The 3-phase output line-currents of the converter are acquired and converted to digital signals by an analog to digital converter. Instantaneous amplitude of the output current of the converter is obtained by by taking the square root of the sum of the squared values. The reference frequency signal is also acquired as digital signals by the analog to digital converter. This signal can be varied from zero to 60 Hz depending on desired shaft speed. Zero Hz corresponds to a synchronous speed of 900 RPM and 60 Hz corresponds to zero RPM (equation 2.1).

The band pass filter upper and lower corner frequencies are determined from the unstable oscillation frequency which is detected from the waveform of the two-pole current. Since a system model or theoretical control strategy is not available, the gain for the feedback signal is chosen by

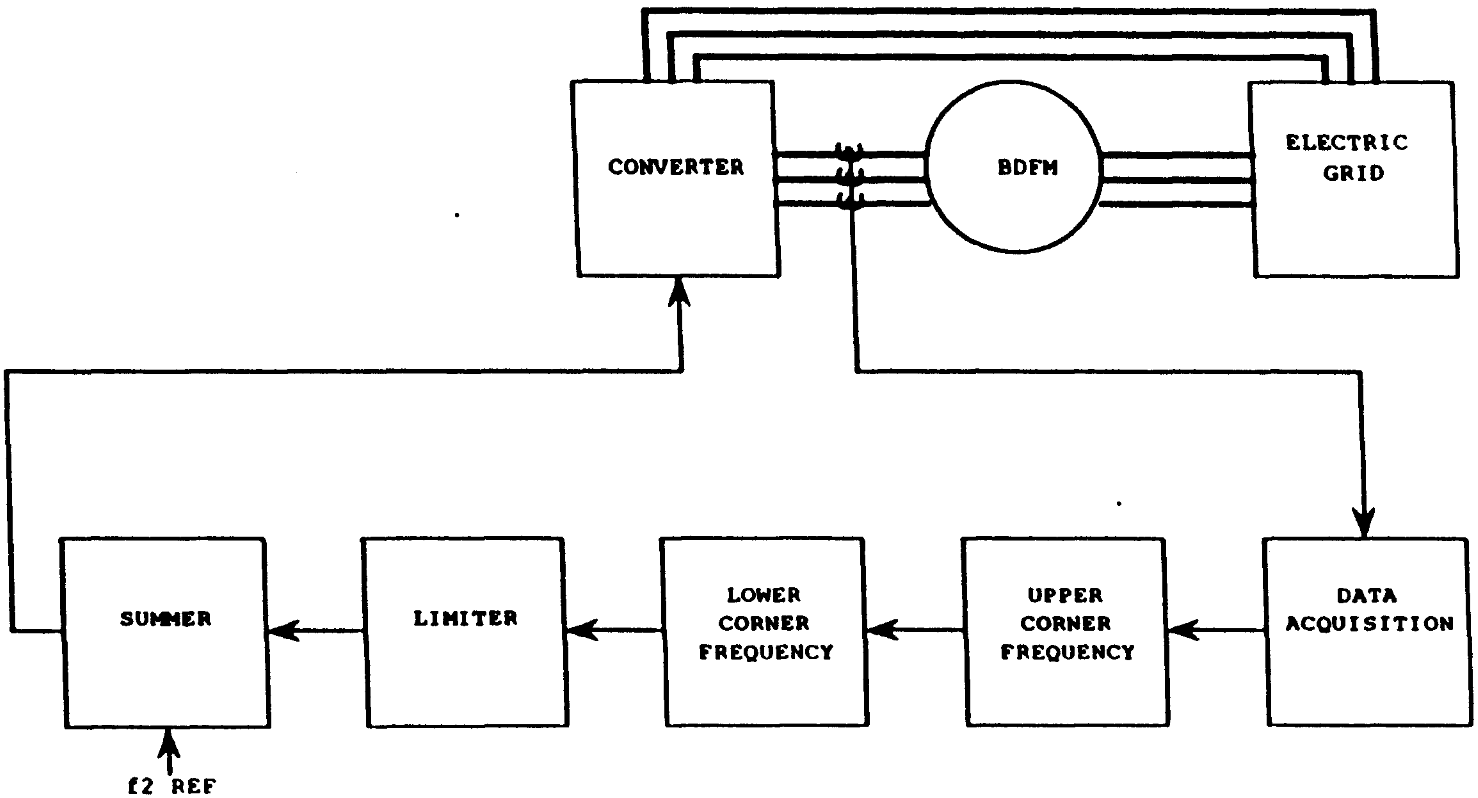


Fig 3.2 **Block Diagram for the Stabilizer**

trial and error.

The feedback signal is added to the reference frequency signal to get the modified frequency of the converter. This is fed back to the converter as analog signals through a digital to analog converter. A limiter is incorporated for protection of the converter. Provision of convenient computer keyboard access to the parameters of the stabilizer simplified on-line experimentation and adjustments.

The integration method chosen is the trapezoidal rule. Being an implicit integration method, this method is numerically stable even if inadequate time-steps are chosen. A wash term is included in the feedback in order to deactivate the stabilizer when the system is stable, i.e. there is no change in amplitude of the two-pole current. This wash term is a differentiator and is implemented digitally using the backward Euler method.

3.2 Choice of Parameters

The choice of the time constants and gain is justified in this section. Frequency f_1 should be less than a certain value inorder to reduce detrimental effects due to noise and data acquisition. It should be greater than a limiting value so as to assure sensitivity of the stabilizer due to amplitude changes of the two-pole current. Frequency f_2 should be less than a certain value in order to assure effectiveness of the stabilizer for a wide speed range. It should be greater than a limiting value in order to assure sensitivity of the differentiation term. This is because if f_2 tends to zero, T_2 tends to infinity,

$$T_2S/\ (1 + T_2S) \rightarrow 1, \qquad 3.9$$

which makes the stabilizer become a first order controller. For effective stabilization, Cook and Smith [2] suggests that the bandwidth of the filter be atleast six times the lowest cutoff frequency.

The following procedure was adopted to adjust the parameters. While operating in the unstable region, the frequency of oscillation of the two-pole current of the machine can be measured using an oscilloscope as

$$f^* = 1/T^*, \qquad 3.1$$

with

f^* - oscillation frequency

T^* - time period .

The corner frequencies of the band pass filter from the band pass margin are chosen by the equations:

$$f_1 - f_2 = 6 * f_2 \qquad 3.2$$

$$f^* = f_2 + (f_1 - f_2)/2, \qquad 3.3$$

with

f_1 - upper corner frequency

f_2 - lower corner frequency.

Thus, for a given f^*, f_1 and f_2 can be calculated from

$$f^* = 4 * f_2 = (4/7) * f_1. \qquad 3.4$$

The time-constants T_1 and T_2 are then found from

$$2\pi f_1 T_1 = 1 \qquad 3.5$$

$$2\pi f_2 T_2 = 1. \qquad 3.6$$

From a given $T^* = 1/f^*$, T_1 and T_2 can be calculated from

$$T_2 = 4/2\pi T^* = 0.64 * T^* \qquad 3.7$$

$$T_1 = T_2/7. \qquad 3.8$$

Thus the time constants are calculated from the unstable oscillation frequency of the two-pole current. The sensitivity of the stabilizer is optimized by varying the stabilizer's gain (k) during run-time, i.e while the machine is running with the feed back control.

CHAPTER 4

IMPLEMENTATION OF THE STABILIZER

4.0 Introduction

This chapter deals with the implementation of the stabilizer for the brushless doubly-fed machine. The feedback control consists of a combination of hardware and software elements. A brief description is given below.

4.1 Hardware

The hardware elements include an IBM PC AT, the data acquisition board and the analog output module. A block diagram of the system is given in figure 4.1.

4.1.1 Central Processing Unit

An IBM PC AT [7] with 80286 central processing unit was used for digital control. The PC provides the capability for enhanced numeric processing by using a 80287 that supports floating point calculations.

4.1.2 Data Acquisition System

The data required for the control are the three-phase line currents on the two-pole of the machine. Three instantaneous current transducers [8] give the analog signals representing these currents. These are acquired through an analog input module. The analog input module is

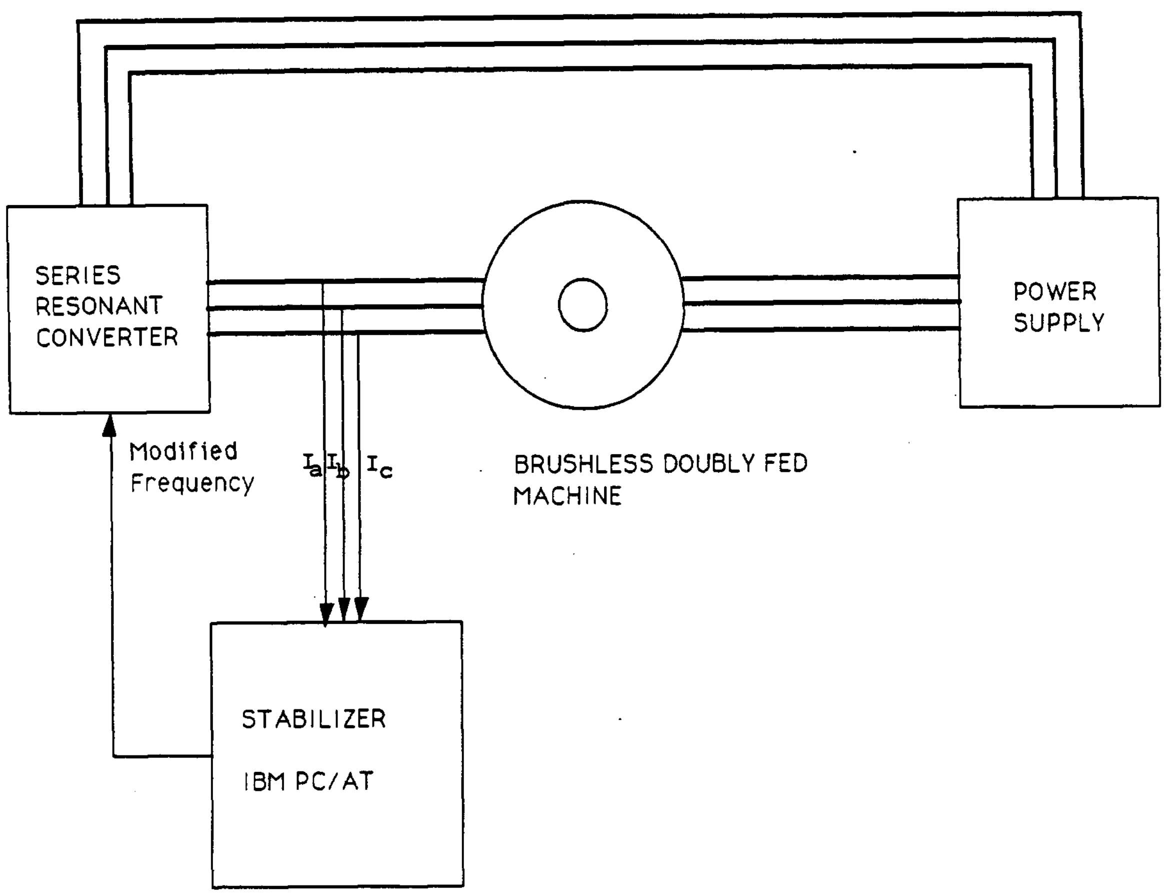


Fig 4.1 Block Diagram Showing Machine with Stabilizer

a real-time interface board which provides direct interface with the IBM PC/AT. The analog reference signal to the converter's waveform synthesizer is provided through an analog output module. The WB-820 [9] used for this research is a multifunction data acquisition board. It has capabilities for various modes of analog and digital input and output. This data acquisition board operates in conjunction with the OMX-STB-HL High-Level Voltage Panel [10], which provides multiplexing of the signals.

4.1.2.1 Analog Input Module

The signals from the transducers are provided to the analog input module of the WB-820 which has the capability to measure voltages on up to 16 single-ended analog input channels. The WB-820 contains a single 12-bit successive-approximation analog-to-digital converter that can receive input voltages within the range of -5V to +5V. Two's complement digital coding was selected for ease of programming. The resolution is twelve bits (4096 counts) corresponding to 2.44 mV. The analog-to-digital conversion speed is 25 microseconds.

4.1.2.2 Analog Output Module

The high-level voltage panel can control four high-level analog output channels. The board contains a single 12-bit digital-to-analog converter. An 8-bit 8741 microprocessor is used by the WB-820 to control the digital-to-analog converter and the output channel address buffer. The microprocessor's principal task is to transmit data from its internal RAM memory to the digital-to-analog converter and periodically update all output lines. Individual sample and hold amplifiers hold the analog output signal constant until the microprocessor updates the value. A timer ensures that each analog output channel is periodically refreshed. The channels can be set to output a voltage within the range of 0 to +5 V or -5 V to +5 V. The digital-to-analog conversion resolution is 12 bits (4096 counts), providing a resolution of 2.44 mV when in the +/-5 V range.

4.1.2.3 Voltage To Current Transducers

The analog output voltages from the digital to analog converter are converted to current signals before being supplied to the reference pins of the series resonant converter. This is to minimize the effect of noise. The circuit used is shown in figure 4.2.

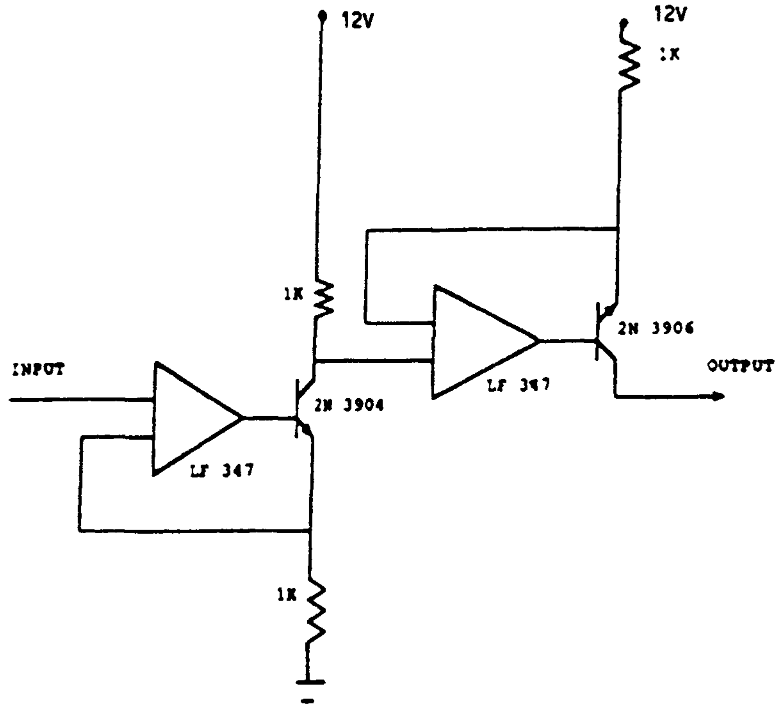


Fig. 4.2 Voltage to Current Converter Circuit

4.2 Software Features

The flow chart of the control program is shown in figure 4.3. The main features of the controller are discussed below.

4.2.1 Data Acquisition Routine

Input signals used for the stabilizer are the three instantaneous three-phase output line currents I_a, I_b and I_c of the converter and the reference frequency (F_{ref}) for the converter. The RMS value of the line current is then

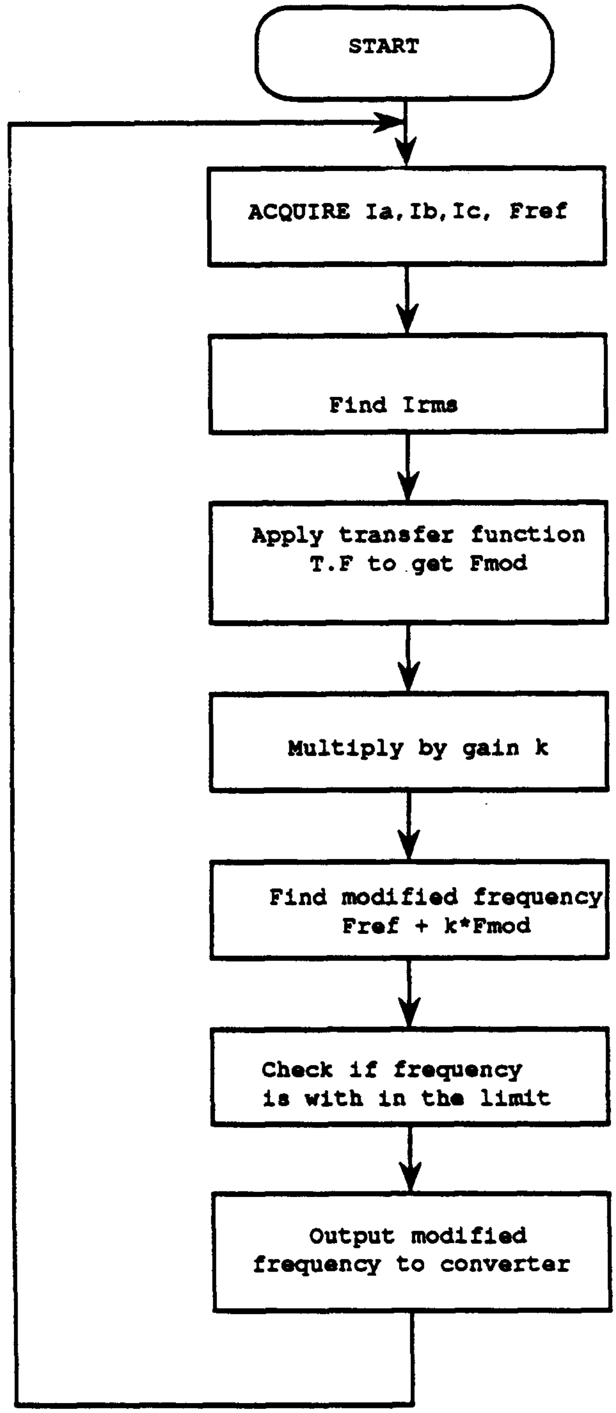


Fig 4.3 Flow Chart for Implementation of Stabilizer

computed according to

$$I_{rms} = ((I_a^2+I_b^2+I_c^2)/3)^{1/2}$$

and used as the input signal to the stabilizer to modify the frequency of the converter.

4.2.2 Implementation Of Bandpass Filter

The controller in the feed back path is of the form shown in figure 3.1. The filter is implemented as a cascade of two first-order filters and a differentiator.

The first-order filters are implemented by means of difference equations [11]. Trapezoidal rule is used because of its inherent stability and ease of implementation. Also, the step size, i.e. the time period between two samples, is not that critical compared to the step size required by other methods. Such a filter is of the form

$$Y(s) = (1/(1 + Ts)) * X(s).$$

Application of the trapezoidal rule results in the following difference equation.

$$Y_0 = Y_{-1} * (Tm - 1) / (Tm + 1) + (X_0 + X_{-1})/(Tm + 1),$$

where,

Y_0 - present output of the filter

Y_{-1} - previous output of the filter

X_0 - present input to the filter

X_{-1} - previous input to the filter

Tm - given by 2 * $T/(t_0 - t_{-1})$

t_0 - present sampling time

t_{-1} - previous sampling time.

The differentiator is implemented using backward Euler, which results in the following equation:

$$Y_0 = 2 * (X_0 - X_{-1})/(t_0 - t_{-1}),$$

where,

Y_0 - present output of the differentiator

X_0 - present input to the differentiator

X_{-1} - previous input to the differentiator

t_0 - present sampling time

t_{-1} - previous sampling time.

The transfer function is applied to I_{rms} to get modifier frequency F_{mod}. This is multiplied by the gain k and added to the reference frequency to obtain the modified frequency.

4.2.3 Limiter

A limiter is incorporated in the software before frequency signal is fed to the converter. This is to avoid damage of the power electronic converter caused by excessive frequency due to any erroneous computation.

4.2.4 Scaling

The transducer outputs are analog values between -5 and +5 volts. These are converted to corresponding digital values between -2047 and +2047. Care was taken to see that all integrator operations would not lead to out-of-bound results.

4.2.5 Stabilizer On-Off Switch

In order to facilitate the operation of the system with or without the stabilizer a digital switch is incorporated into the software.

4.2.6 Display Program

An important objective of this program is to facilitate observation of the various brushless doubly-fed machine system parameters including a flexible means for on-line adjustment of the filter coefficients and gain. The program facilitates convenient switching from automatic control to manual control.

4.3 Speed Considerations

An essential consideration in developing the software for real-time control is the speed of operation. Frequency of oscillation during unstable operation of the doubly-fed machine is in the order of 1 to 5 Hz. It is therefore reasonable to assume that the stabilizer requires a minimum speed of response corresponding to 15 Hz (higher cut off frequency). Hence a processing time of the order of 10 milliseconds is required in order to render the stabilizer effective in assuring stable operation. The signal processing effort meets these requirements. The overall processing time was found to be 3 milliseconds.

Attempts were made to use an optimal mix of Assembly and C language to achieve accurate and fast results. The programming was done in C as much as possible to suit user operation and maintenance. The data acquisition was extremely slow when implemented in C and was therefore written in 80286 Assembly language. All computations were done in floating point in order to prevent truncation errors inherent in integer calculations. An optimized Turbo C compiler further reduced execution speed.

CHAPTER 5

VERIFICATION OF RESULTS

This chapter discusses the results of the implementation of the stabilizer for the brushless doubly-fed machine. The effectiveness of the stabilizer over the entire range of operation including comparison of the performance of the machine with and without the stabilizer is presented.

5.0 Performance Evaluation

The experimental set up consisted of the six-pole side of the brushless doubly-fed machine connected to the 60 Hz, 115 volts power supply grid and the two-pole side connected to the series resonant converter. The behavior of the machine in synchronous mode was observed by varying the frequency of the two-pole current from 0 to 50 Hz. Frequencies above 50 Hz were avoided because the amplitude of the two-pole side current required at this frequency exceeded the ratings of the series resonant converter.

The following default values were chosen when the machine was operated with the stabilizer on:

o time constants of the band pass filter,

T_1 = 50 milliseconds, T_2 = 1500 milliseconds

o gain of the system, k = 3.5

o limiter value, L = +/- 5 Hz.

The machine operates in the stable mode without the stabilizer when the two-pole side is at frequencies ranging from 0 to 15 Hz and 25 to 50 Hz. This is referred to as the stable frequency region. However, when the two-pole is excited between 15 and 25 Hz, the machine is unstable.

The purpose of implementing the feed back control (stabilizer) is to stabilize the operation of the brushless doubly-fed machine over the entire speed range. This objective was accomplished and it was verified that the machine could be operated in synchronous mode in the unstable region as well. The improvement in the performance of the machine was evaluated by comparisons with and without the stabilizer.

5.1 Steady State Stability Limits

The steady-state stability limit constrains the two pole current to a minimum and maximum limit, beyond which the machine falls out of synchronism and runs in the induction mode. This minimum and maximum limit defines a stability margin of the machine. This margin was predicted to be dependant on the shaft-speed or output frequency of the converter [5].

The brushless doubly-fed machine has an inherently unstable region of operation. This occurs when two-pole frequency is between 15 to 25 Hz as shown in figure 5.1(a).

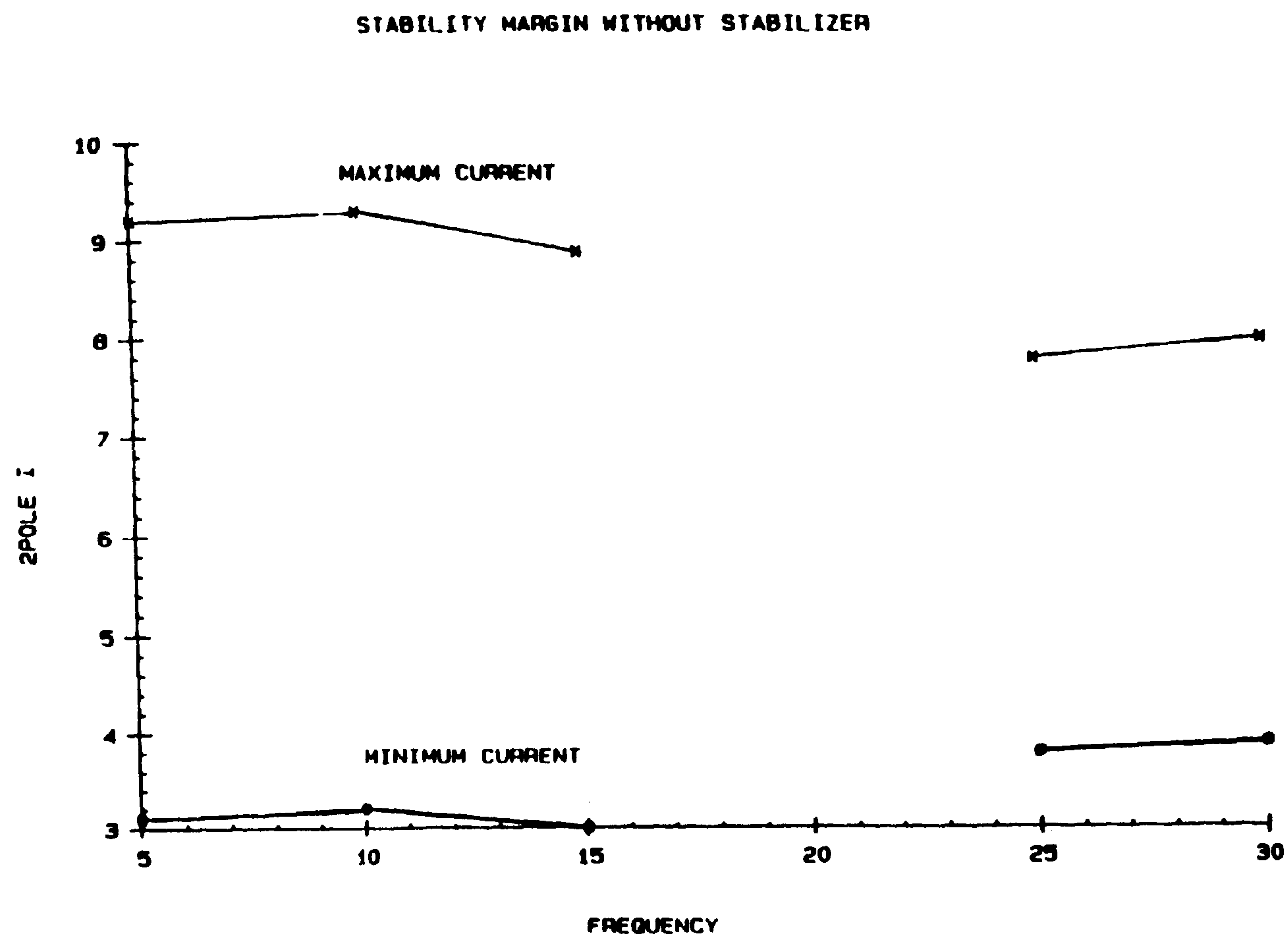


Fig 5.1(a) Stability Limits Without Stabilizer

The stabilizer is successful in eliminating this region of instability. This is shown in figure 5.1(b) when the machine is operated with the stabilizer on.

Repeatability of experimental data is quantified by means of sample standard deviation and standard error of mean. The lower limit of two-pole current at 5 Hz was measured six times and the mean value was found as 3.08 amps. The standard deviation is .07 and error of mean is 0.028.

Even though the overall stability margin has not widened by implementation of the stabilizer, it has been successful in providing a margin which covers the unstable speed region. Further investigation is required concerning widening of the stability margin.

5.2 Synchronization

The machine is synchronized using the following procedure: The six-pole is switched on to the grid which results in the machine running at 956 RPM. At this stage the machine runs in the singly-fed mode. The two-pole is then excited at DC and the amplitude of the two-pole current is increased manually to 5 Amps. This causes the machine to lock into synchronism at 900 RPM. Figures 5.2 (a) and (b) give the speed performance of the brushless doubly-fed machine with this procedure of synchronization. In figure

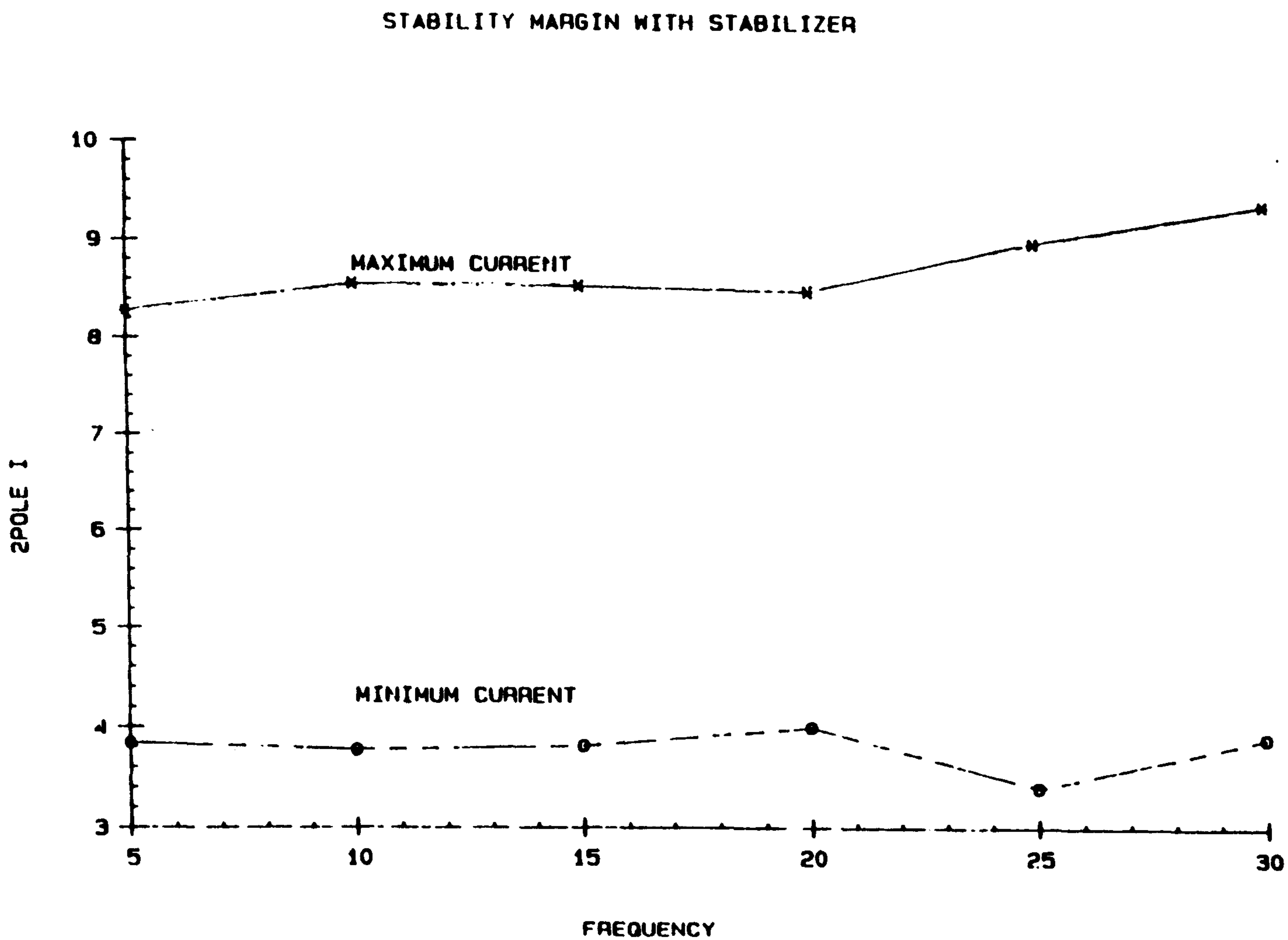


Fig 5.1(b) Stability Limits With Stabilizer

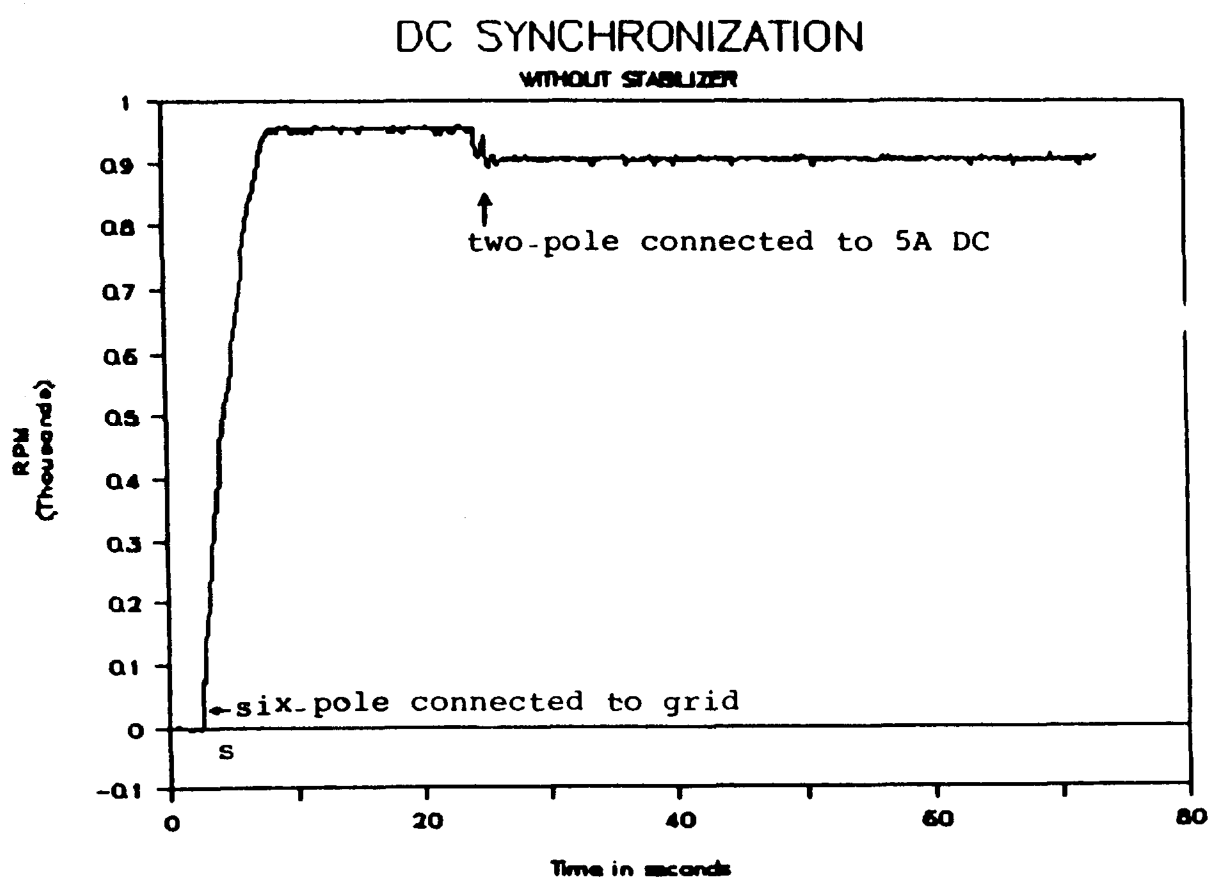


Fig 5.2(a). DC Synchronization
Without Stabilizer

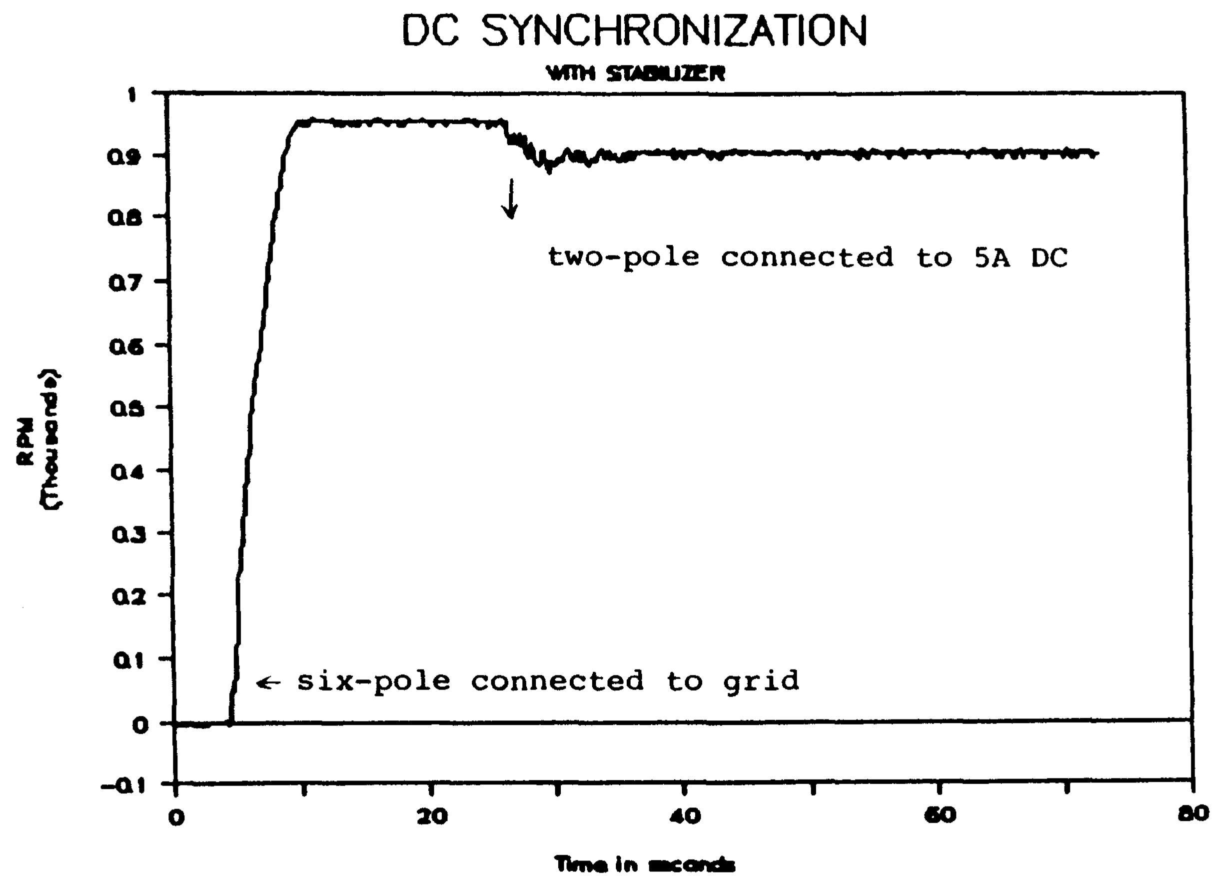


Fig 5.2(b) DC Synchronization With Stabilizer

5.2 (a) the machine is synchronized at DC with the stabilizer off.

In figure 5.2 (b) the same procedure is repeated for the machine with the stabilizer on and it can be observed that both graphs are identical. This shows that the inclusion of the stabilizer does not cause any detrimental effects on the DC synchronization characteristics of the doubly-fed machine.

5.3 Speed Control

For application in variable-speed generation systems as well as adjustable frequency drives, it is desirable to control the speed of the brushless doubly-fed machine. Synchronous mode of operation is preferred to induction mode due to efficiency considerations. Speed in synchronous mode is related to the frequency of the two-pole and 6-pole current according to equation 2.1.

Since the frequency of the six-pole current is constant at 60 Hz, the speed is dependant only on the frequency of the two-pole current in synchronous mode. Therefore, control of shaft speed is simply done by controlling the frequency of the two-pole current, provided that synchronous operation is maintained.

The two-pole current frequency was varied from 0 to 40 hz. The corresponding of speed is shown in figures 5.3 (a)

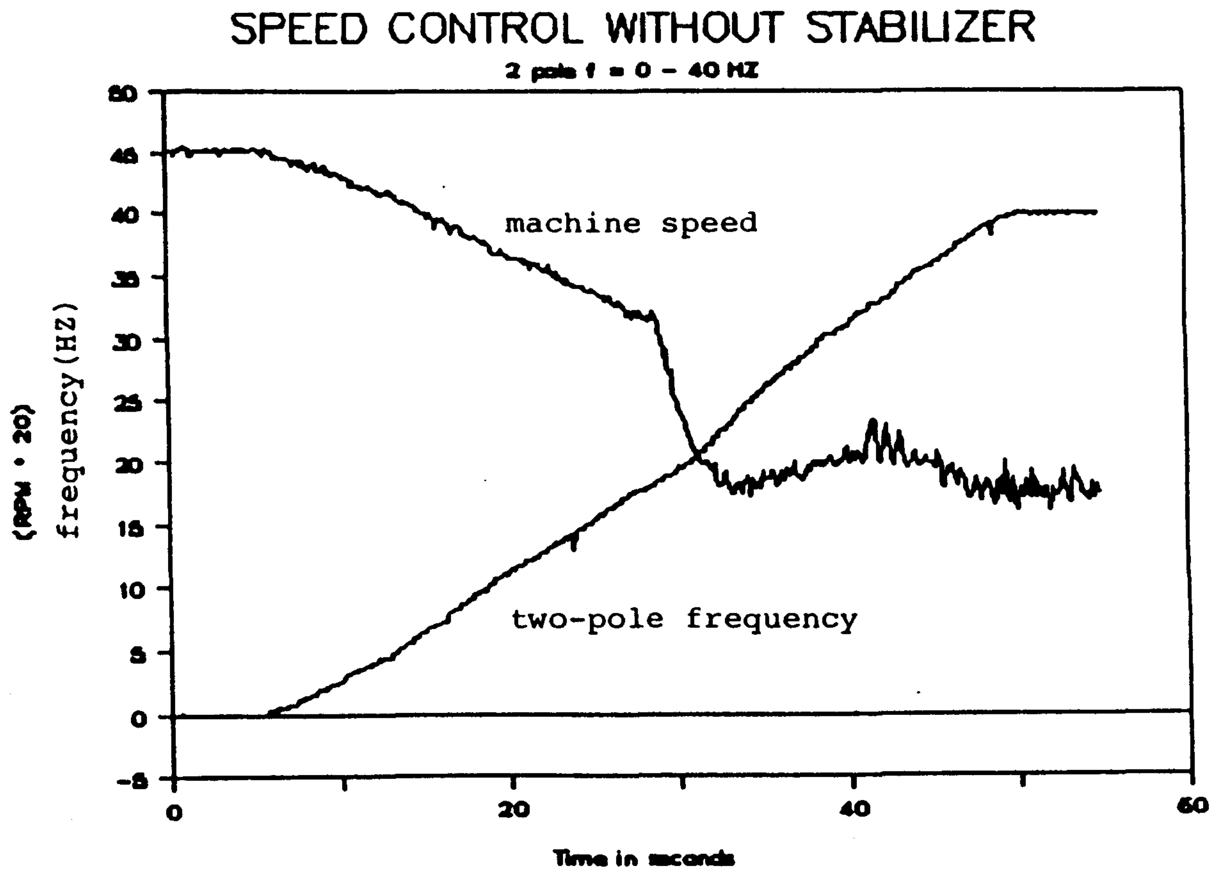


Fig 5.3(a). Speed Control Without Stabilizer

and 5.3 (b) with the stabilizer switch on and off respectively.

An increase in frequency should cause a linear decrease in speed. Speed is controllable in the stable region. It does not follow frequency in the unstable region without the stabilizer simply because synchronous operation is lost. However, with the stabilizer on, as shown in figure 5.3(b), speed follows the two-pole frequency in the entire speed range.

5.4 Speed Performance

This paragraph deals with the performance of the doubly-fed machine with regard to its speed at a particular frequency. The machine is operated at a known value of the frequency of the two-pole current and the speed is plotted with respect to time. Figure 5.4 (a) shows the speed versus time when the machine is operated with the stabilizer off and with the two-pole current at 10 Hz.

The shaft speed is 750 RPM which is in accordance with the relationship given by equation 2.1 for the synchronous mode. The speed characteristic of the machine shows that the machine is very stable at this frequency. The same experiment was repeated with the stabilizer on and similar observations were made as shown by figure 5.4 (b), from which it can be inferred that the speed performance of the

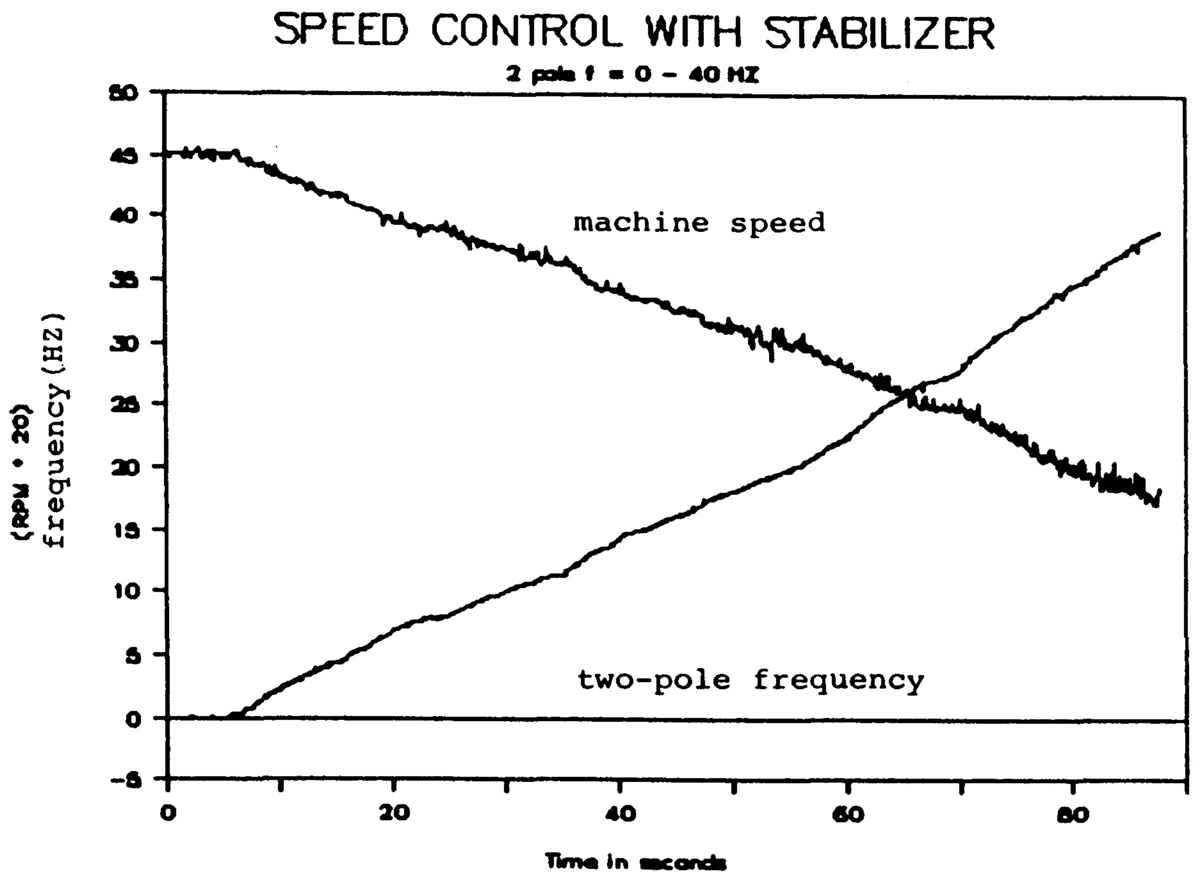


Fig 5.3(b). Speed Control With Stabilizer

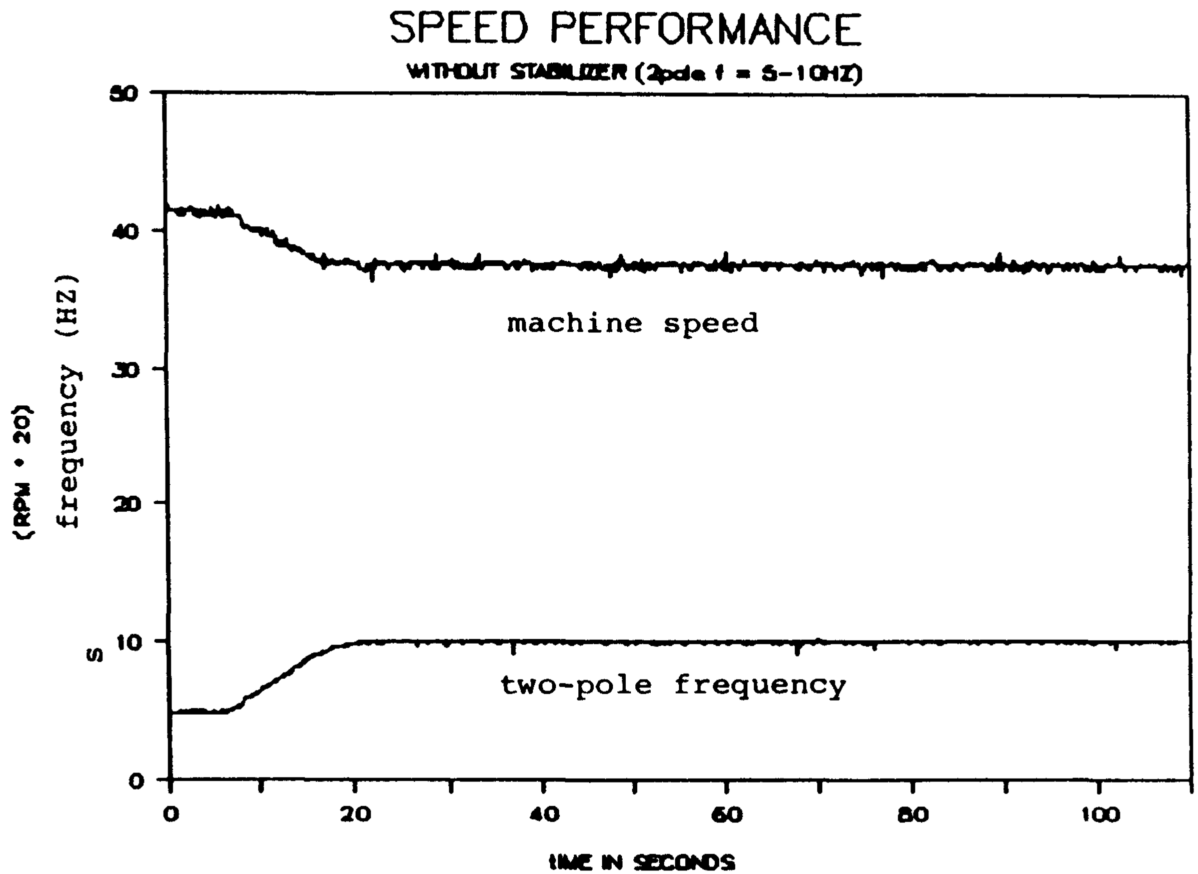


Fig 5.4(a) Speed Performance at 10Hz
Without Stabilizer

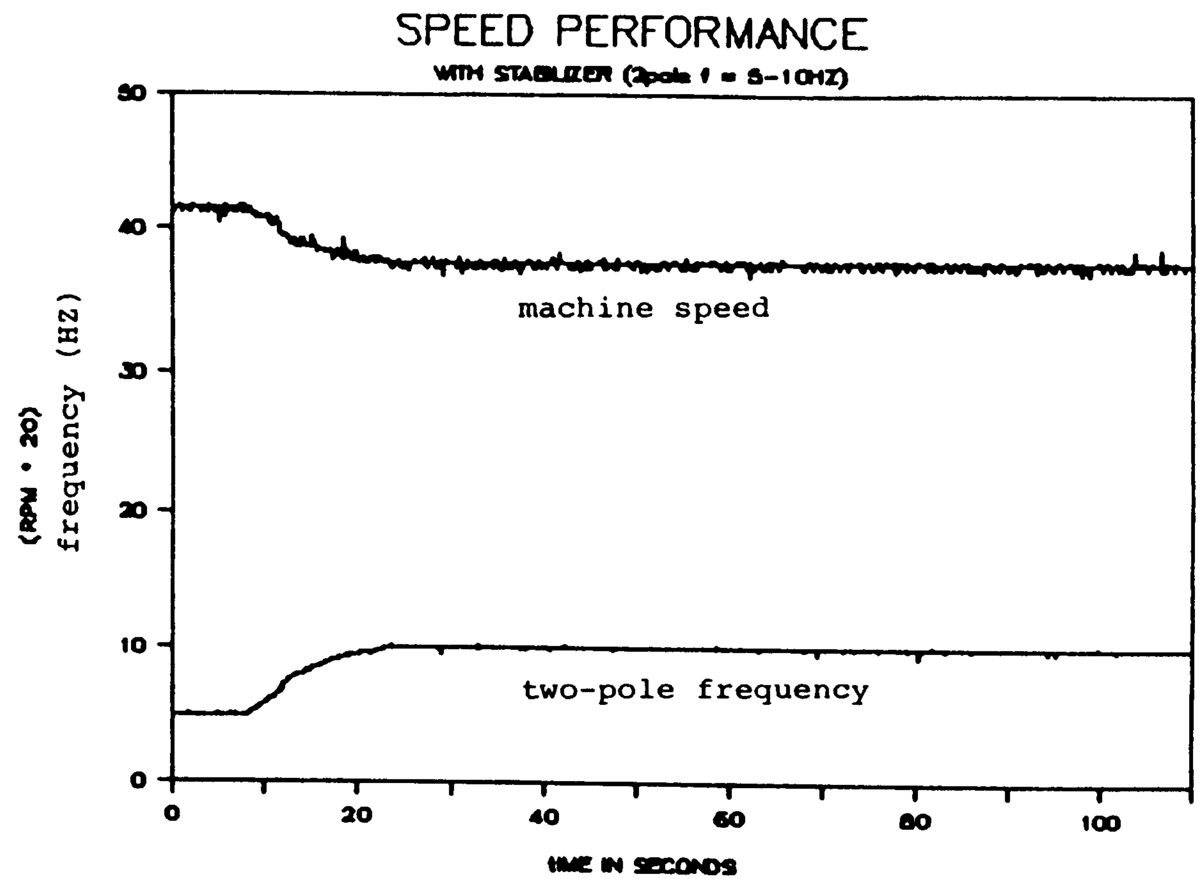


Fig 5.4 (b). Speed Performance at 10Hz
With Stabilizer

doubly-fed machine is the same with and without the stabilizer.

Figure 5.4 (c) is a plot of the speed versus time when the machine is operated in the unstable frequency region with the stabilizer off. It can be seen from the graph that the machine has lost synchrononism and the speed of the shaft is only 270 RPM. This RPM value should be 615 if synchronous operation was maintained since the frequency of the two pole current was set to 19 Hz. Figure 5.4 (d) gives the speed versus time with the stabilizer on and the frequency of the two-pole current again set at 19 Hz. The machine can be observed to run in the synchronous mode at 615 RPM. The graph shows the presence of oscillations. This is because the speed of the machine does not stay steady at 600 RPM, but fluctuates around this value. This may be due to the fact that the selected structure of the stabilizer is not the best one. Further research is recommended in this respect.

It is concluded from these observations that the overall speed performance of the machine with respect to the synchronous mode of operation has improved by employment of the stabilizer.

5.5 Frequency Separation

Frequency separation is a peculiar feature of the

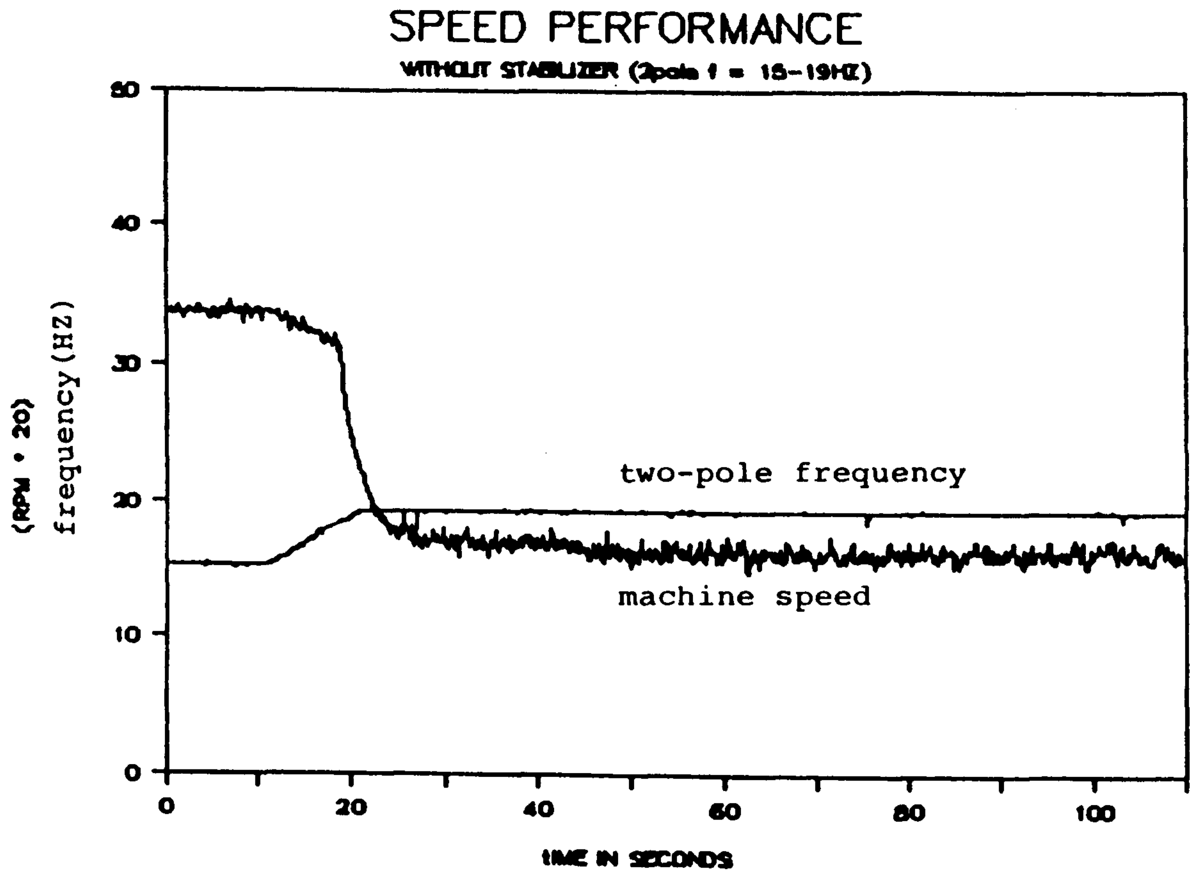


Fig 5.4(c). Speed Performance at 19Hz
Without Stabilizer

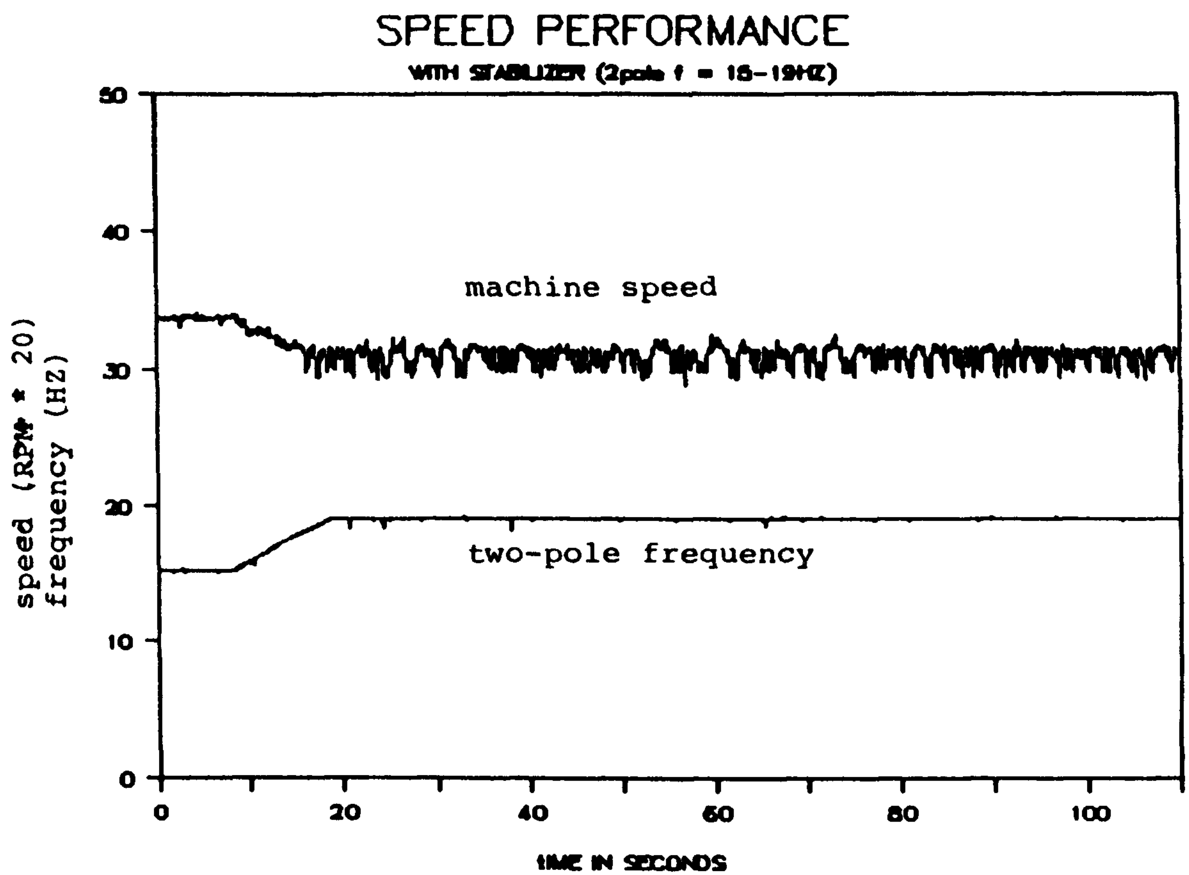


Fig 5.4(d). Speed Performance at 19Hz
With Stabilizer

brushless doubly-fed machine. This means that when operated in the synchronous mode, the six-pole waveform should retain its shape and the two-pole current should not have any 60 Hz component.

The waveforms of the two-pole current corresponding to a frequency of 40 Hz and the six-pole current at 60 Hz were acquired and plotted as in figure 5.5. Figure 5.5 (a) shows the wavefrom with the stabilizer off. It can be seen that six-pole frequency is purely sinusoidal at 60 Hz and two-pole current frequency is 40 Hz with no 60 Hz component present. Slight fluctuations can be seen in the two-pole waveforms due to harmonics imposed by the converter. Similar graphs were obtained with the stabilizer off, which show that there is no variation in performance of the brushless doubly-fed machine with regard to frequency separation in the stable region. However, when operated in the unstable region, with the stabilizer off (figure 5.5 (b)), the six-pole current is no longer sinusoidal, which means that proper frequency separation is not achieved. With the stabilizer on, the current waveforms given in figure 5.5 (c) show an improvement with regard to frequency separation. The six-pole current has a low frequency component due to bounded oscillations, the elimination of which has not been successful.

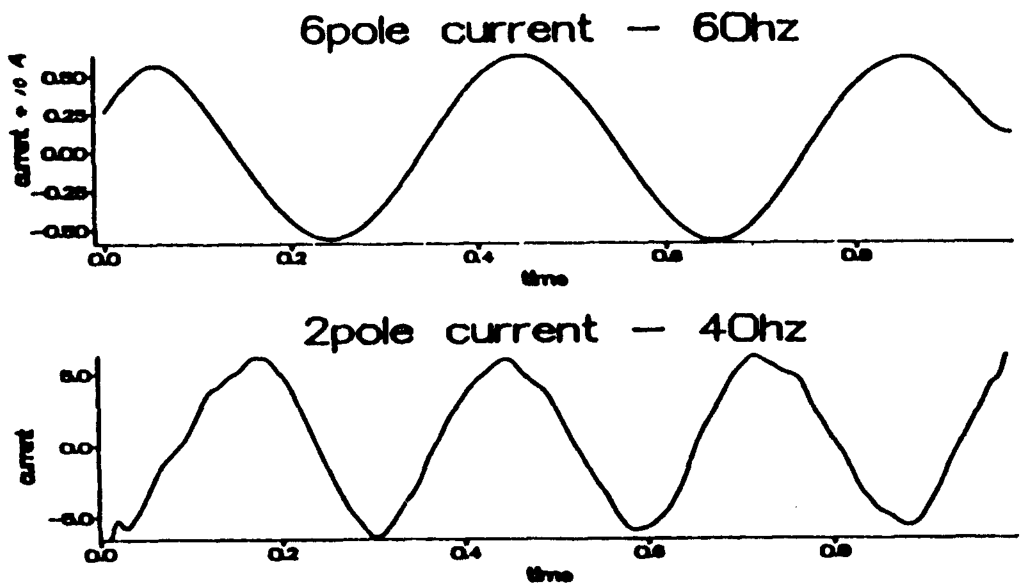


Fig . 5.5 (a) Frequency Separation in Stable Region

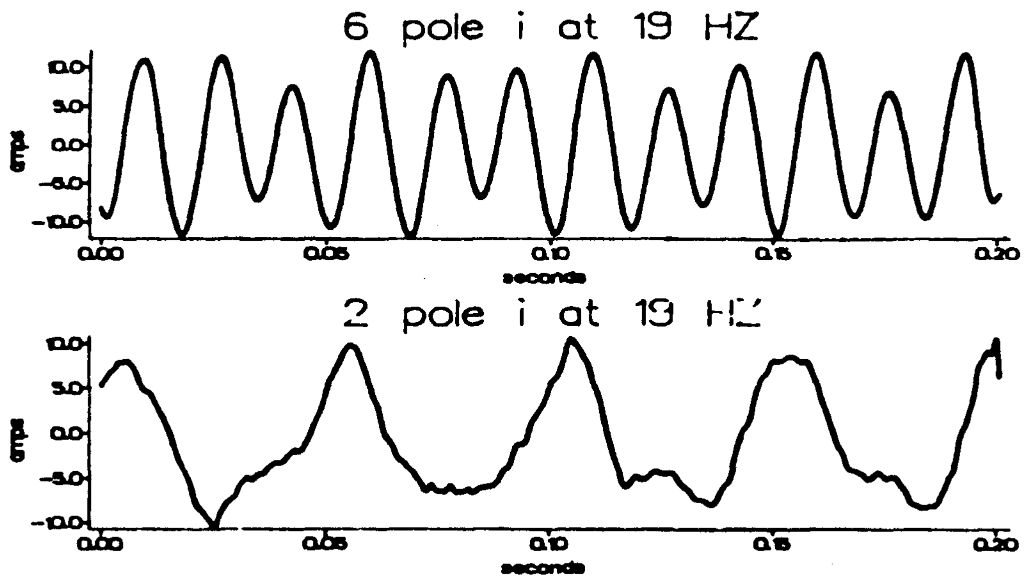


Fig. 5.5 (b) Frequency Separation in Unstable Region Without Stabilizer

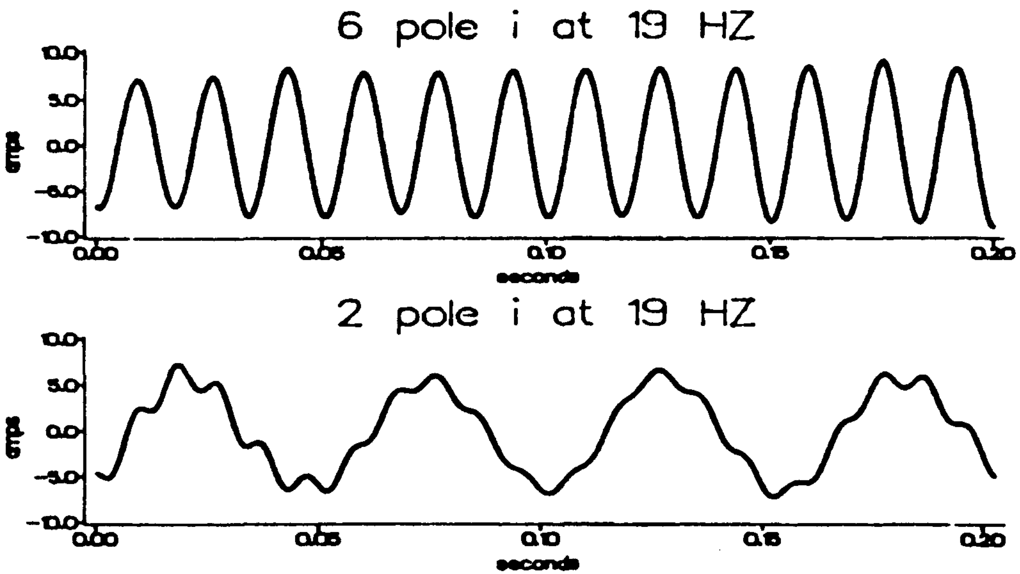


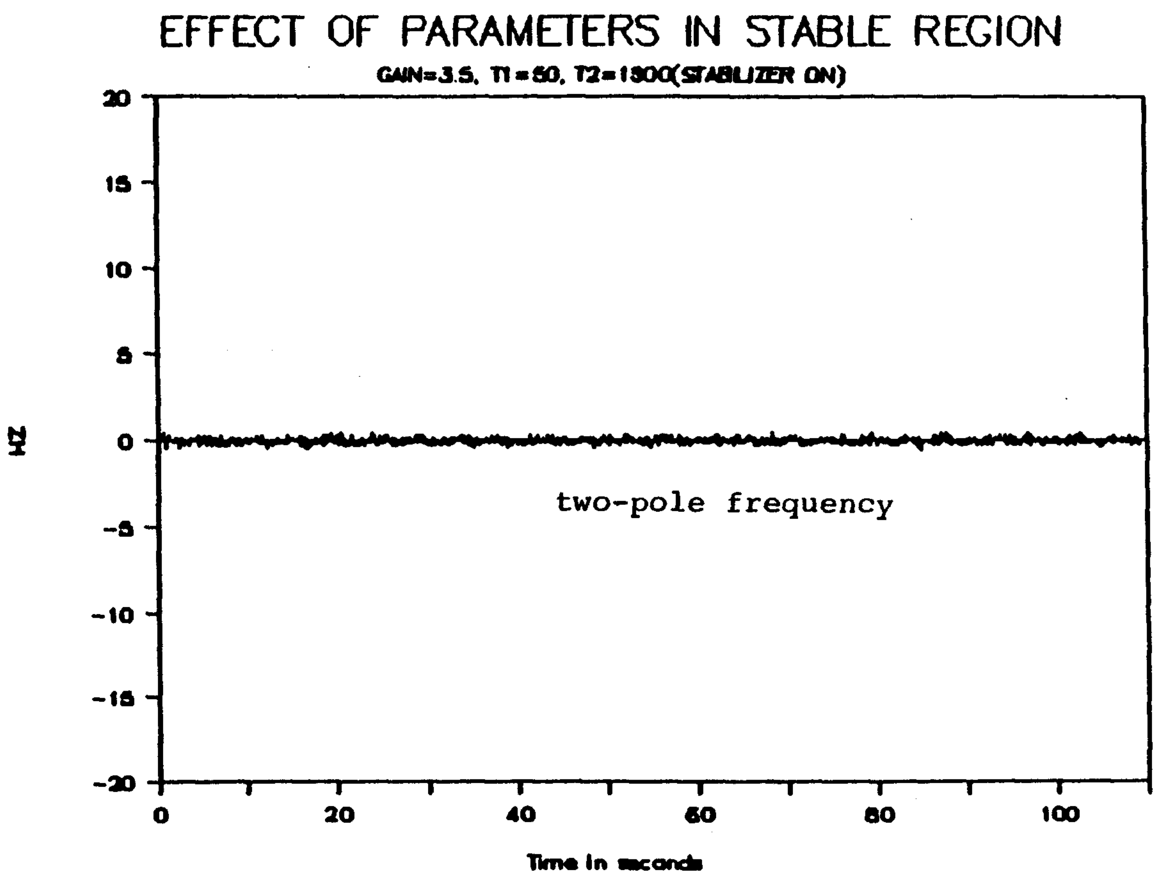
Fig. 5.5(c) Frequency Separation in Unstable Region With Stabilizer

5.6 Effect of Parameters

This section deals with the effect of parameters on the stabilizer output. Since a proper system model or control model was not available for the brushless doubly-fed machine, parameters were chosen on the basis of trial and error. The machine was operated with arbitrary values assigned to the parameters. These values were varied until the desired performance was achieved.

A differentiator term was incorporated to deactivate the stabilizer when there was no change in input frequency. With the right set of parameters, the output of the stabilizer has to be zero when the machine is stable (see figure 5.6 (a)). When the machine operates in the unstable region, the output of the stabilizer should be such that it can compensate for unwanted oscillations in the shaft speed. With a high value of the gain k, the system was unstable. A low value of k resulted in the stabilizer not having any effect - apparently the stabilizer was ignored (figure 5.6 (b)). This is similar to the output when the stabilizer is off (figure 5.6 (c)). The high and low values of k were chosen as extreme cases and the optimum value of k for stabilizing the stabilizing the machine was determined by trial and error.

The choice of values of time constants T_1 and T_2 were guided by factors mentioned in chapter III. When T_1 was



5.6(a). Effect of Parameters in Stable Region With Stabilizer

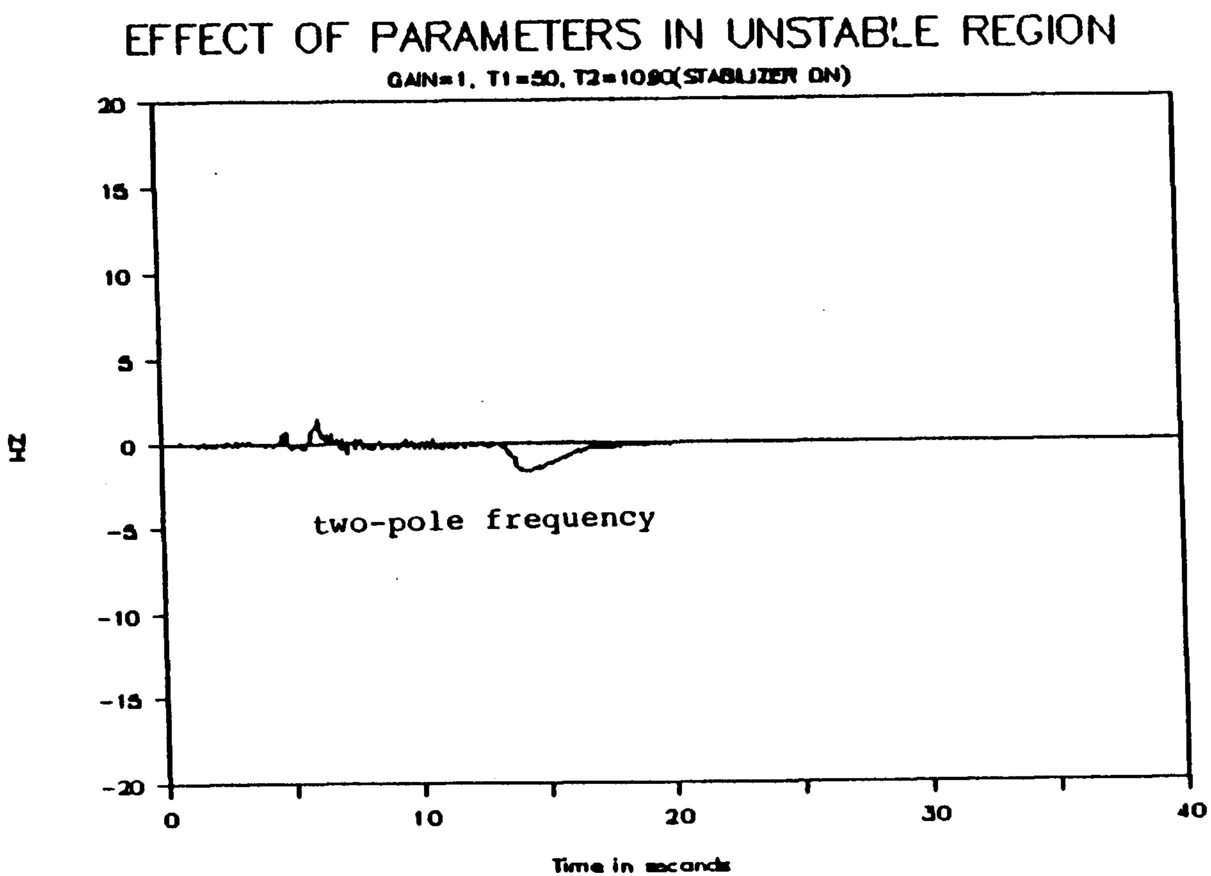


Fig 5.6(b). Effect of Parameters in
Unstable Region With Incorrect Gain

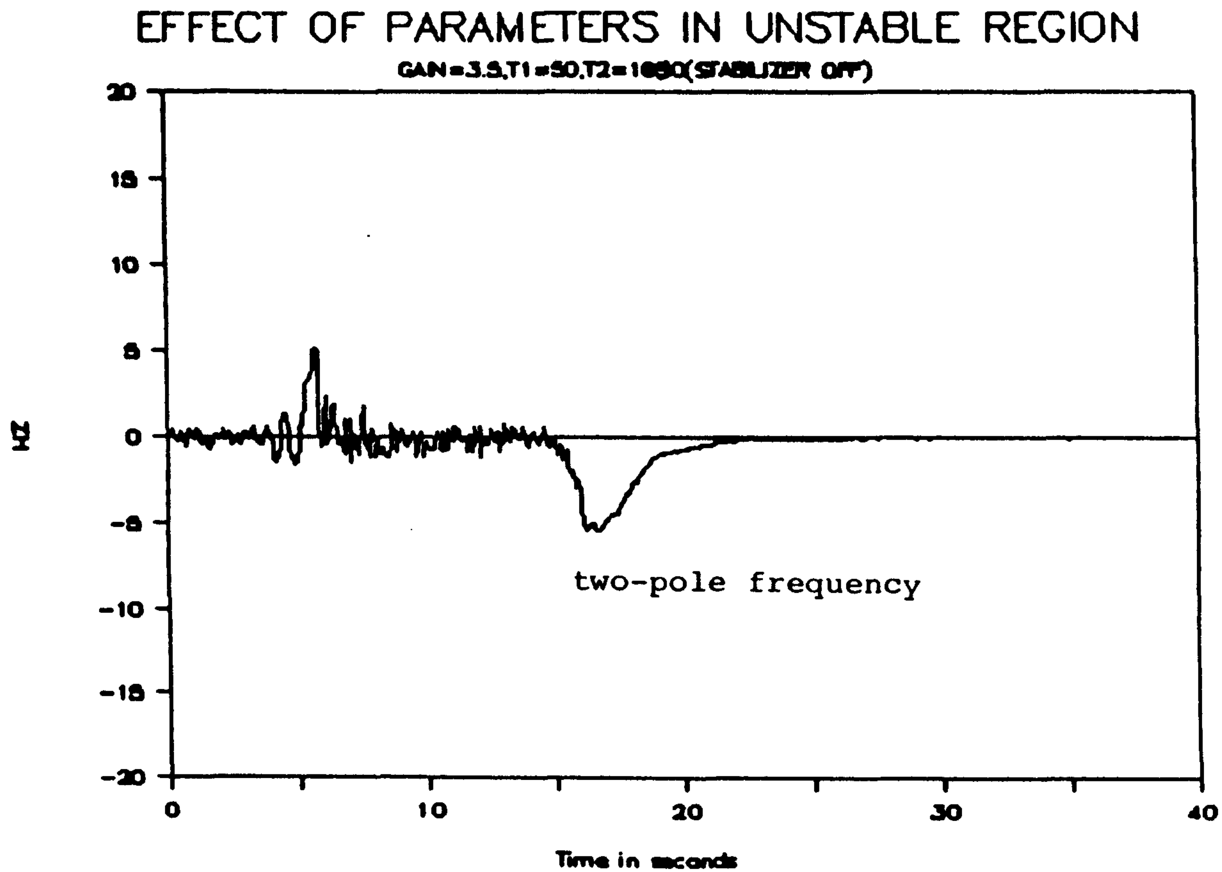


Fig. 5.6 (c) Effect of Parameters in Unstable Region Without Stabilizer

given a value lower than 1 millisecond, the input waveform was found succeptable to harmful effects due to noise. A value of T_1 greater than 100 milliseconds resulted in the stabilizer loosing sensitivity to RPM changes. The best value of T_1 was found to be 50 milliseconds. Similarly the effect of time constant T_2 was studied at a high value of 2500 milliseconds and a low value of 500 milliseconds. The best value was found to be 1500 milliseconds, at which the machine was found to operate in the stable mode (Figure 5.6 (d)).

The best values of k, T_1 and T_2 were taken and the limiter set at +/- 5 Hz. The output waveform shows that there are undesirable oscillations present in the system. This shows that the control is not optimal and requires modification in order to enable smoother operation in the unstable region.

5.7 Conclusion

The results described above demonstrate that the stabilizer enables the brushless doubly-fed machine to be operated in the synchronous mode over the entire speed range. Although it was found that the machine does not exhibit significant difference in its behavior in the stable region, there is a remarkable improvement in the

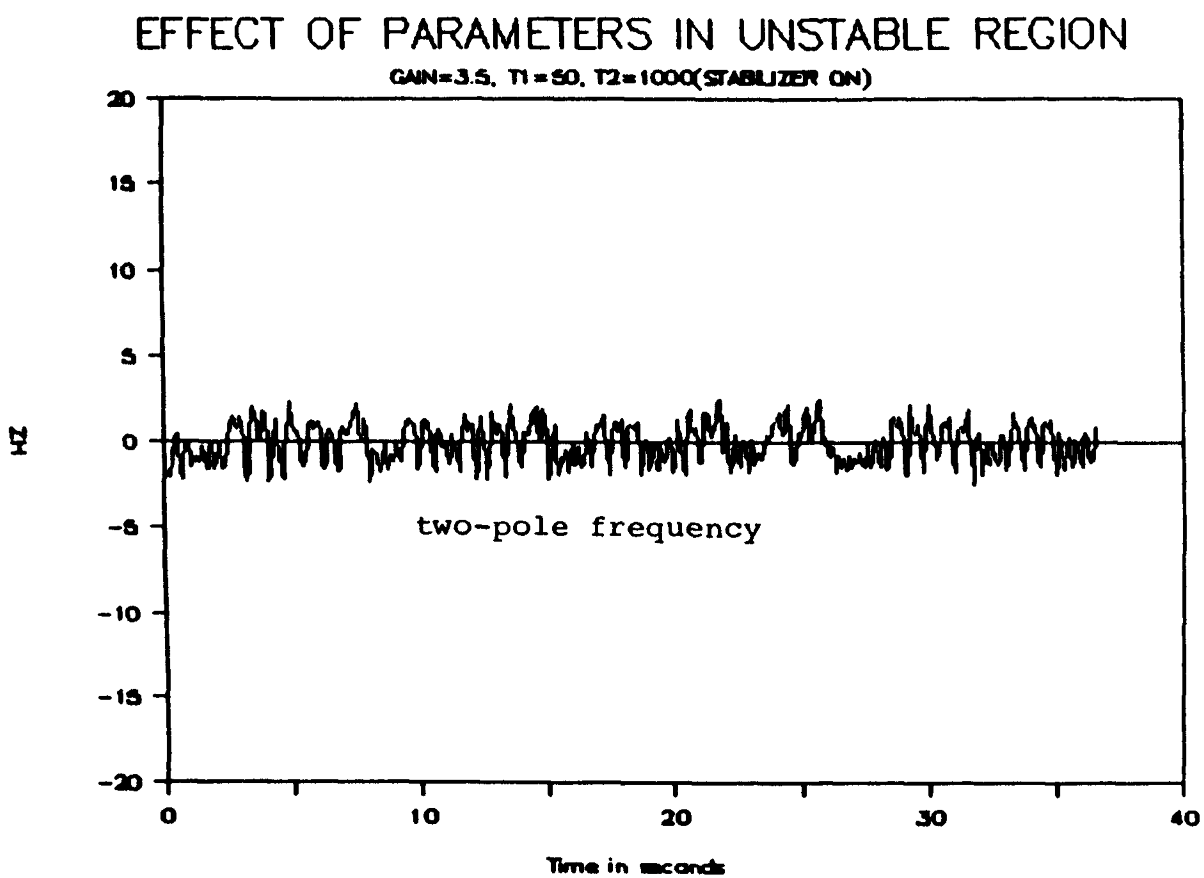


Fig 5.6(d)Effect of Parameters in Unstable Region With Stabilizer

unstable region. However, the performance of the brushless doubly-fed machine in the unstable region was found to be rather marginal and some bounded oscillations could still be observed. Significant improvement in the stabilizing control strategy is needed before the result can be classified as acceptable for the purpose of employing the brushless doubly-fed machine for any practical use. Suggestions for improvement will be included in the next chapter.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The outstanding feature of the brushless doubly-fed machine is the lack of need for a wound rotor with slip rings. Implementation of a stabilizer to eliminate the inherent instability of this machine facilitates its use in adjustable-frequency drives and in variable-speed generation systems. Reduced cost and maintenance requirements are benefits as compared to other kinds of electric machinery.

The characteristics of the brushless doubly-fed machine, the nature of its instability, an easily implemented feed back control and results of implementation have been presented. The stabilizer is of the form of a band pass filter applied to a feed back signal of the output current amplitude of the converter. This feed back enables the eigen-value of the system matrix responsible for the instability to be shifted into the left-half plane of the complex domain, thus rendering the system stable.

In order to overcome oscillations due to unstable operation, the stabilizer requires a minimum speed of response of 15 Hz which corresponds to a processing time of 10 milliseconds. The data acquisition and signal processing routines developed were within 3 milliseconds, rendering the stabilizer effective in achieving stable operation.

The task of achieving synchronous operation and speed control over the entire speed range is successful. There is significant improvement in the performance of the machine with regard to synchronization characteristics, frequency separation, speed control and speed performance in the unstable region.

It is found that the stability of the machine in certain speed regions is still marginal and some bounded oscillations can be observed in spite of using the stabilizer. Moreover, the rate of change of shaft-speed has to be rather low in order to maintain stable operation. Improvements on the control strategy of the stabilizer is necessary before the result can be classified as acceptable for application of the machine in practical applications.

6.1 Further Research

A rigorous method for designing the stabilizer based on the D-Q model of the brushless doubly-fed machine is suggested to obtain optimal results. A minimal-order representation of the machine based on its D-Q model and its performance relevant to stabilization process has to be developed. The stabilizer should be designed by using a root-locus based approach on the minimal-order representation to determine the necessary compensation.

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