Dsp Implementation Of Dc Voltage Regulation Using Adaptive Control For 200 Kw 62000 Rpm Induction Generator

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DSP IMPLEMENTATION OF DC VOLTAGE REGULATION USING
ADAPTIVE CONTROL FOR 200 KW 62000 RPM
INDUCTION GENERATOR

by

OTHMAN ELKHOMRI
B.S. University of Central Florida, 2003

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
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in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

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2006
ABSTRACT

The thesis discusses the development of closed loop system to control the DC voltage for 200 kW induction generator rated at a speed of 62000 RPM under different load conditions. The voltage regulation has been implemented using PI controller. A gain scheduling control algorithm has been developed to select the appropriate controller gains with respect to the generator load. Further, a relationship between the generator loads and the controller gains has been established. This relationship has been modeled using adaptive control technique to vary the gains automatically at any load condition.

The adaptive control technique has been successfully generalized for real time DSP implementation to regulate the DC voltage for high speed induction generators rated from 5 kW to 200 kW.
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LIST OF SYMBOLS

$\omega_e$  
 electrically synchronous angular velocity

$i_{ds}^e$  
 d-axis stator current in the synchronously rotating reference frame

$\lambda_{dr}^e$  
 d-axis rotor flux in the synchronously rotating reference frame

$\lambda_{qr}^e$  
 q-axis rotor flux in the synchronously rotating reference frame

$v_{qs}^e$  
 q-axis stator voltage in the synchronously rotating reference frame

$i_{qr}^e$  
 q-axis stator current in the synchronously rotating reference frame

$v_{ds}^e$  
 d-axis stator voltage in the synchronously rotating reference frame

$\omega_{sl}$  
 electrically slip angular velocity

$L_m$  
 magnetizing inductance

$T_e$  
 electromagnetic torque

$\lambda_{qs}^e$  
 q-axis stator current in the synchronously rotating reference frame

$\lambda_{ds}^e$  
 d-axis rotor flux in the synchronously rotating reference frame

$\omega_{sl}$  
 electrically slip angular velocity

$\omega_e$  
 electrically synchronous angular velocity

$\omega_r$  
 electrically rotor angular velocity

$f$  
 supply frequency

$K_i$  
 integral gain

$K_p$  
 proportional gain

$K_T$  
 torque constant
\( L_m \)  \hspace{1cm} \text{mutual inductance}

\( L_r \)  \hspace{1cm} \text{rotor inductance}

\( P \)  \hspace{1cm} \text{number of poles}

\( R_r \)  \hspace{1cm} \text{rotor resistance}

\( \Theta_r \)  \hspace{1cm} \text{angular position (phase) of the vector of rotor flux in the stator reference frame}

\( \tau_r \)  \hspace{1cm} \text{rotor time constant}

\( \omega \)  \hspace{1cm} \text{supply radian frequency}

\( \omega_r \)  \hspace{1cm} \text{slip}
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional and Integral (controller)</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>EMF</td>
<td>Electro Motive Force</td>
</tr>
<tr>
<td>FOC</td>
<td>Field Oriented Control</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Plus-Integral (controller)</td>
</tr>
<tr>
<td>SVM</td>
<td>Space Vector Modulation</td>
</tr>
<tr>
<td>TI</td>
<td>Texas Instruments</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per Minute</td>
</tr>
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</table>
CHAPTER ONE: INTRODUCTION

1.1 Background

When an induction machine is driven from external prime mover at a speed greater than synchronous speed, it works as induction generator as long as reactive power is supplied. Basically, the excitation current is supplied to the armature winding from which it is induced into the short circuited squirrel cage secondary winding in the rotor.

At no load the induction generator can be excited provided with enough excitation current. DC voltage can stay constant as long as a constant speed is maintained. However, as the generator load is increased or the speed varies, the DC voltage decreases or become unstable respectively. In order to maintain a constant voltage, the excitation current needs to be adjusted during load variation from no load to full load. Using high power switching IGBT’s, this issue can be solved. Induction generator can be controlled by adjusting the excitation current based on the load condition.

DC voltage control of induction generators is a topic that has been investigated by engineers and researchers for the last decade [1-4]. Many numerical methods have been proposed to predict the transient and the steady state performance of induction generators [2, 3, 4], most of them were unpractical for implementation. The complication was that the generator mathematical model is composed of linear differential equations with periodically time-varying inductance coefficients assuming rotor speed constant [4].

In 1965, Krause noted [8] that all known real transformations used in induction machine analysis could be described by one general transformation (Park transformation) which eliminates all time-varying inductance by referring the stator and rotor variables to a frame of
reference which may rotate at any angular velocity or remain stationary. The physical meaning of the Park transformation is to define a new set of stator and rotor variables in \((dq)\) frame in terms of the actual winding variables \((abc)\) in stationary frame. This method has been further developed to Field oriented control (FOC) schemes.

FOC schemes are implemented to operate the generator in the maximum torque conditions available and to decouple the maximum torque from the field under transient and steady state operation. The FOC algorithm transforms the three phase sinusoidal currents from the stationary reference frame to DC quantities in rotating reference frame. The rotating reference frame is composed of the direct current component and the quadrature current component which are to be orthogonal to each other. Typically, these currents are regulated by Classical Proportional and Integral (PI) controllers because of their simple implementation. However, PI controllers do not perform well when controlling high order non-linear dynamic plants - such as the high speed induction generators - due to the overshoot response and the output saturation when generator is loaded.

The focus of this work was the development and implementation of the closed loop control system for a high speed induction generator using LF 2407 Texas Instruments (TI) Digital Signal Processor (DSP). A motor closed loop controller was also developed to drive the generator. A gain scheduling algorithm was developed and applied to the PI DC voltage regulator to enhance the overall closed loop performance at three load conditions. This algorithm was successfully implemented and experimentally verified. Furthermore, an adaptive control algorithm was generalized and implemented in real-time to regulate DC voltage for any load condition.
1.2 Problem Statement

DC voltage regulation using PI controller with FOC algorithm determines the overall system performance for the generator. When a sudden step load is applied, the PI controller became unstable. The transient voltage response was not well controlled due to the characteristics of the PI controller. Two issues have been found: (1) overshoot response caused by a large error between the DC voltage command to the sensed DC voltage. (2) the voltage response between step loads is very slow due to the fixed proportional and integral gain controller. Furthermore, DC voltage regulation becomes unstable and causes the generator to de-excitation. The source of this issue is that PI controller gains cannot be set to satisfy both the overshoot and load variation simultaneously.

To overcome this issue, the proportional gains need adjustments with respect to the load variation as well as the overshoot response in real-time. A gain scheduling control algorithm has been developed. This algorithm represents a set of linear controllers, each of them designed for a specific load condition. Thus, when the generator is under a certain load condition, the algorithm control signal determines which linear controller to activate. The gain scheduling algorithm was implemented successfully to regulate the DC voltage at load conditions where the gains were predetermined. Later a relationship between the proportional, integral gains and the load conditions has been established. The relationship allowed the development of an adaptive control technique to vary the gains automatically at any load condition. The adaptive control technique has been tested from 0 to 5 kW.
1.3 Thesis Overview

Beginning with Chapter 2, the generator closed loop control is discussed in details including induction generator dynamic modeling, principle of the FOC conditions and schemes. Also, closed algorithm implementation including space vector modulation is discussed. Finally, digital control implementation issues using fixed point programming with the TI C2000 platform are mentioned. Chapter 3 discusses the development of the gain scheduling algorithm and how the proportional and integral gains have been obtained. Verification of this method was tested at 44000 RPM with a 48.6 kW load. Chapter 4 addresses the developed adaptive control algorithm including the curve fitting analysis. The adaptive control algorithm has been tested at 12000 RPM with a 5.1 kW load. Finally, Chapter 5 is a conclusion of the work.
CHAPTER TWO: GENERATOR CLOSED LOOP CONTROL

2.1 Introduction

As mentioned previously, in order to maintain a constant DC output voltage, the excitation current need to be adjusted accordingly to the generator load condition. For high performance control, closed loop algorithm using FOC are implemented to control the generator at various loads.

2.2 Induction Machine Dynamic Modeling

The mathematical model of the induction machine (IM) in the synchronously rotating reference frame when \( w = w_e \) is shown as follow:

\[
\frac{di_{qs}}{dt} = -\gamma_{qs} i_{qs} - \omega_{e} i_{ds} - \beta \omega_{e} \lambda_{dr} + \beta \alpha \lambda_{qr} e + \beta \lambda_{qs} \quad (2.1)
\]

\[
\frac{di_{ds}}{dt} = -\gamma_{ds} i_{ds} + \omega_{e} i_{qs} + \beta \omega_{e} \lambda_{qr} e + \beta \alpha \lambda_{dr} e + \beta \lambda_{qs} \quad (2.2)
\]

\[
\frac{d\lambda_{qr} e}{dt} = -\alpha \lambda_{qr} e - \omega_{e} \lambda_{dr} e + \alpha L_{m} i_{qs} e \quad (2.3)
\]

\[
\frac{d\lambda_{dr} e}{dt} = -\alpha \lambda_{dr} e + \omega_{e} \lambda_{qr} e + \alpha L_{m} i_{ds} e \quad (2.4)
\]

\[
T_e = \frac{3}{2} \frac{p}{2} \frac{L_m}{L_r} (\lambda_{dr} e i_{qs} - \lambda_{qr} e i_{ds}) \quad (2.5)
\]

where:

\[
\lambda_{qs} e = \left(\frac{L_s L_r - L_m^2}{L_r}\right) i_{qs} e + \frac{L_m}{L_r} \lambda_{qr} e \quad (2.6)
\]
\[
\chi_{ds} = \left( \frac{L_s L_r - L_m^2}{L_r} \right) i_{ds} + \frac{L_m}{L_r} \chi_{dr}
\]  
(2.7)

\[
\omega_s = \omega_c - \omega_r
\]  
(2.8)

\[
\sigma = 1 - \frac{L_m^2}{L_s L_r}
\]  
(2.9)

\[
\alpha = \frac{R_r}{L_r}
\]  
(2.10)

\[
\beta = \frac{L_m}{\sigma L_s L_r}
\]  
(2.11)

\[
\beta_1 = \frac{1}{\sigma L_s}
\]  
(2.12)

\[
\gamma = \frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_s L_r^2}
\]  
(2.13)

To visualize the induction machine dynamic model, a block diagram of the dynamic model has been drawn in Figure 1.
The block diagram illustrates the source of difficulties in the control. Four multipliers make the model nonlinear. The FOC scheme represents a special case to simplify the dynamic model.

2.3 Field Orientation Condition

When the synchronously rotating reference frame is aligned with the rotor flux angle, d-axis angle will be defined on the total rotor flux angle. The condition is made when \( \omega_r = \omega_s \).

Then the q-axis rotor flux becomes zero, \( \lambda^r_{qr} = 0 \). This condition reduces the model to:

\[
T = K_T \lambda^r_{sr} i^r_{qs} \tag{2.14}
\]

where
\[ K_r = \frac{P}{3R_c} \frac{L_m}{\tau_r} \] \hspace{1cm} (2.15)

So now when \( \lambda_{QR} = 0 \) and \( \lambda_{DR} = Cons \tan t \) is a constant, the induction generator can be linearly controlled. Figure 2 illustrates the block diagram of the equation.

![Figure 2: Simplified induction machine dynamic model](image)

2.4 Field Oriented Control Scheme

The main goal of the FOC system is to independently control torque and flux of an AC generator by using the rotor flux angle to transform the sinusoidal variables (i.e., currents, voltages, flux, etc.) to the DC-type quantities. Such transformation is called Park transformation [1]. The Park Transformation converts vectors in balanced two-phase orthogonal stationary system into orthogonal rotating reference frame. The transformation equation is of the form:

\[ [f_{dq}] = [T_{dq} (\theta_d)] [f_{αβ}] \] \hspace{1cm} (2.16)

where variable \( f \) can be currents, voltages, or fluxes and \( \theta_d \) is the angle between \( α \)-axis and \( d \)-axis as shown in Figure 3.
and the $dq$ transformation matrix is defined as

$$[T_{dq}(\theta)] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \quad (2.17)$$

For the transformation to occur correctly and the dq-axis currents become DC component, it is mandatory that $\alpha$-axis and $\beta$-axis to be 90° phase shifted and no offset in the amplitude and also rotor flux angle to be correct. Otherwise, the vector control scheme fails. To obtain the two-phase orthogonal stationary system, another transformation, called Clarke Transformation [2], which is used as an intermediary between abc-axis stationary reference frame to dq-axis synchronously rotating reference frame. The Clarke Transformation is the method to transfer the three-phase into the two-phase in stationary coordinate system. In Figure 4, the three-phase variables are denoted as $a$, $b$ and $c$ and the two-phase variables are denoted as $\alpha$ and $\beta$. 

![Figure 3: Relationship between $a\beta$ axis and $dq$ axis.](image)
A third variable known as the zero-sequence component is added to make the transformation to be bi-directional

\[
\begin{bmatrix}
    f_{\alpha\beta 0} \\
    \vdots
\end{bmatrix} = \begin{bmatrix}
    T_{\alpha\beta 0}
\end{bmatrix}\begin{bmatrix}
    f_{abc}
\end{bmatrix}
\]  \hspace{1cm} (2.18)

where variable f can be currents, voltages, or fluxes, and the transformation matrix is given by

\[
T_{\alpha\beta 0} = \frac{2}{3} \begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\
    \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  \hspace{1cm} (2.19)

As mentioned previously, The FOC defines conditions for maximum torque and the decoupling of torque control from the field control for both steady state and transient conditions. To operate in the maximum torque region, the rotor currents and the flux vectors must be maintained orthogonal to each other at all times.
However, to meet orthogonality during transient conditions, FOC special techniques are required. Two approaches are mainly implemented in induction generator control. First, the direct FOC scheme that is based on measuring the magnetic field using a sensor mechanically installed in the generator. Second, the Indirect FOC scheme that does not involve a direct measurement of the flux but the mechanical speed is sensed instead. The speed information is used to align the rotating and excitation reference frame with the rotor flux vector.

The 200 kW induction motor and generator closed loop control has been implemented using the indirect FOC techniques. Also a special case of the indirect FOC scheme [7] has been implemented which operates at maximum torque at all operation. The next section will discuss this scheme.
2.5 200 kW Induction Generator Closed Loop Algorithm

The closed loop control algorithm is based on selecting the D-Q axes so that the direct current and the quadrature current are equal. Equation 2.20 shows the developed torque as a result of $I_D = I_Q$.

$$T = K_T (I_{DQ}^2) \left( \frac{\tau_r \omega_s}{\tau_r^2 \omega_s^2 + 1} \right)$$  \hspace{1cm} (2.20)

where

- $K_T$ = Torque Constant, $\frac{Nm}{A^2}$
- $I_{DQ}$ = $\sqrt{2}I_D$, A
- $\tau_r$ = Rotor time constant, s
- $\omega_s$ = Slip frequency, $\frac{rad}{s}$

For maximum torque,

$$\tau_r = \frac{1}{\omega_s}$$  \hspace{1cm} (2.21)

$$T = \frac{1}{2} K_T I_{DQ}^2$$  \hspace{1cm} (2.22)

Equation (2.22) summarizes the mechanism of the generator closed loop algorithm. The $I_{DQ}^2$ total current is generated from two loops. The voltage loop generates the reference and the current loop generates the feedback then compared and controlled by PI current regulator. The output of the PI regulator provides the duty ratio information to the three-phase inverter power switches. Figure 5 illustrates the $I_{DQ}$ generated from the current loop.
Figure 5: $I_{dq}$ from the current loop

Phase a and Phase c currents are sensed and Phase b current is calculated. The calculation of Phase b is based on equation 2.23

$$i_a + i_b + i_c = 0 \quad (2.23)$$

Figure 6 and 7 illustrate the actual Phase a and c currents with 240° phase shift respectively.

Figure 6: Phase a current
Then the Clarke Transformation is implemented to convert the phase currents into $\alpha$ and $\beta$ currents which are 90° phase shifted. Figures 8 and 9 illustrate the actual $\alpha$ and $\beta$ currents respectively.

Figure 8: $\alpha$ current
Further, $I_{DQ}$ is calculated by normalizing the output of the Clarke Transformation as:

$$I_{DQ} = \sqrt{I_\alpha^2 + I_\beta^2}$$

(2.24)

The square calculation $I_\alpha$ and $I_\beta$ contributes into spikes in the $I_{DQ}$ current. Furthermore, $I_{DQ}$ current signal fidelity deteriorated and resulted into instability of the loop. A first order low pass digital filter has been implemented to remove unwanted data. Figure 10 shows the filtered $I_{DQ}$. 

![Figure 9: $\beta$ current](image)
Secondly, the $I_{dq}$ reference generated by the voltage loop is illustrated in Figure 11.

![Figure 11: DC voltage control loop](image)

Both the DC voltage command and DC voltage feedback are sensed and controlled by a PI regulator. The output of the PI regulator is the $I_{dq}^2$ current that will act as the reference to the PI current regulator. The $I_{dq}^2$ current is then taken through an absolute value and square root...
function to obtain $I_{dq}$. The absolute value function is necessary because when the generator is under load, the $I_{dq}^2$ current may become negative in a short time and the square function will not work. Figure 12 shows $I_{dq}$ generated from the voltage loop.

![Figure 12: $I_{dq}$ generated from the voltage loop](image)

The generator speed is sensed and the slip is subtracted from it. The generator slip needs to be always subtracted for the generator to operate. Figure 13 illustrates the speed loop.

![Figure 13: Speed loop](image)
When the generator is under load, the \( I_{DQ}^2 \) current may become negative. The sign of the slip need change accordingly. Otherwise the \( I_{DQ}^2 \) current will saturate and results to instability of the loop. A sign function is implemented to control the slip sign. The sign function branches to two conditions:

1) If \( I_{DQ}^2 > 0 \) → slip subtracted

2) If \( I_{DQ}^2 < 0 \) → slip added

Figure 14 illustrates the 200 kW induction generator closed loop control algorithm.

Figure 14: Block diagram for closed loop control algorithm.
The closed loop algorithm inputs are shown on the left side of Figure 14. The commanded voltage, measured generator bus voltage, measured shaft speed, and measured three phase ac generator currents. Total \( I_{dq}^2 \) current is calculated from the current feedback loop. Then from the difference of the output voltage and the voltage command, the \( I_{dq}^2 \) current command is then generated. Both currents are compared and based on the error; (PI) current regulator generates the necessary switching commands for the six switches in the three-phase full bridge inverter using space vector modulation technique.

### 2.6 Space Vector Modulation for Three Phase Voltage Source Inverter

One of the most widely used method to control AC output of power electronic converters is the pulse width modulation (PWM) technique, which varies the duty cycle of the converter switches at a high switching frequency to achieve the desired output voltage or current [3]. The combination of both the fast switching IGBT and the advanced DSP technologies, make it possible to improve systems efficiency. Several PWM techniques are available, the 200 kW generator inverter used the Space Vector PWM technique (SVPWM). SVPWM is an advanced, computation-intensive PWM method with superior performance characteristics. It has been shown that SVPWM generates less harmonic distortion in the output voltage or current in comparison with sine wave PWM and hysteresis control [9].

#### 2.6.1 Three-Leg Voltage Source Inverter

The topology of a three-leg voltage source inverter is shown in Figure 15.
Figure 15: Three-leg voltage source inverter

Because of the constraint that the input lines must never be shorted and the output current must always be continuous, the voltage source inverter can assume only eight distinct topologies.

2.6.2 Voltage Space Vector

For a three-phase voltage source inverter (VSI), shown in Figure 15, $V_a$, $V_b$ and $V_c$ are the output voltages and $M_1$, $M_2$, ... through $M_6$ are power IGBT which are controlled by gate signal. When the upper IGBT's are turned on, i.e. $a$, $b$ or $c$ is 1, the lower sides are turned off, i.e. $a^*$, $b^*$ or $c^*$ is 0. SV PWM determines the switching sequence of upper sides. The on and off status of the three upper transistors compose eight possible vectors. They are denoted by $U_0$, $U_{60}$, $U_{120}$, $U_{180}$, $U_{240}$, $U_{300}$, $O_{000}$ and $O_{111}$, as shown in Figure 16.
There are six non-zero vectors and two zero vectors. The six nonzero vectors form a hexagon as shown in figure 16. The angle between any two adjacent non-zero vectors is 60 degrees. Six out of these eight cases produce a nonzero output voltage and are known as non-zero switching states and the remaining two topologies produce zero output voltage and are known as zero switching states.

2.6.1 Space Vector Modulation

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector $V$ rotating in the counter clock wise direction. The magnitude of this vector is related to the magnitude of the output voltage. The time this vector takes to complete one revolution is the same as the fundamental time period of the output voltage. Table 1 gives a
summary of the switching states and the corresponding line to line voltages after normalized by DC voltage $V_{dc}$ of the three-phase voltage source inverter.

Table 1

SV PWM switching states [5]

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>$v_{ab}$</th>
<th>$v_{bc}$</th>
<th>$v_{ca}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Simulation of the space vector has been conducted to verify the functionality of the space vector modulation. Figure 17 illustrates space vector generation loop.
Three-phase currents are multiplied by the modulation index (M) which is the ratio of the peak to peak AC voltage to the DC voltage. It determines the width of the pulses and therefore the RMS value of the inverter output voltage. M is usually adjusted by varying the amplitude of the reference wave while keeping the carrier wave amplitude fixed. The inverter output frequency is varied by varying the reference wave frequency [6]. This loop generates the control signal that includes the duty ratio information. Figure 18 illustrates the control signal.

Figure 17: Block diagram of space vector
Then, Figure 19 illustrates the loop for PWM generation and Figure 20 illustrates the simulated three phase.
The output space vector trajectory has been modeled to verify the magnitude and frequency of the output voltage. Figure 21 illustrates the output space vector trajectory.

Figure 20: Three phase PWM signals
Figure 21: Output space vector trajectory

2.6 Digital Controller Implementation Issues

This section discusses some of the issues involved in implementing digital controllers including finite word length effect, closed loop algorithm sampling rate and code development.

2.6.1 Finite Word Length Effects

The Texas Instruments C2000 platform uses a fixed arithmetic processor. For the case of the 2407 DSP, it has 16 bits available for representing the magnitude of a signal. Signals have to be scaled to fit into the dynamic range and word length of the processor. Otherwise noise is
created and results in program instability. Word length can also be an issue when multiplying two 16 bit variables which require 32 bit storage. The higher 16 bits are stored and the lower are thrown away. This situation results in loss of precision due to round off error. This error grows as the closed loop algorithm iterates. Therefore, the selection of proper scaling is very critical in minimizing the round off error caused by a finite word length.

2.6.2 Closed Loop Algorithm Sampling Rate

One of most important design parameters in control system is the algorithm sampling rate. The 200 kW induction generator closed loop algorithm is chosen to be ten times the system bandwidth. Figure 22 illustrates the closed loop algorithm sampling rate.

![Diagram](image)

Figure 22: Closed algorithm sampling rate

The interrupt service routine period is 28 kHz and the closed loop algorithm sampling rate is $12.5 \text{us}$. 

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2.6.3 Software Development

Software for the 200 kW was developed using TI assembly language. Assembly language was used to save on the code overhead. The software loops were verified in real-time using kernel routines. Debugging in real-time implementation was necessary in order to access memory and register without stopping the processor. All software routines are available in the Appendix.
CHAPTER THREE: GAIN SCHEDULING METHOD

3.1 Gain Scheduling For Specific Load Conditions

Voltage regulation of the 200 kW induction generator has been implemented using a (PI) controller. For a nonlinear dynamic plant such as the 200 kW generator, PI controller’s are characterized by an overshoot response caused by a large error between the DC voltage command to the sensed DC voltage and also the voltage response between step loads is very slow due to the fixed proportional and integral gain controller Figure 23 shows a block diagram of a PI controller.

Figure 23: Classical proportional and integral controller

The proportional path adjusts the $I_{Qref}$ in direct proportion to the $V_{fdb}$. The larger the proportional gain, the larger the $I_{Qref}$ will change for a given error. The proportional path reduces the error however, does not eliminate it; there is always an offset between $V_{ref}$ and $V_{fdb}$. The integral path corrects for any offset that may occur between $V_{ref}$ and $V_{fdb}$ automatically over time.
As the 200 kW generator load varied, the DC voltage regulation became unstable in the transient region (between loads) when the PI gains were fixed to a constant value. Furthermore, this instability contributed to the 200 kW generator de-Excitation. To eliminate this issue, the proportional gains are required adjustments with respect to the load conditions. Finding the gains for each load condition was the key to appropriately regulate the voltage. A closed loop algorithm was developed with capability to change $K_p$ and $K_i$ as the generator load varies in real-time. Transient tests have been conducted to find the gains at 44000 RPM at no load then at 32.8 kW and 48.6 kW.

3.2 Search of Proportional & Integral Gain Using Ziegler-Nichols Tuning Method

The search for $K_p$ and $K_i$ in the unstable regions has been conducted through transient tests. The gains were obtained by using Ziegler-Nichols tuning method [10], since the generator is not been modeled mathematically. The procedure of this method is conducted by setting $K_p$ to a low value and $K_i$ to zero. Then a voltage step is applied at no-load then at 32.8 kW and 48.6 kW to investigate the DC voltage transient. When the PI output oscillations decay, $K_p$ has to be increased. Then, when the oscillations increase in amplitude (unstable system), $K_p$ has to be reduced. At the point of stability, $K_i$ is set to a value to eliminate the steady state error. This method is iterated until the range over which $K_p$ and $K_i$ varied is obtained.

A constant value of $K_i$ is found to be adequate under both load conditions. However, $K_p$ has to be increased by 36 % when the step load was applied from 32.8 kW to 48.6 kW. Table 2 shows the values for $K_p$ and $K_i$ under 0, 32.8kW, and 48.6 kW load conditions.


Table 2

$K_p$ and $K_i$, under different load condition

<table>
<thead>
<tr>
<th>POWER, kW</th>
<th>REGULATED VOLTAGE, Volt DC</th>
<th>$K_p$</th>
<th>$K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>270</td>
<td>0</td>
<td>9000</td>
</tr>
<tr>
<td>32.8</td>
<td>270</td>
<td>1100</td>
<td>9000</td>
</tr>
<tr>
<td>48.6</td>
<td>270</td>
<td>1500</td>
<td>9000</td>
</tr>
</tbody>
</table>

After gathering $K_p$ and $K_i$ with respect to their load conditions, these values have been programmed into a scheduling algorithm. Figure 24 shows block diagram of the generator closed loop algorithm.
The product between the DC voltage and the DC current signals has been established to obtain the power. The power value is processed in a look up table module to search for the pre-selected load conditions to use. Then, each set of $K_p$ and $K_i$ values is reserved in an array and
stored until triggered by the power signal. This method works such as there is a linear controller for each condition. Based on the load, the PI regulator receives the corresponding gains for that condition. Figure 25 illustrates the responses of the DC voltage, DC current and space vector command respectively under the tested load conditions.

Figure 25: DC voltage, DC current and space vector command versus time
The gain scheduling method has been successfully implemented to regulate DC voltage of the 200 kW generator under 32.8 kW and 48.6 kW. However, in order to regulate at all load conditions, this method has been generalized and was able to tune the PI controller gains over all load condition. The next chapter discusses a generalized adaptive method.
CHAPTER FOUR: ADAPTIVE METHOD

4.1 Adaptive Method For Any Load Condition

The gain scheduling method discussed in chapter 3 is further developed to maintain a constant DC voltage of the generator to any load condition. The idea is to implement an algorithm that automatically regulates $K_p$ according to any load condition. To develop this kind of algorithm, a relationship between $K_p$, $K_i$ and power needs to be established. However, in the case of the 200 kW generator, a constant $K_i$ is found to be adequate. Only $K_p$ and power relationship needs to be established. Based on the transient tests data, proportional gains are fitted through polynomial curves to represent this relationship. Figure 26 illustrates $K_p$ versus power.
Figure 26: $K_p$ versus power
Analysis of curve fitting has been conducted for first and second order polynomial to find the best fit. The reason to sequentially implement from a lower order polynomial is related to the algorithm computation speed. The lower the order of the polynomial the faster the closed loop algorithm will compute. Figure 27 illustrates the curve fit for the first and second order polynomial.
Figure 27: First and second order polynomial
4.2 First Order Polynomial

The first order polynomial has been implemented and tested initially. Figure 28 illustrates the curve fitting and offsets.

Figure 28: First order fit
The first order polynomial is not capable of regulating $K_p$ because at start up an offset of 173 exists and results in instability of the loop. This results further the investigation into the second order fit.

4.3 Second Order Polynomial

The second order polynomial has been implemented and tested. Figure 29 below illustrates the curve fitting and offsets.

![Graph showing the second order fit with equation $y = -0.47x^2 + 52x + 34$.](image)

Figure 29: Second order fit
The second order polynomial has been successfully implemented to regulate $K_p$. The concern is that an offset of 35 existed, however it does not affect the stability of the loop. The second order polynomial has been programmed in the Texas Instrument DSP 2407 and tested at 12000 RPM with four load conditions from 0 to 5.1 kW.

4.4 Results

The relationship between the proportional gains and power has been established with a second order polynomial. The 200 kW generator DC voltage regulation has been successfully tested at 12000 RPM with four load conditions from 0 to 5.1 kW. The proportional gains are automatically computed using the second order polynomial. Table 3 illustrates four load conditions from 0 to 5.1 kW and Figure 30 illustrates the responses of the DC Current, DC Voltage.

Table 3
Four Load conditions from 0 to 5.1 kW

<table>
<thead>
<tr>
<th>POWER, kW</th>
<th>VOLTAGE REGULATION</th>
<th>DC CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>2.7</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>4.02</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>4.74</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>5.1</td>
<td>60</td>
<td>85</td>
</tr>
</tbody>
</table>
Figure 30: DC current, DC voltage Versus Time
CHAPTER FIVE: CONCLUSION

In this thesis, closed control system has been developed successfully to control the DC voltage output of the 200 kW induction generator using Field Oriented Control. A gain scheduling control algorithm has been developed by selecting the appropriate controller gains with respect to the generator load. The gain scheduling control algorithm facilitates the understanding of the generator behavior which resulted in developing a better approach to control the DC voltage adaptively. Both the gain scheduling and adaptive control methods have been implemented to successfully regulate DC voltage. However, the adaptive method is better approach because it can be tailored to work for high speed induction generators rated from 5 kW to 200 kW.

Finally, some suggestions can be provided for future development: (1) use of a more powerful DSP such as the TI 28XX series to implement adaptive based algorithms (sensorless speed sensing, slip control based on rotor temperature) to improve the generator controls, and (2) investigation of a compact packaging using DSP based system for noise-free operation.
APPENDIX : SYSTEM CLOSED LOOP SOFTWARE

System Reference

.include "x24x_app.h"
.global MON_RT_CNFG
.ref SYS_INIT
.ref RAMP_CNTL, RAMP_CNTL_INIT
.ref target_value
.ref rmp_dly_max, rmp_lo_limit
.ref rmp_hi_limit
.ref setpt_value, s_eq_t_flg
.ref DATA_LOG, DATA_LOG_INIT
.ref dlog_iptr1, dlog_iptr2
.ref trig_value
.ref FC_PWM_DRV, FC_PWM_DRV_INIT
.ref Mfunc_c1, Mfunc_c2, Mfunc_c3, Mfunc_p
.ref n_period
.ref ILEG2DRV, ILEG2DRV_INIT
.ref la_gain, lb_gain, la_offset, lb_offset
.ref la_out, lb_out
.ref CLARKE, CLARKE_INIT
.ref clark_a, clark_b
.ref clark_d, clark_q
.ref SPEED_PRD, SPEED_PRD_INIT
.ref time_stamp
.ref rpm_max, speed_scaler, shift
.ref speed_prd, speed_rpm
.ref event_period
.ref CAP_EVENT_DRV, CAP_EVENT_DRV_INIT
.ref CAP_EVENT_DRV_CLKPS_INIT
.ref CLK_prescaler_bits
.ref pid_reg_iq, pid_reg_iq_init
.ref iq_fdb, iq_ref, Kp_q, Ki_q, Kc_q
.ref Umax_q, Umin_q
.ref uq_int
.ref uq_out
.ref CURRENT_MODEL, CURRENT_MODEL_INIT;
.ref spd_cur_mod
.ref theta_cur_mod
.ref fs
.ref slip_freq
.ref pid_reg_spd,pid_reg_spd_init ; function call
.ref spd_fdb,spd_ref,Kp_spd,Ki_spd,Kc_spd
.ref spd_out
.ref spd_int
.ref qsqrt
.ref sqrt_input,sqrt_output
.ref sqrt2
.ref sqrt_input2,sqrt_output2
.ref SVGEN_MF, SVGEN_MF_INIT
.ref sv_gain, sv_offset, sv_freq
.ref Ta, Tb, Tc
.def GPR0
.bss GPR0,1
.bss GPR1,1
.bss GPR2,1
.bss my_iq_ref,1
.bss my_id_ref,1
.bss speed_reference,1
.bss isr_ticker,1
.bss test_cur_mod1,1
.bss test_cur_mod2,1
.bss test_cur_mod3,1
.bss speed_prdnew,1
.bss speed_prdlo,1
.bss speed_prdhi,1
.bss speedcoeff,1
.bss speedtemp,1
.bss speederrorlo,1
.bss speederrorhi,1
.bss sqrt_outputnew,1
.bss sqrt_outputlo,1
.bss sqrt_outputhi,1
.bss sqrt_outputcoeff,1
.bss sqrt_outputtemp,1
.bss sqrt_outputerrorlo,1
.bss sqrt_outputerrorhi,1
.bss sqrt_outputnew2,1
.bss sqrt_outputlo2,1
.bss sqrt_outputhi2,1
.bss sqrt_outputcoeff2,1
.bss sqrt_outputtemp2,1
.bss sqrt_outputerrorlo2,1
.bss sqrt_outputerrorhi2,1
.bss spd_out,1
System Interrupt Configuration

.sect "vectors"
.def _c_int0
RESET B _c_int0
INT1 B PHANTOM
INT2 B T1_PERIOD_ISR
INT3 B PHANTOM
INT4 B PHANTOM
INT5 B PHANTOM
INT6 B PHANTOM
.include "rtvecs.h"
.text
_c_int0:

System Initialization

CALL SYS_INIT
CALL FC_PWM_DRV_INIT

System Infinite Loop

MAIN:
M_1 NOP
NOP
NOP
B MAIN

System Interrupt Save & Restore
T1_PERIOD_ISR:
  MAR *,AR1 ;AR1 is stack pointer
  MAR *+ ;skip one position
  SST #1,*+ ;save ST1
  SST #0,*+ ;save ST0
  SACH *+ ;save acc high
  SACL * ;save acc low
  POINT_EV
  SPLK #0FFFFh,IFRA ; Clear all Group A interrupt flags (T1 ISR)
  SETC SXM ; set sign extension mode
  CLRC OVM ; clear overflow mode
  POINT_B0
    LACC isr_ticker
    ADD #1
    SACL isr_ticker

System Algorithm

CALL ILEG2DRV
LDP #clark_a
BLDD #Ia_out,clark_a
ldp #Ia_out
lacc Ia_out,16
add Ib_out,16
NEG
sach Ib_out
ldp #clark_b
BLDD #Ib_out,clark_b
CALL CLARKE
LDP #GPR0
BLDD #clark_d,GPR0
BLDD #clark_q,GPR1
spm 0
LT GPR0
MPY GPR0
PAC
LT GPR1
MPY GPR1
APAC
LDP #sqrt_input ;
sach
sacI sqt_input ;
call qsqrt
LDP #spd_ref
bldd #speed_prd,spd_fdb;non filtered
bldd #speed_prdnew,spd_fdb;filtered
CALL pid_reg_spd
LDP #test_cur_mod4
LACC test_cur_mod4
BCND TestMod4, NEQ
CALL RAMP_CNTL
LDP #target_value
LDP #spd_ref
BLDD #setpt_value,spd_ref
ldp #spd_out1
lacc spd_out1,15
LDP #sqrt_input2
sach sqrt_input2+1
sacl sqrt_input2
call qr2
setc SXM
cloc OVM
spm #1
ldp #sqrt_output
lacc sqrt_output,16
ldp #sqrt_outputlo
subs sqrt_outputlo
sub sqrt_outputnew,16
sacl sqrt_outputerrorlo
sach sqrt_outputerrorhi
lt sqrt_outputerrorlo
mpyu sqrt_outputcoeff
pac
sach speedtemp
lt sqrt_outputerrorhi
mpy sqrt_outputcoeff
pac
add speedtemp
adds sqrt_outputlo
add sqrt_outputnew,16
sacl sqrt_outputlo
sach sqrt_outputnew
LDP #iq_fdb
BLDD #sqrt_outputnew,iq_fdb
LDP #sqrt_output2
setc SXM
cloc OVM
spm #1
ldp #sqrt_output2
; Check for Capture event from Hall sensor (sprocket)

POINT_EV
BIT IFRC, BIT0

BCND SKIP_SPEED, NTC
CALL CAP_EVENT_DRV
LACC FIFO1

LDP #time_stamp
SACL time_stamp
CALL SPEED_PRD

setc SXM
clr OVM
spm #1
ldp #speed_prd
lacc speed_prd,16
ldp    #speed_prdlo
subs   speed_prdlo
sub    speed_prdnew,16
sacl   speederrorlo
sach   speederrorhi
lt     speederrorlo
mpyu   speedcoeff
pac
tsach speedtemp
lt     speederrorhi
mpy    speedcoeff
pac
add    speedtemp
adds   speed_prdlo
add    speed_prdnew,16
sacl   speed_prdlo
sach   speed_prdnew1
lacc   speed_prdnew1
sub     min
bcnd   S_gminq,GEQ   ; Continue if tmp_q>=U_min
lacc   min           ; otherwise, saturate
B      NextS
S_gminq
lacc   speed_prdnew1
sub     max
BCND   S_lmaxq,LEQ   ; Continue if tmp_q<=U_max
lacc   max           ; otherwise, saturate
b      NextS
S_lmaxq
lacc   speed_prdnew1
NextS
sacl   speed_prdnew
Int_termq
POINT_EV
SPLK   #0FFFFh,IFRC   ;Clear all CAP flags

SKIP_SPEED
Ldp    #spd_out1
Lacc   spd_out1
bcnd   TestMod3, gt
ldp    #skip_const
lacc   slip_input
neg
sacl   skip_const
LDP    #slip_freq
BLDD   #skip_const,slip_freq
b    TestModEnd33
TestMod3
  LDP  #slip_freq
  bldd  #slip_input, slip_freq
TestModEnd33
  LDP  #spd_cur_mod
  BLDD  #speed_prdnew, spd_cur_mod; Filtered
  BLDD  #speed_prd, spd_cur_mod; non filtered
  CALL  CURRENT_MODEL
  ldp  #test_cur_mod2
  lacc  test_cur_mod2
  bcnd  TestMod55, NEQ
  ldp  #sv_gain
  bldd  #uq_out, sv_gain
  b    TestModEnd55
TestMod55
  CALL  SVGEN_MF
  ldp  #sv_gain
  ldp  #test_cur_mod1
  lacc  test_cur_mod1
  bcnd  TestMod2, NEQ
  for test = 0
  ldp  #fs
  lacc  fs
  ldp  #sv_freq
  BLDD  #fs, sv_freq
  B    TestModEnd2
TestMod2
  ldp  #target_value
  ldp  #sv_freq
  bldd  #setpt_value, sv_freq
TestModEnd2
  LDP  #Mfunc_c1
  BLDD  #Ta, Mfunc_c1
  BLDD  #Tb, Mfunc_c2
  BLDD  #Tc, Mfunc_c3
  CALL  FC_PWM_DRV
  spm  #0
  ldp  #spd_out
  lt  spd_out
  ldp  #KT
  mpy  KT
  pac
  ldp  #spd_out1
sacl    spd_out1
sach    spd_outh

SETC XF
END_ISR:

POINT_PG0
MAR  *, AR1 ; make stack pointer active
LACL *- ; Restore Acc low
ADDH*- ; Restore Acc high
LST   #0, *- ; load ST0
LST   #1, *- ; load ST1
EINT
RET

PHANTOM  B  PHANTOM
LIST OF REFERENCES


