STUDY OF DIESEL DRIVEN LOCOMOTIVES WITH AC TRACTION

A Project Report

submitted by

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in partial fulfilment of the requirements
for the award of the degree of

MASTER OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS.

June 2017

THESIS CERTIFICATE

This is to certify that the thesis titled **STUDY OF DIESEL DRIVEN LOCOMOTIVES WITH AC TRACTION**, submitted by **PALEM BENNY SUDHAKAR**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bonafide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Date: 20th June 2017

ACKNOWLEDGEMENTS

This project would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this work.

First and foremost, my gratitude to Dr. Krishna Vasudevan, Project Guide and Professor, Dept. of Electrical Engineering, IIT Madras. It gives me great pleasure to express my sincere and heartfelt gratitude to him for his excellent guidance, motivation and constant support throughout my project. I consider myself extremely fortunate to have had a chance to work under his supervision. In spite of his hectic schedule, he was always approachable and took his time off to discuss problems and give his advice and encouragement.

I am grateful to Mr. Arun Chitrabhanu, research Scholar, without whose assistance this project would not have been successful. The discussions I had with him helped me to think in optimistic way. I am also thankful to Ms. Amrutha for providing her computer system to handle my simulation code.

Special thanks to Harikrishnan P, Pruthvi Chaithanya N and many others for their knowledge sharing in the time of need. I am also thankful to my friends Harshavardhan M, Chandra Kumarreddy U, Subodhkanth K, Madhav Rao D, Siva prasad K with whom I had most memorable time during my stay in IIT Madras.

ABSTRACT

KEYWORDS: Field Oriented Control; Automatic Voltage Regulator; Simulink; Diesel-electric locomotive.

The main focus of this project is towards studying and implementing the control schemes of diesel-electric locomotive which includes FOC and AVR. The Field Oriented Control (FOC) of induction machine is a control scheme which enables independent control of torque and speed, similar to that of a DC machine. AVR is used to regulate the generated voltage of alternator. The output AC voitage of alternator is rectified and given that DC voltage to inverter which is controlling the induction drive. There are some strategies based on controlling of induction machine and alternator.

This thesis presents a comprehensive study of two different control strategies of diesel-electric locomotives. Both the strategies were simulated in Simulink. Implementations of both the strategies have been carried out and their results have been listed and analysed. The conclusion also gives a brief overview of the possible research studies that can be carried after this study.

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ABBREVIATIONS

FOC	Field Oriented Control
PI	Proportional and Integral
DC	Direct Current
AC	Alternating Current
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
IGBT	Insulated Gate Bipolar Transistor
GE	General Electric
AVR	Automatic Voltage Regulator
CSI	Current Source Inverter
MI	modulation index

NOTATION

v_a, v_b, v_c	Instantaneous voltages in *abc* frame, V
$v_{s\alpha}, v_{s\beta}$	Instantaneous stator voltages in $\alpha\beta$ frame, V
v_{sd}, v_{sq}	Instantaneous stator voltages in *dq* frame, V
i_{rd}, i_{rq}	Instantaneous rotor currents in *dq* frame, A
$i_{s\alpha}, i_{s\beta}$	Instantaneous stator currents in $\alpha\beta$ frame, A
$i_{r\alpha}, i_{r\beta}$	Instantaneous rotor currents in $\alpha\beta$ frame, A
$\psi_{s\alpha}, \psi_{s\beta}$	Instantaneous stator flux in $\alpha\beta$ frame, Wb
$\psi_{r\alpha}, \psi_{r\beta}$	Instantaneous rotor flux in $\alpha\beta$ frame, Wb
L_s	Stator inductance , mH
L_r	Rotor inductance , mH
L_m	Magnetising inductance , mH
L_{ls}	Stator leakage inductance , mH
L_{lr}	Rotor leakage inductance , mH
R_s	Stator resistance , Ω
R_r	Rotor resistance , Ω
τ_r	Rotor time constant , sec
V_{dc}	Inverter DC bus voltage, V
ω_s	Rotor flux speed, rad/s
ω_r	Rotor speed, rad/s
$s\omega_s$	Slip speed, rad/s
K_p	Proportional gain of the PI controller
K_i	Integral gain of the PI controller
T_s	Sampling time for the control loops
G_i	Gain of the inverter

CHAPTER 1

INTRODUCTION

Locomotives is a rail transport vehicle that provides the motive power for a train. Locomotives may generate their power from fuel (wood, coal, petroleum or natural gas), or they may take power from an outside source of electricity. It is common to classify locomotives by their source of energy. Classification[12] of traction systems based on motive power is as follows.

1. Steam engine drive
2. Diesel engine drive
3. Electric engine drive
4. Hybrid engine drive

1.1 Steam engine drive

It is the first railway locomotives were powered by steam, usually generated from water by burning fuel like wood, coal, or oil in a boiler. Both fuel and water supplies are carried with the locomotive, the steam moves reciprocating pistons which are mechanically connected to the locomotive's main wheels (drivers).

Steam locomotive require much greater manpower to operate and service and less efficient than their more modern diesel and electric counterparts. The cost of crewing and fuelling a steam locomotive was some two and a half times that of diesel power, and the daily mileage achievable was far lower. It generates more heat and dirt. It require intensive maintenance, lubrication, and cleaning before, during, and after use.

1.2 Diesel engine drive

In this type of railway locomotive in which the prime mover is a diesel engine. The process of mechanical power generated by diesel engine is conveyed to driving wheels has been developed in different ways. Based on this it can be classified as Diesel-mechanical, diesel-electrical etc are discussed in Hybrid engine drive type.

Diesel locomotives offer significant operating advantages over steam locomotives. This is fully weather proof and without the dirt and heat. One person is enough to operate. It can be started and stopped almost instantly. Maintenance and operational coat is less compare to steam engine.

1.3 Electric engine drive

An electric locomotive is a locomotive powered by electricity from overhead line. Electricity is used to eliminate smoke and take advantage of the high efficiency of electric motors. It recovered the kinetic energy during braking to put power back on the line. Electrification results in higher performance, lower maintenance costs and lower energy costs. The circuit diagram of electric locomotive is shown in Fig. 1.1.

The choice of AC or DC over head line depends up on the distance. For long distance AC line is preferred to reduce losses. In order to supply power for long distances, it needs to be maintain high voltage and low current. Transformer is used to get the required rated voltage to driving wheels. This transformation is not possible in DC over head line.

From figure 1.1 DC motor is used as driving wheels, so AC supply is rectified to DC. In order to control this DC motor, the DC-DC chopper is used. If Induction motor is used as the driving wheels, the rectified DC voltage again have to convert to AC voltage by inverter. For controlling the induction motor PWM techniques are used. This can be easily explained from the table shown below

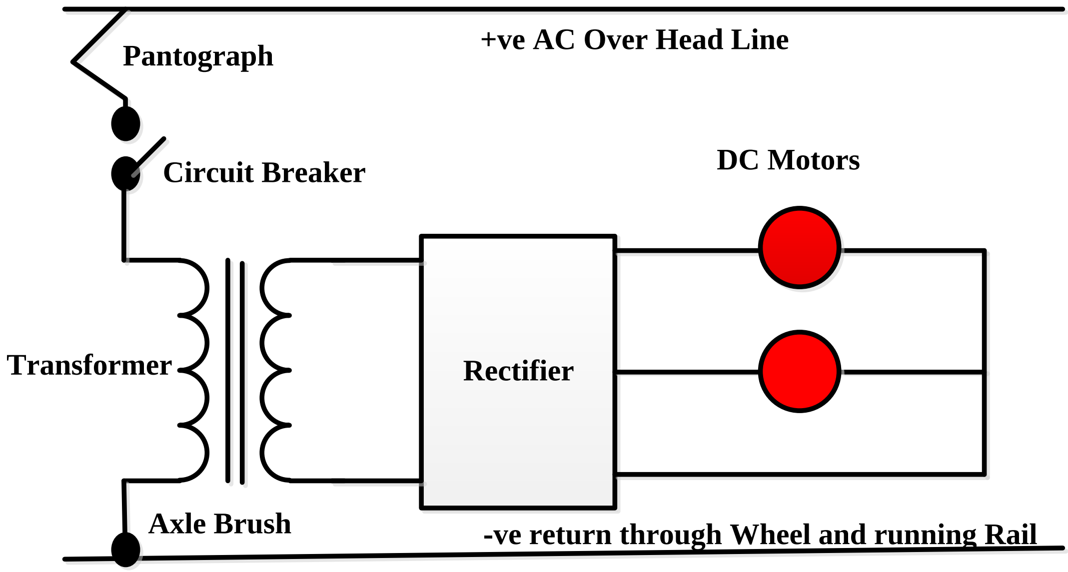

Figure 1.1: schematic diagram of electric locomotive

TO ⇓ FROM ⇒	DC SUPPLY SOURCE	AC SUPPLY SOURCE
DC Machine	Switched resistance or Chopper Control	Transformer and Phase Angle Control Rectifier
AC Machine	Chopper Input and Three Phase Inverter	Transformer and PWM Input and Inverter

The induction motor offer more advantage over DC motor[3], the three-phase motors had a higher power-to-weight ratio than DC motors. The manufacture and maintenance is simpler, because of absence of commutator. At starting it requires high torque, this can be achieved by DC series motor but speed control is not possible to this motor. After starting it necessary to change from DC series motor to DC shunt motor. Speed control is possible for DC shunt motor.

By using vector control or field oriented control, the flux producing component and the torque producing component of the input current is identified and controlled separately in a similar fashion of that of a separately excited DC machine.

Electric locomotives are quiet compared to diesel locomotives since there is no engine and exhaust noise and less mechanical noise. No need to carry their own fuel and fuel is supplied through the overhead cables. Electric trains are more environmentally friendly as emitting between 20 to 30 percent less carbon monoxide than their diesel counterparts. The efficiency and acceleration of this locomotive is much better than that of Diesel-electric locomotive.

The main disadvantages of using electric locomotives are the cost of the equipment is high, especially for long distances cost of over head line with electric equipment. Upgrading lines where obstructions, such as tunnels or bridges need to be altered. There is some fixed cost for electric traction that is not present for diesel locomotive. The consumption of power from the grid is very fluctuating.

Based on cost of operation Diesel locomotives are suitable for low traffic density, as for higher traffic density electric locomotives are the best choice of selection. Both have their respective pros and cons, then hybrid locomotives came into picture to overcome some of these limitations.

1.4 Hybrid engine drive

Hybrid locomotives are which in addition of locomotive they have fuel power source, electric engine. which additionally use a battery which acts as a temporary energy store used for the implementation of regenerative braking. Gas turbine-electric, fuel cell-electric, diesel-electric are some of the Hybrid locomotives. Out of these Diesel-electric locomotive with super capacitive energy storage[4] is more efficiently works. The working of Diesel-electric locomotive is explains as follows.

1.4.1 Diesel-electric locomotive

Diesel engine generates power used to rotate the driving wheels by mechanical gears is nothing but Diesel-mechanical drive. In order to utilise the advantages of electric drive, the power generated by Diesel engine used to rotate the rotor of alternator for getting Electric AC supply. Use that supply to run electric motors. Rectified that AC supply to

DC and then invert that DC to Variable AC by using SPWM techniques for controlling of driving wheels (Induction motor). This is the flowing mechanism of Diesel-electric locomotive. The schematic diagram of this locomotive[2] is shown below.

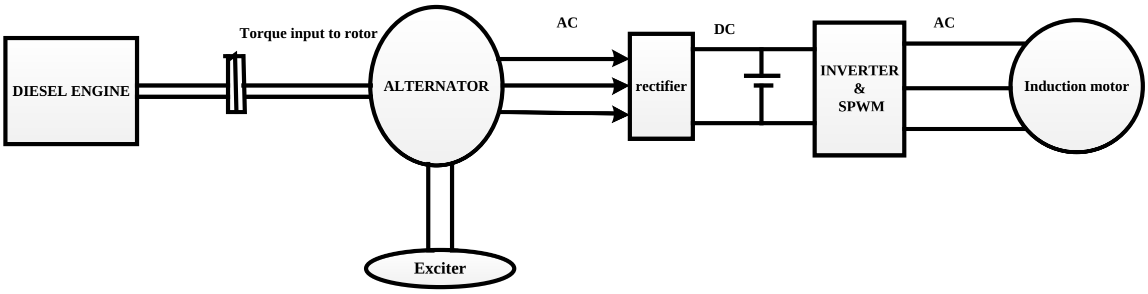

Figure 1.2: schematic diagram of Diesel-electric locomotive

The problems of Diesel-electric locomotive[10] are noisy, polluting and thus cannot suitable to roam in the populated suburbs. This locomotive providers another problem to commuter train. The slow acceleration typical to this engine increases travel and reduces number of trains on the track. The fuel efficiency is low due to the type of the prime engine. The energy is not recaptured while braking and is merely lost as heat.

1.5 Conclusion

Diesel-electric locomotive was a major improvement to compare with the steam engine and took its place in most of the world. Its noisy, unable to recapture energy while braking and pollution leads to go to electric locomotive. The over head lines are mandatory for electric locomotives and this cause height limitation to enter tunnels, under ground stations. Electric locomotives consumes power during peak time and It cause high risk (nature, man, terror), high loss in the gird, huge building cost, huge maintenance cost. New technologies[8] have proposed to overcome some of problems mentioned above.

Proposed technologies

- Diesel-electric with super capacitive energy storage is the new proposed technology enables kinetic braking energy to be reclaimed by storing electrical energy in super capacitors. This stored energy is used when accelerating the trains, when high current is needed. Same thing applies to electric locomotives to reduce the peak currents in the over head wires.
- Hydrogen-diesel, this proposal is to feed the diesel engine with hydrogen. This will reduce pollution drastically, but due to the nature of internal combustion is still very noisy.
- Diesel and over head wire, this technology is particularly suited to meet high reliability, economy, flexibility, and eco-friendliness on track networks that are only partially electrified. This is mainly suits for the huge distances and will enable the locomotives to operate the traction which include both electrified and non-electrified lines.

1.6 Motivation

ABB, alstom, GE, bombardier, siemens etc are the locomotive manufacture companies. In India locomotives are manufactured by taking equipment, technologies from above companies. India also planned to start the company for manufacturing the diesel-electric locomotive.

This gives motivation to study the types of locomotives , the advantages of diesel-electric locomotive over the other locomotives, the new technologies proposed for effectiveness and to explain the operation and different control strategies of diesel-electric locomotives.

1.7 Objectives

There are two main objectives of this report.

1. Study of different types of locomotive, advantages and disadvantages of diesel-electric locomotive over other locomotives.
2. Describes the vector control of induction motor, automatic voltage regulator of alternator and working structure of diesel-electric locomotive, explains the two different controlling schemes of diesel-electric locomotive and comparison of two schemes.

1.8 Organisation of Thesis

Chapter 2 discusses about the FOC of induction motor, AVR of alternator, control strategy of diesel-electric locomotive in which speed of locomotive is controlled automatically to the reference speed irrespective of load. Also presents the another control strategy of diesel-electric locomotive in which speed is controlled by driver itself by changing the fuel input to the diesel engine based on load.

Chapter 3 describes design of controllers used in two control strategies. Design of current controllers and speed controllers used in the vector control are presented. Design of AVR parameters and alternator speed control parameters are also presented.

Chapter 4 discusses the simulation results of the two control strategies and compares their performance.

Chapter 5 presents the summary of the work done and the future scope for improving the work.

CHAPTER 2

STUDY OF CONTROL STRATEGIES

2.1 Introduction

The diesel-electric locomotive has both induction motor and alternator. The control of locomotive is developed by considering the FOC[7] of induction motor and AVR of alternator. By knowing the indirect vector control of induction motor and automatic voltage regulator of alternator its becomes easy to develop the control strategies of locomotive.

In this chapter the basic theory of indirect FOC with synchronous reference frame is presented from the dynamic space model of the induction machine. Basic theory of AVR of alternator is discussed. The detailed design of various controllers used in vector control of induction motor is presented and design of controllers which are used in AVR and in speed control of alternator is discussed.

2.2 Vector control of induction machine

DC motors were widely used for variable speed drive applications in industry owing to simple speed control algorithm and fairly good dynamic response over wide speed range. The flux producing current and the torque producing current exist mutually orthogonal in two separate windings in a DC machine. Because of this arrangement flux and torque can be independently controlled making the speed control of DC machine fairly simple over wide speed ranges. This advantage is not available in an induction machine drive, where there is only a three phase winding supplied by a three phase source. Implementation in which the synchronous reference frame is aligned with the fundamental wave of one of the fluxes in the machine (rotor, stator, or airgap) is advantageous for analysis and control purposes. consequently, three types of vector control schemes can be considered, namely

- rotor flux oriented vector control or field oriented control.
- stator flux oriented vector control
- airgap flux oriented vector control

Owing to this, rotor flux oriented vector control has become the most popular choice. However, rotor flux orientation gives natural decoupling control, where air gap or stator flux orientation gives a coupling effect which has to be compensated by a decoupling compensation currents. Only FOC strategy is covered in this chapter. Field Oriented Control (FOC) of induction machine is a control methodology which enable the induction machine be controlled like a DC machine. In FOC of induction machine, the flux producing component and the torque producing component are identified and controlled separately. This is achieved by transforming the instantaneous stator currents to a rotating frame of reference aligned with the rotor flux axis (Rotor flux oriented FOC). The direction along the rotor flux is taken as d-axis and the direction in quadrature to the rotor flux taken as q-axis. The development of field oriented control makes the induction machine drives a preferable choice in industry for high performance applications like traction drive.

2.2.1 Rotor flux oriented vector control (or) Field oriented control

Analysis of induction machine is often realised using per-phase equivalent circuits. While such equivalent circuits are simple and useful for machines operating in steady state, they are inadequate for the analysis of machines operated from electronics power converters, which are frequently subject to changing operating conditions. Complex space vector representation provides an alternative mean for the modelling and analysis of three phase induction machines. Compared to other notations, complex space vectors provide a much simpler and insightful representation of the dynamic effects that physically occur in the machine, i.e the relationships among voltages, currents and fluxes, as well as electromechanical power conversion.

The space vector modelling equations[13] of induction machine in synchronous reference frame are as follows

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -L_s\omega_s & L_m p & -L_m\omega_s \\ L_s\omega_s & R_s + L_s p & L_m\omega_s & L_m p \\ L_m p & -L_m(\omega_s - \omega_r) & R_r + L_r p & -L_r(\omega_s - \omega_r) \\ L_m(\omega_s - \omega_r) & L_m p & L_r(\omega_s - \omega_r) & R_r + L_r p \end{bmatrix} \times \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{2.1}$$

$$T_e = L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{2.2}$$

where p=$\frac{d}{dt}$, ω_r=rotor speed, ω_s=synchronous speed , s=slip

The equations of rotor flux linkages are:

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{2.3}$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{2.4}$$

From above equations 2.3 and 2.4 we get i_{dr} , i_{qr} in terms of ψ_{dr} , ψ_{qr} respectively.

$$i_{dr} = \frac{\psi_{dr} - L_m i_{ds}}{L_r} \tag{2.5}$$

$$i_{qr} = \frac{\psi_{qr} - L_m i_{qs}}{L_r} \tag{2.6}$$

Substitute above equations 2.5 and 2.6 in equation 2.1 , then the equations becomes

$$V_{ds} = [R_s + \sigma L_s p]i_{ds} - [\sigma L_s\omega_s]i_{qs} + [\frac{L_m}{L_r}p]\psi_{dr} - [\frac{L_m}{L_r}\omega_s]\psi qr \tag{2.7}$$

$$V_{qs} = [R_s + \sigma L_s p]i_{qs} + [\sigma L_s \omega_s]i_{ds} + [\frac{L_m}{L_r}p]\psi_{qr} + [\frac{L_m}{L_r}\omega_s]\psi dr \tag{2.8}$$

$$V_{dr} = [-\frac{R_r L_m}{L_r}]i_{ds} + [\frac{R_r}{L_r} + p]\psi_{dr} - [s\omega_s]\psi_{qr} \tag{2.9}$$

$$V_{qr} = [-\frac{R_r L_m}{L_r}]i_{qs} + [\frac{R_r}{L_r} + p]\psi_{qr} + [s\omega_s]\psi_{dr} \tag{2.10}$$

In squirrel cage induction motor , rotor is short circuited then the above rotor voltage equations equals to zero, The resultant equations are

$$p\psi_{dr} = [\frac{R_r L_m}{L_r}]i_{ds} - [\frac{R_r}{L_r}]\psi_{dr} + [s\omega_s]\psi_{qr} \tag{2.11}$$

$$p\psi_{qr} = [\frac{R_r L_m}{L_r}]i_{qs} - [\frac{R_r}{L_r}]\psi_{qr} - [s\omega_s]\psi_{dr} \tag{2.12}$$

Substitute the equations 2.5 and 2.6 in 2.2 then the torque equation becomes

$$T_e = L_m(i_{qs}[\frac{\psi_{dr} - L_m i_{ds}}{L_r}] - i_{ds}[\frac{\psi_{qr} - L_m i_{qs}}{L_r}])$$

$$T_e = \frac{L_m}{L_r}(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}) \tag{2.13}$$

Based on above all equations the signal flow graph representation of induction machine is shown in figure 2.1

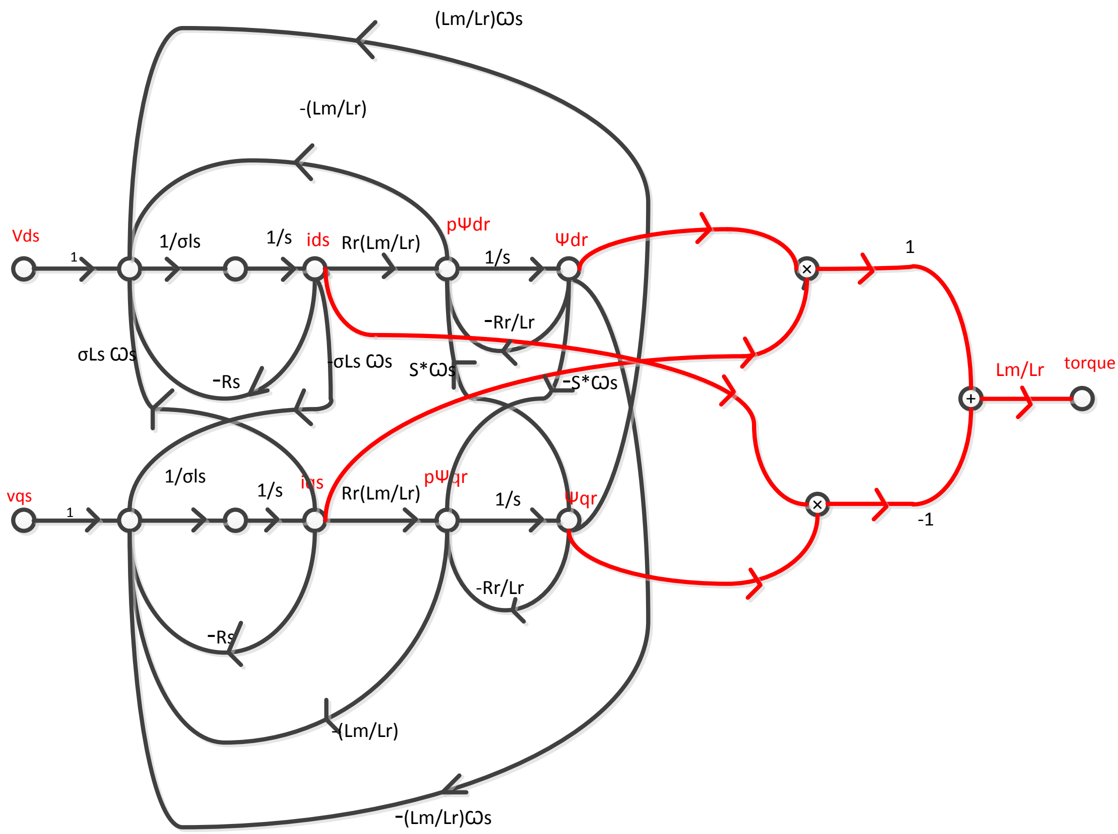

Figure 2.1: Signal flow graph of induction machine

The currents i_{ds}, i_{qs} are the direct axis component and quadrature axis component of the stator current respectively, in a synchronous reference frame. With vector control i_{ds} is analogous to field current i_f and i_{qs} is analogous to armature current i_a of a dc machine. This dc machine-like performance is only possible if i_{ds} is aligned in the direction of flux $\vec{\psi}_r$ and i_{qs} is established perpendicular to it. This means that when i_{qs} is controlled, it affects the actual i_{qs} current only, does not affects the flux $\vec{\psi}_r$. Similarly, when i_{ds} is controlled, it controls the flux only and does not affect the i_{qs} component of the current. This vector or field orientation of currents is essential under all operating conditions in a vector-controlled drive.

If d-axis aligned along $\vec{\psi_r}$ axis, then this current is only responsible for $\vec{\psi_r}$. then ψ_{dr}=$\vec{\psi_r}$ and $\psi_{qr} = 0$. If ψ_{qr}=0 it also tends to $p\psi_{qr}$=0, suppose the input variables themselves are i_{ds} and i_{qs}, the signal flow graph be looking like as shown in figure 2.2

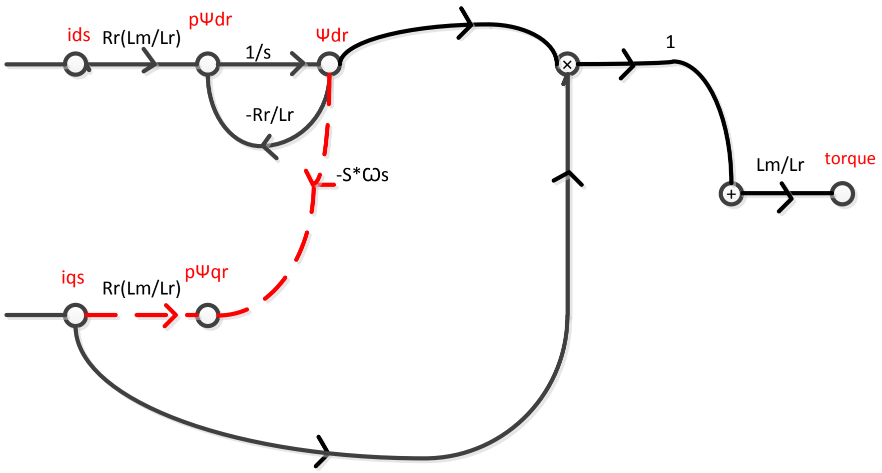

Figure 2.2: Signal flow graph of induction machine,after FOC

substitute $p\psi_{qr}$=0 and ψ_{qr}=0 in equations 2.3 and 2.4 i.e.,$p\psi_{dr}$,$p\psi_{qr}$ we get

$$R_r \frac{Lm}{Lr} i_{qs} = s\omega_s \psi_{dr} \tag{2.14}$$

$$p\psi_{dr} = R_r \frac{L_m}{L_r} i_{ds} - \frac{R_r}{L_r} \psi_{dr} \tag{2.15}$$

At steady state the above equation becomes

$$0 = R_r \frac{L_m}{L_r} i_{ds} - \frac{R_r}{L_r} \psi_{dr}$$

$$\psi_{dr} = L_m i_{ds} \tag{2.16}$$

from above figure 2.2 , ψ_{dr} is kept as constant by controlling i_{ds}, then torque can be controlled by i_{qs}.so flux and torque are decoupled.now it is similar to Dc motor. Now the torque equation is

$$T_e = \frac{L_m}{L_r} [\psi_{dr} i_{sq}] \tag{2.17}$$

By using above equations it is possible to make FOC with a current source inverter. In order to achieve decoupled torque and speed control, the current components i_{sd} and i_{sq} needs to be controlled. Therefore, the basic structure of an induction motor drive[11] with Field Oriented Control will be as shown in Fig.2.3.

The current references calculated by the drive are translated to three phase reference currents for the PWM Current Source Inverter(CSI). This is done by transforming the references from the rotating *dq* rotor flux frame to the stationary $\alpha\beta$ frame and then to the three phase stator reference frame. The relevant equations for the transformation are:

$$i_{sa}^* = \frac{2}{3}[i_{sd} \cos \rho(t) - i_{sq} \sin \rho(t)] \tag{2.18}$$

$$i_{sb}^* = -\frac{1}{3}[i_{sd} \cos \rho(t) - i_{sq} \sin \rho(t)] + \frac{1}{\sqrt{3}}[i_{sq} \cos \rho(t) + i_{sd} \sin \rho(t)] \tag{2.19}$$

$$i_{sc}^* = -\frac{1}{3}[i_{sd} \cos \rho(t) - i_{sq} \sin \rho(t)] - \frac{1}{\sqrt{3}}[i_{sq} \cos \rho(t) + i_{sd} \sin \rho(t)] \tag{2.20}$$

Thus if the command references from the controllers are to be properly translated into the reference phase currents for the inverter, an accurate knowledge about the position of the rotor flux is essential. In the previous discussion, it was assumed that the stator windings were impressed with the desired currents using the inverter. This could

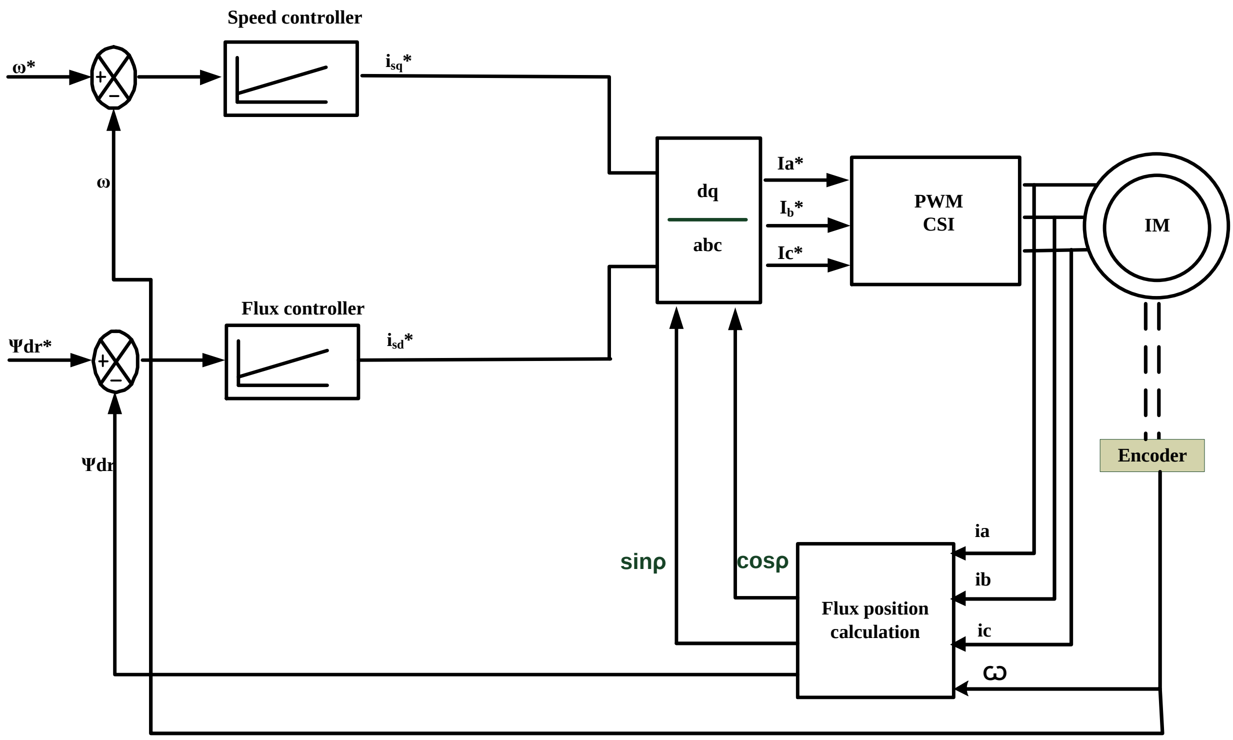

Figure 2.3: Basic structure of FOC with a current sourcr inverter

be done using a current source inverter. However at high speeds, the assumption of a constant current may not be valid when the inverter dc bus cannot force current against the back emf of the machine. Also, when voltage source inverters are used, the stator voltage dynamics needs to be considered. So now, the necessary equations representing the stator voltage dynamics in the rotor flux frame will be obtained.

By substituting the conditions 2.14 and 2.15 in equations V_{ds} ,V_{qs} that is equations 2.7 ,2.8 new V_{ds},V_{qs} equations obtained.

$$V_{ds} = i_{ds}R_s^{'} + \sigma L_s p i_{ds} - \sigma L_s \omega_s i_{qs} - R_r \frac{L_m}{L_r^2}\psi_{dr} \tag{2.21}$$

$$V_{qs} = i_{qs}R_s^{'} + \sigma L_s p i_{qs} + \sigma L_s \omega_s i_{ds} + \frac{L_m}{L_r}\psi_{dr}\omega_r \tag{2.22}$$

where

$$R_s^{'} = [R_s + R_r \frac{L_m^2}{L_r^2}] \tag{2.23}$$

Now the signal flow diagram of Induction motor will be

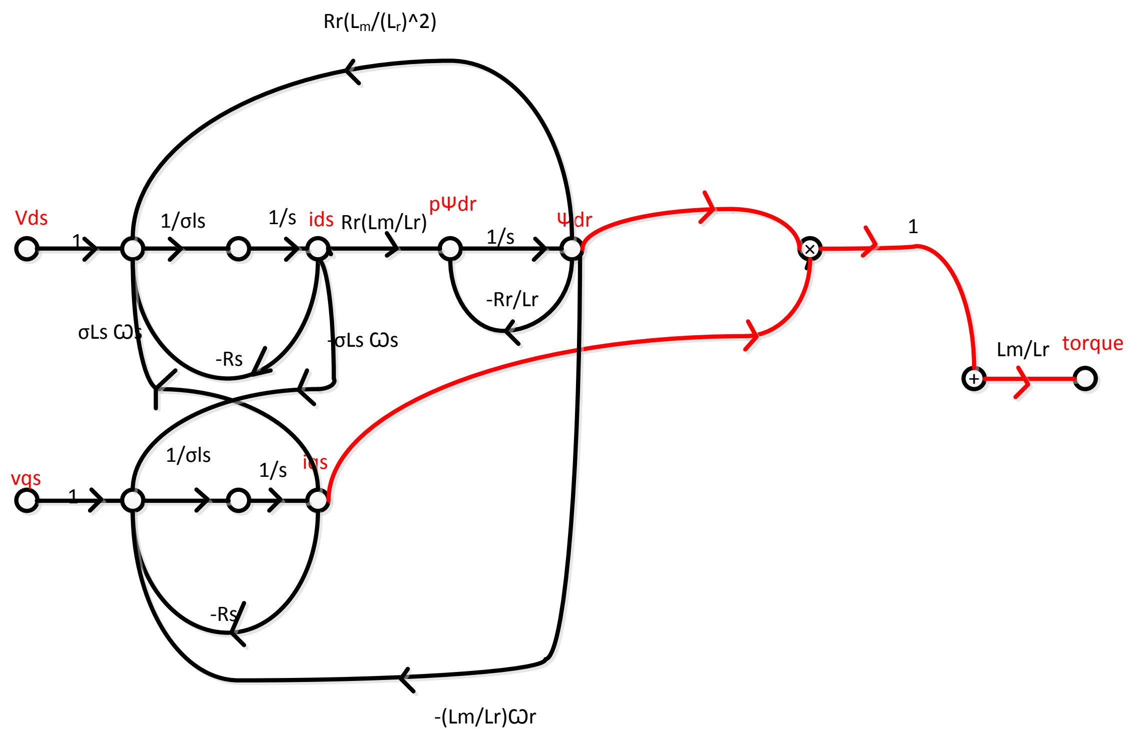

Figure 2.4: model of induction machine

Eq.(2.21) and Eq.(2.22) are the required expressions that represent the stator voltage dynamics of the machine in the rotor flux frame. These can now be used to calculate the required values of the d and q axis stator voltages which are then realised using a pulse width modulated Voltage Source Inverter(VSI). Feed forward can be used to improve the response of the d and q axis currents to the respective voltages. The feed forward terms are given as,

$$v_{ffd} = -\sigma L_s i_{sq}\omega_{mr} - R_r\psi_{dr}\frac{L_m}{L_r^2} \tag{2.24}$$

$$v_{ffq} = \sigma L_s i_{sd}\omega_{mr} + \frac{L_m}{L_r}\omega_r\psi dr \tag{2.25}$$

where v_{ffd} denotes the d-axis feed forward term and v_{ffq} denotes the q-axis feed forward term. The addition of these terms to the ouput of the d axis and q axis current controllers respectively gives a first order response of the dq axis currents to the respective dq axis voltages.

2.2.2 Indirect method (or) feedforward method of vector control

There are two general methods of vector control. One is direct or feed-back method, and the other, known as the indirect or feed-forward method[5]. These methods are different essentially by how the unit vector (cosρ and sinρ) is generated for the control.

In direct method it is necessary to estimate the rotor flux components $\psi_{r\alpha}$ and $\psi_{r\beta}$ so that the unit vector and the rotor flux can be calculated. At low frequency, voltage signals $v_{s\alpha}$ and $v_{s\beta}$ are very low. In addition, ideal integration becomes difficult because dc offset tends to build up at the integrator output.

Indirect vector control method is essentially same as direct vector control, expect the unit vector signals (cosρ and sinρ) are generated in feed-forward manner. ω_{slip} can be calculated from i_{qs} , i_{ds}. The condition 2.15 is correct only when ψ_{dr} is aligned with i_{ds}. If the condition is correct, then ω_{slip} is obtained. By adding ω_r (speed of the rotor) and ω_{slip} synchronous speed changing with respect to time i.e.,ω_s(t) is determined. Finding the ρ is achieved by integrating this ω_s(t). That ρ is necessary in converting abc to dq (or) dq to abc axis frame.

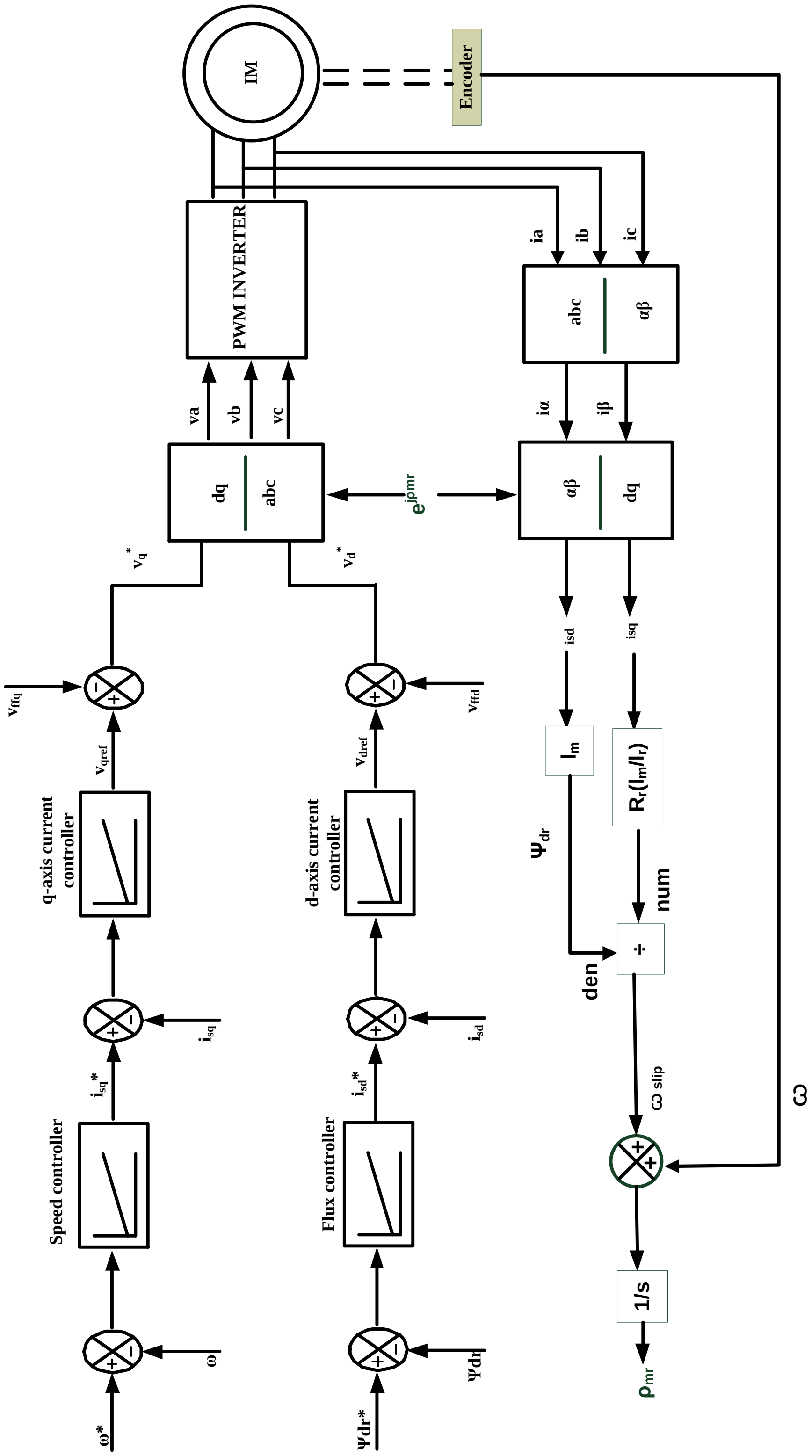

Figure 2.5: Block diagram for Indirect method of vector control

In figure 2.5 the three phase stator currents are transformed to equivalent two phase quantities and then to rotating dq reference frame fixed to the rotor flux space vector. This is done by using the information about the rotor flux position obtained from the machine model to implement the following equations.

$$i_{s\alpha} = \frac{3}{2} i_{sa} \tag{2.26}$$

$$i_{s\beta} = \frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) \tag{2.27}$$

$$i_{sd}(t) = i_{s\alpha}(t)\cos\rho(t) + i_{s\beta}(t)\sin\rho(t) \tag{2.28}$$

$$i_{sq}(t) = i_{s\beta}(t)\cos\rho(t) - i_{s\alpha}(t)\sin\rho(t) \tag{2.29}$$

where $\rho(t)$ denotes the instantaneous position of the rotor flux w.r.t the stator axis.

2.3 Controlling of alternator

The rotor of the alternator is rotated at synchronous speed by engine or turbine, then by increasing the field voltage, the voltage generated by alternator is also increase. The output voltage magnitude is varying by vary the field voltage and frequency of output voltage varying by vary the speed of the rotor. So the output voltage is controlled by changing field voltage and rotor speed. AVR[9] is used to change field voltage, diesel engine is used to change speed of rotor.

2.3.1 Automatic voltage regulator (AVR)

The basic function of an excitation system is to provide necessary direct current to the field winding of the synchronous generator. The excitation system must be able to automatically adjust the field current to maintain the required terminal voltage.

The DC field current is obtained from a separate source called an exciter. The excitation systems have taken many forms over the years of their evolution. The following are the different types of excitation systems.

1. DC excitation systems
2. AC excitation systems
3. Brushless AC excitation systems
4. Static excitation systems

DC excitation systems: In DC excitation system, the field of the main synchronous generator is fed from a DC generator, called exciter. Since the field of the synchronous generator is in the rotor, the required field current is supplied to it through slip rings and brushes. The DC generator is driven from the same turbine shaft as the generator itself. This DC excitation system has slow response. Normally for 10 MVA synchronous generator, the exciter power rating should be 20 to 35 KW for which we require huge the DC generator. For these reasons, DC excitation systems are gradually disappearing.

AC excitation systems: In AC excitation system, the DC generator is replaced by an alternator of sufficient rating, so that it can supply the required field current to the field of the main synchronous generator. In this scheme, three phase alternator voltage is rectified and the necessary DC supply is obtained. Generally, two sets of slip rings, one to feed the rotating field of the alternator and the other to supply the rotating field of the synchronous generator, are required.

Brushless AC excitation systems: Old type AC excitation system has been replaced by brushless AC excitation system wherein, inverted alternator (with field at the stator and armature at the rotor) is used as exciter. A full wave rectifier converts the exciter AC voltage to DC voltage. The armature of the exciter, the full wave rectifier and the field of the synchronous generator form the rotating components. The rotating components are mounted on a common shaft.

Static excitation systems: In static excitation system, a portion of the AC from each phase of synchronous generator output is fed back to the field windings, as DC excitations, through a system of transformers, rectifiers, and reactors. An external source of DC is necessary for initial excitation of the field windings. On engine driven generators, the initial excitation may be obtained from the storage batteries used to start the engine.

2.3.2 Introduction to exciters

It is necessary to provide constancy of the alternator terminal voltage during normal small and slow changes in the load. For this purpose the alternators are provided with AVR. The exciter is the main component in the AVR loop. It delivers DC power to the alternator field. It must have adequate power capacity (In the low MW range for large alternator) and sufficient speed of response (rise time less than 0.1 sec). There exists a variety of exciter types. In older power plants, the exciter consisted of a DC generator driven by the main shaft. This arrangement requires the transfer of DC power to the synchronous generator field via slip rings and brushes. Modern exciters tend to be of either brushless or static design. A typical brushless AVR loop is shown in Figure 2.6.

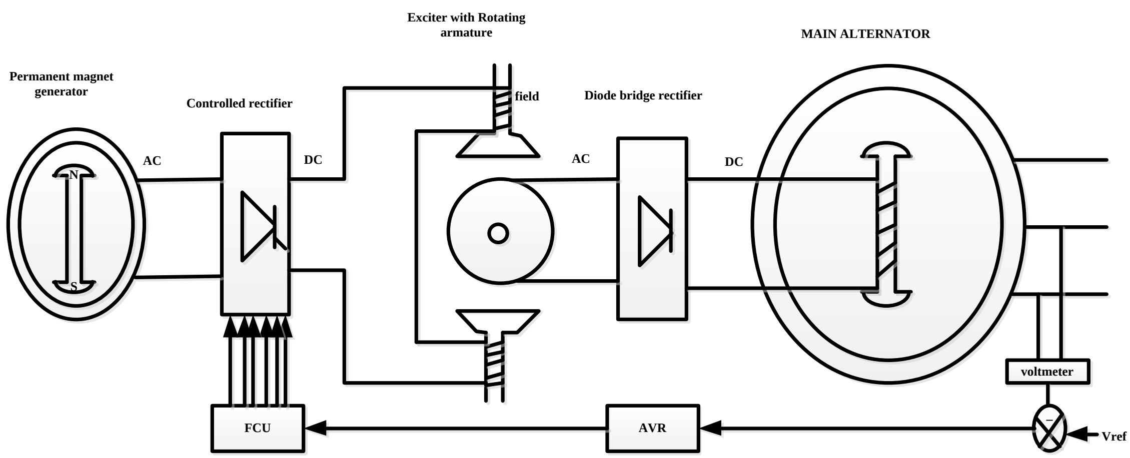

Figure 2.6: Brushless AC Excitation system

In this arrangement, the exciter consists of an inverted three phase alternator which has its three phase armature on the rotor and its field on the stator. Its AC armature voltage is rectified in diodes mounted on the rotating shaft and then fed directly into the field of the main synchronous generator.

2.3.3 Model of exciter

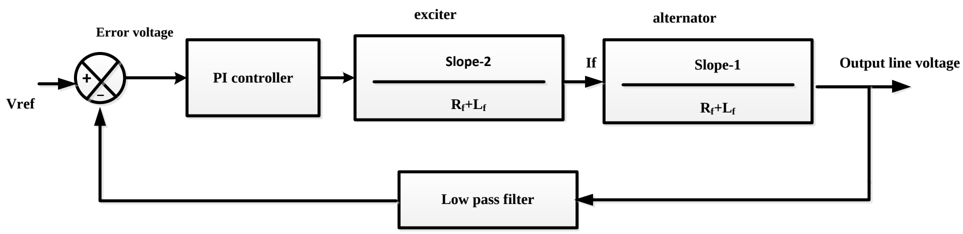

Figure 2.7: Block diagram representation of AVR loop

It is to be noted that the error voltage is the difference between the output voltage and reference voltage. Assume that for some reason the terminal voltage of the main generator decreases. This immediately results in an increased error voltage which in turn, causes increased values of field current of exciter and field current of alternator. As a result of the boost in field current, the d axis generator flex increases, thus raising the magnitude of the internal generator emf and hence the terminal voltage. Higher setting of Vref also will have the same effect of increasing the terminal voltage.

From figure 2.7, the representation of blocks from error voltage to controlled rectifier output is modelled as PI controller block, that voltage is given to exciter nothing but alternator. So the model of both exciter and alternator is represented as same. This model is approximated for designing the control parameters. That approximated diagram is discussed in control design chapter.

2.3.4 Speed control of alternator

Speed control of alternator is necessary to maintain output voltage of alternator. The model of AVR is valid only for frequency deviation of ±5 percent and the oscillations are less than 3hz. For this reason the speed of the alternator is to be controlled.

Diesel engine is used to rotate the rotor of alternator. The speed of alternator is compare with reference speed, error is given to PI controller that gives information about how much fuel input is enough to generate the torque required to rotate rotor at reference speed. This control block diagram is shown in figure 3.7.

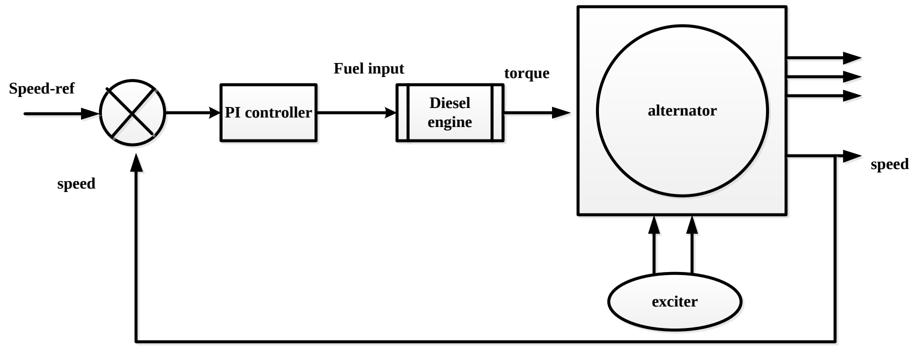

Figure 2.8: Block diagram representation of speed loop

2.4 Control strategy-1

Diesel engine and AVR are used to regulate the V_{dc} irrespective of load. Diesel engine is used to rotate the rotor of alternator at the speed which is given as reference even the load is varying rom no load to full load. If load is increasing then engine require more fuel to rotate at reference speed. In the same way AVR is used to maintain the V_{dc} at a particular value, whenever load is raised more voltage have to give to the field. In this way these are working.

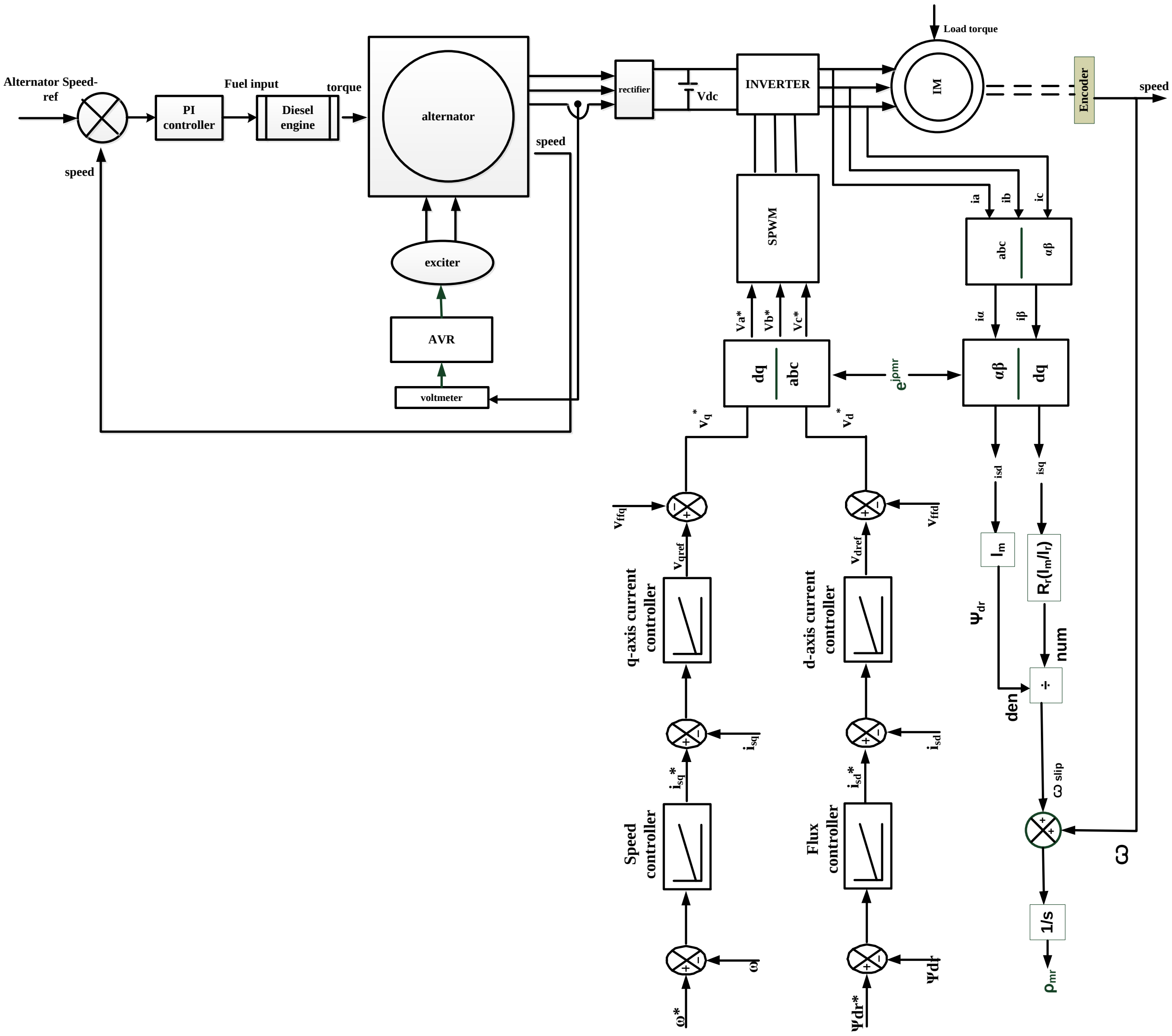

Figure 2.9: Block diagram representation of strategy-1

Once V_{dc} is constant, flux and speed controllers generate i_{sd}^{*},i_{sq}^{*} respectively. This currents are given as reference to current controllers which generate voltages$V_{sd}$and V_{sq} respectively. These voltages are convert into three phase quantities for which rotor position angle ρ is needed. By using SPWM and inverter these voltages are generated from V_{dc}. So in this method, the controlling of speed and flux is possible when V_{dc} is constant.

The speed of the induction motor nothing but driving wheels of locomotive is regulated with the speed which is given as reference speed of induction drive irrespective of load.

2.5 Control strategy-2

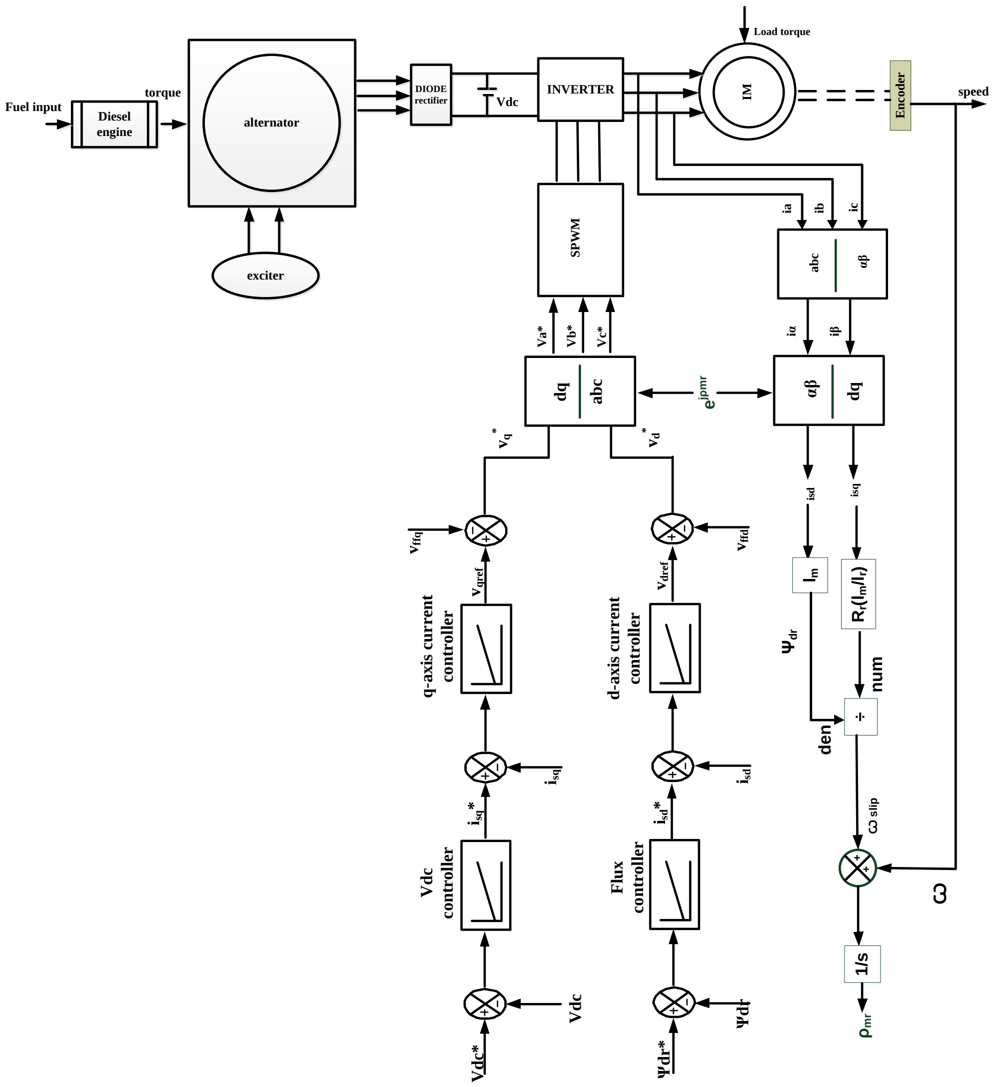

Figure 2.10: Block diagram representation of strategy-2

In this scheme driver of locomotive is a controller, when ever load is increasing speed of the motor is to be reduced. In order to maintain the same speed more fuel is required to give to the engine. As shown in figure 2.10 flux controller is responsible to develop i_{ds} current and ψ_{dr} is aligned with $\widehat{\psi_r}$. By indirect vector control method ρ can be determined. The difference between Vdc reference and Vdc is responsible for generating i_{sq} indirectly cause for torque and then induction motor starts rotating. As there is no field control it takes more time for speed is to be settled compare to previous scheme. Constant voltage is given to field of value is enough for full load.

At particular load how speed is varying by vary fuel input is to be noted. Based on all these values the controlling of speed at any load is possible. Normally practical locomotive follow this strategy. Constant speed is not main objective for locomotives. In some applications where constant speed is needed strategy-1 is better choice.

2.6 Conclusion

This chapter introduced the consept of FOC of induction machine and controlling methods of alternator. The basic idea of control of locomotive were discussed and the complete block diagrams of locomotive control was presented. Induction motors are used as driving wheels in locomotives and alternator is main power source to all driving wheels. Explanation of modelling and controlling of diesel-electric locomotive was discussed in this chapter. The design of control parameters of these methods will be discussed in the next chapter.

CHAPTER 3

DESIGN OF CONTROL STRATEGIES

3.1 Control design of strategy-1

The detailed design of various controllers are used for alternator and in vector control is presented.

The vector control for the 160 kW induction motor whose ratings are specified in Table3.1. The design of vector control for a machine requires the knowledge of the parameters of the machine which are used for designing the control parameters.

Table 3.1: Equivalent circuit parameters

Parameter	R_s	$R_r^{'}$	L_{ls}	L_{lr}	L_m
Value	0.01379 Ω	0.007728 Ω	0.152 mH	0.152 mH	0.00769 mH

3.1.1 SPWM switching for inverter

By using the sinusoidal pulse width modulation (SPWM) technique, the conversion of DC to AC is possible. The power circuit topology for a 2-level VSI using IGBT switches is shown in Fig. 3.1. The comparison of carrier signal of frequency 9000 hz to reference signal of fundamental frequency, it will generate pulses. Modulation index is the ratio of peak values of reference signal to carrier signal. That pulses is given as gate signal to switch-1, inversion of that given to switch-4. Same pulses with 120 and 240 degrees phase shift is given to switch-3 and switch-5 respectively, inversion of that given to switch-6 and switch-2.

The maximum value of the fundamental component of inverted phase voltage is given as

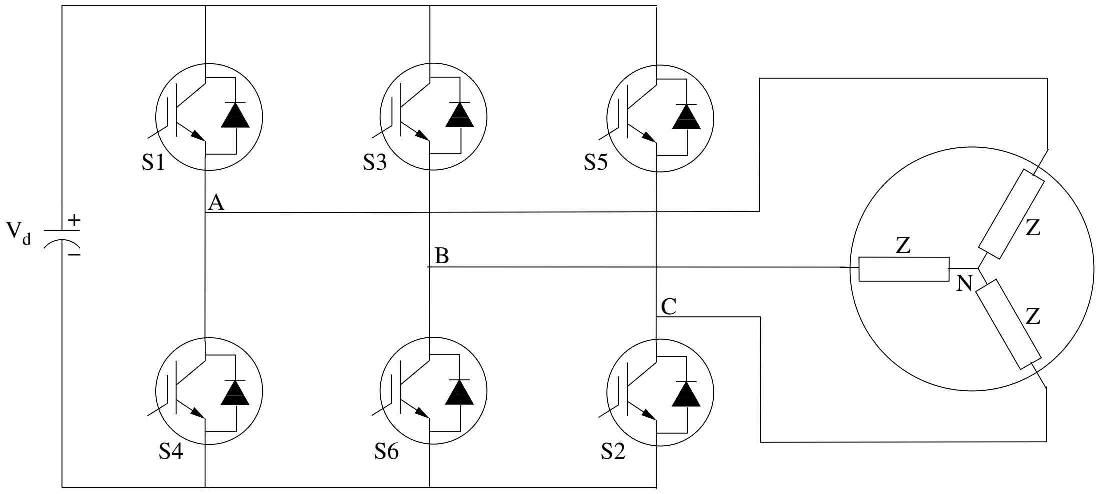

Figure 3.1: 2-level VSI topology

$$= (M.I)\frac{Vdc}{2} \tag{3.1}$$

The RMS value of the fundamental component of inverted phase voltage is given as

$$= (M.I)\frac{Vdc}{2}\frac{1}{\sqrt{2}} \tag{3.2}$$

The RMS value of the fundamental component of inverted line voltage is given as

$$V_{line} = (M.I)(\frac{Vdc}{2}\frac{1}{\sqrt{2}})\sqrt{3} \tag{3.3}$$

This is the relation between Vdc and output line RMS value. In order to get the RMS of line voltage as 400v with modulation index (MI) of 0.8, the required Vdc value is calculated as follows:

$$400 = (0.8)(\frac{Vdc}{2}\frac{1}{\sqrt{2}})\sqrt{3} \tag{3.4}$$

Then required Vdc=816.

3.1.2 d and q axis current controllers

The vector control system uses PI controllers for controlling the flux, speed, d-axis current and q-axis current. The dynamic performance of the drive is determined by these controllers and therefore it is important to design them for the required performance. Also, the output limiters of the PI controllers ensure that the currents and voltages of the motor are always within the limits. Thus the limiter values should also be designed appropriately.

In this work, the PI controllers have been designed so as to have a first order response for the closed loop system. The inverter and sensor dynamics are neglected and they are treated as constant gain blocks. The bandwidth of the outer loops are selected much smaller than that of the inner loops. This allows us to neglect the inner loop dynamics while designing the outer loops.

Current controllers[6] primarily deal with the dynamics of the power supply and armature. These should have a response slower than the inverter, but faster than the speed controller and flux controller. From 2.21 and 2.22,

$$V_{ds} = i_{ds}R_s^{'} + \sigma L_s p i_{ds} - \sigma L_s \omega_s i_{qs} - R_r \frac{L_m}{L_r^2}\psi_{dr}$$

$$V_{qs} = i_{qs}R_s^{'} + \sigma L_s p i_{qs} + \sigma L_s \omega_s i_{ds} + \frac{L_m}{L_r}\psi_{dr}\omega_r$$

where

$$R_s^{'} = [R_s + R_r \frac{L_m^2}{L_r^2}]$$

Thus by adding appropriate feed forward terms to the input voltages, a first order response can be obtained for the currents and the plant model can be written as a first order transfer function. The feed forward terms are given as

$$v_{ffd} = -\sigma L_s i_{sq} \omega_{mr} - R_r \psi_{dr} \frac{L_m}{L_r^2} \tag{3.5}$$

$$v_{ffq} = \sigma L_s i_{sd} \omega_{mr} + \frac{L_m}{L_r} \omega_r \psi dr \tag{3.6}$$

where v_{ffd} and v_{ffq} are respectively the feed forward terms of the d and q axis voltages. Since the loop structure is the same for both d and q axis current loops, the design and controller parameters for both are the same. The block diagram of the current control loop is as shown in Fig. 3.2

If the bandwidth of the current control loop is chosen as f_b Hz,

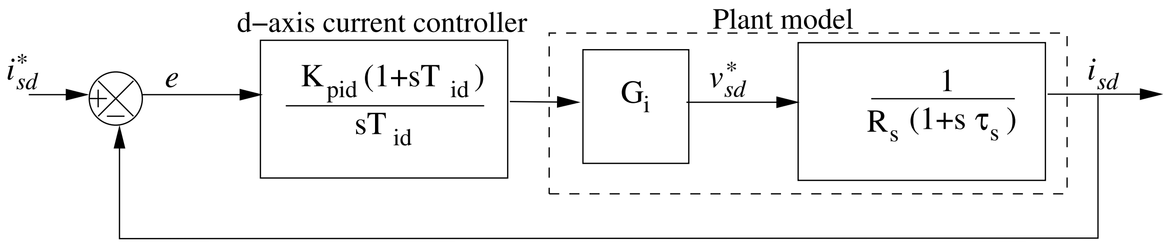

Figure 3.2: Structure of the current control loop

$$\tau_b = \frac{1}{2\pi f_b} \tag{3.7}$$

Then the condition for the loop to have a first order response can be written as

$$\frac{K_p(1 + sT_{id})}{sT_{id}} \times G_i \times \frac{1}{R_s(1 + s\tau_s)} = \frac{1}{s\tau_b} \tag{3.8}$$

where $\tau_s = \frac{\sigma L_s}{R_s}$. By choosing $T_{id} = \tau_s$, then from Eqn. 3.8,

$$\frac{K_p G_i}{R_s \tau_s} = \frac{1}{\tau_b} \implies \boldsymbol{K_p = \frac{R_s \tau_s 2\pi f_b}{G_i}} \tag{3.9}$$

Now the integral gain of the PI controller can be obtained as

$$K_i = \frac{K_p}{T_{id}} \implies \boldsymbol{K_i = \frac{K_p R_s}{\sigma L_s}} \tag{3.10}$$

3.1.3 Flux controller

The flux controller controls the flux inside the machine by controlling the magnetising current i_{mr}. The controller output is the reference for the d-axis current. Thus this controller bandwidth is to be chosen much lower than the d-axis current controller. This allows to neglect the dynamics of the d-axis current controller in the design. The basic structure of the control loop is as shown in Fig. 3.3.

If the bandwidth of the i_{mr} control loop is chosen as f_{bmr} Hz, then

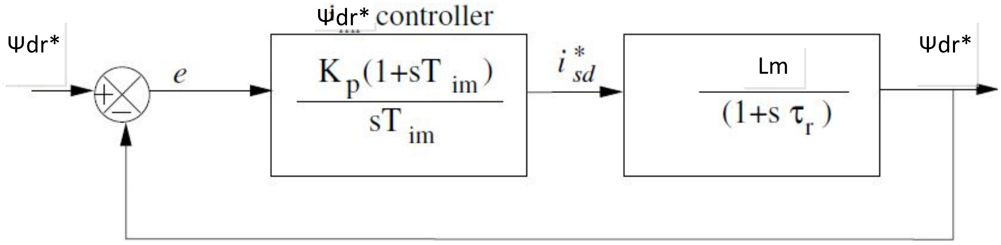

Figure 3.3: Structure of the i_{mr} control loop

$$\tau_{bmr} = \frac{1}{2\pi f_{bmr}}$$

Then the condition for the loop to have a first order response can be written as

$$\frac{K_p(1+sT_{im})}{sT_{im}} \times \frac{L_m}{(1+s\tau_r)} = \frac{1}{s\tau_{bmr}} \tag{3.11}$$

where $\tau_r = \frac{L_r}{R_r}$. By choosing $T_{im} = \tau_r$,

$$\frac{K_p}{\tau_r} = \frac{1}{\tau_{bmr}} \implies \boldsymbol{K_p = \frac{\tau_r}{\tau_{bmr} L_m}} \tag{3.12}$$

Now, the integral gain of the controller is obtained as

$$K_i = \frac{K_p}{\tau_r} \implies \boldsymbol{K_i = \frac{1}{\tau_{bmr} L_m}} \tag{3.13}$$

3.1.4 Speed controller

The speed control loop is as shown in fig. 3.4. The output of the speed PI controller is the reference value of the q-axis current. The current control loop is replaced by its equivalent first order transfer function of bandwidth as designed above. The inverter and speed sensor are treated as constant gain blocks and their dynamics are neglected. The sensor gain is taken as unity.

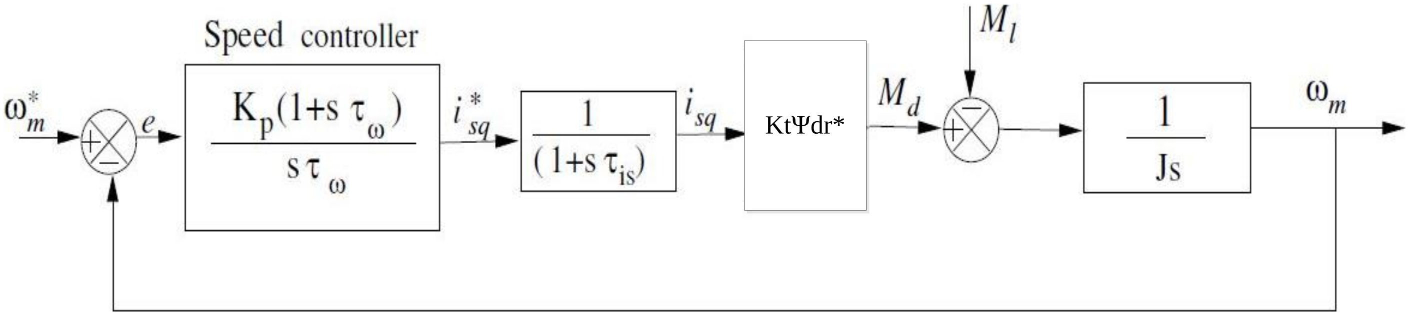

Figure 3.4: Structure of the speed control loop

The design is done using a symmetric optimal pole placement method. The objective here is to design the controller so that the maximum phase angle is obtained at the gain crossover frequency. Considering the block diagram of the control loop shown in Fig. 3.4, the open loop transfer function of the loop can be written as

$$G(s) = \frac{K_p K_t \psi_{dr}^* (1 + s\tau_\omega)}{J\tau_\omega s^2 (1 + s\tau_{is})} \tag{3.14}$$

Where

$$k_t = \frac{L_m}{L_r} \tag{3.15}$$

The bode plot of this transfer function has the form shown in Fig. 3.5. It has an initial slope of -40 dB/decade and then changes to -20 dB/decade due to the effect of the zero of the controller. It again changes back to -40 dB/decade due to the pole in the current control loop. For such a system, the maximum phase angle can be shown to occur at the geometric mean of the two corner frequencies. Thus the aim is to design the speed controller such that the system gain crosses the 0 dB point at this frequency, with a slope of -20 dB/decade.

Thus, once the value of f_{bw} is chosen appropriately, the value of f_w required can be calculated as

$$f_w = \frac{f_{bw}^2}{f_{is}} \tag{3.16}$$

The value of τ_ω for the controller is then obtained as

$$\boldsymbol{\tau_\omega = \frac{1}{2\pi} \frac{f_{is}}{f_{bw}^2}} \tag{3.17}$$

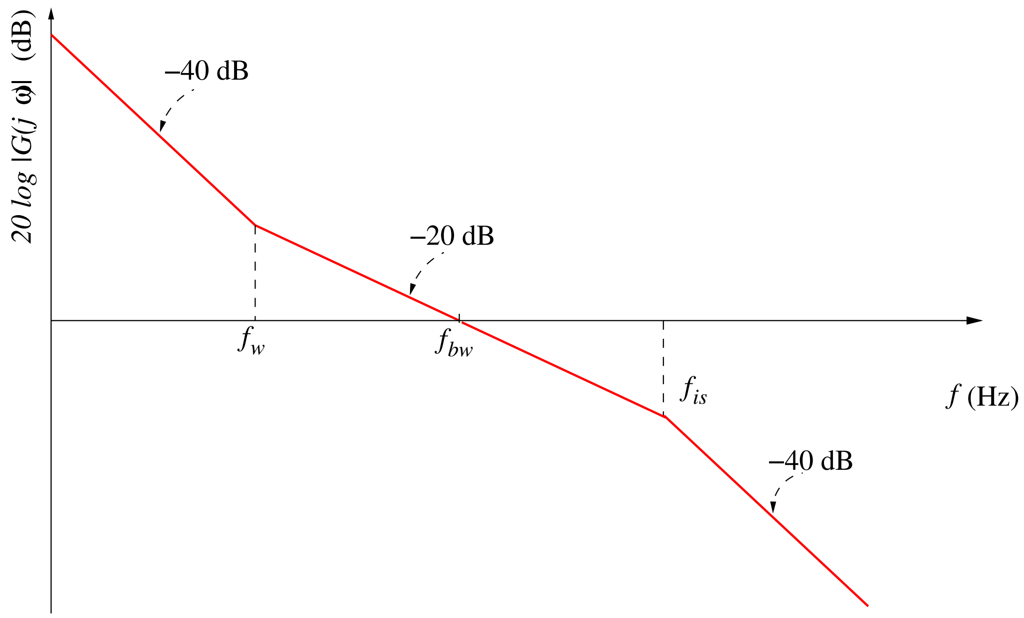

Figure 3.5: Bode plot for the speed loop

Then the condition for f_{bw} to be the gain crossover frequency of the system can be written as

$$\left.\frac{K_p K_t \psi^*_{dr}(1 + s\tau_\omega)}{J\tau_\omega s^2(1 + s\tau_{is})}\right|_{s=2\pi f_{bw}} = 1 \tag{3.18}$$

Since $\tau_\omega >> \tau_{b\omega}$ and $\tau_{is} << \tau_{b\omega}$, approximations can be made as $1 + s\tau_\omega \approx s\tau_\omega$ and $1 + s\tau_{is} \approx 1$. Then Eq. 3.18 simplifies to

$$\frac{K_p K_t \psi^*_{dr}}{2\pi J f_{b\omega}} = 1$$

$$\implies \boldsymbol{K_p = \frac{2\pi f_{bw} J}{K_t \psi^*_{dr}}} \tag{3.19}$$

Since the output of the PI controller is a current, the proportional and integral gains of the controller can be written as

$$\boldsymbol{K_p = \frac{2\pi f_{bw} J}{K_t \psi^*_{dr}}} \qquad \boldsymbol{K_i = \frac{K_p}{\tau_\omega}} \tag{3.20}$$

3.1.5 Output limits for the PI controllers

As discussed in Sec. 3.1.2 , all the PI controllers have limiters at their outputs and integrator antiwindups. The limits of the speed controller and flux controller are set at the rated values of the q-axis and d-axis currents respectively, while that of the current controllers are set at the rated values of the dq axis voltages. Thus the rated values of these quantities are to be calculated for properly setting the output limits.

For the 160kW machine whose parameters are given in Table 3.1,

For 4 pole, 50 hz, 400v machine,

Rated speed of rotor flux=1500 rpm = 157.07 rad/sec

Rated speed of the rotor= 1487 rpm = 155.71 rad/sec

Rated torque m_d=$\frac{Ratedpower}{Ratedspeed}$=$\frac{160000}{155.71}$=*1027.55 Nm*

Also,

$$\tau_r = \frac{L_r}{R_r} = 1.0148\, s \qquad \sigma_r = \frac{L_{lr}}{L_m} = 0.0198 \qquad \sigma = \frac{L_s L_r - L_m^2}{L_s L_r} = 0.0384$$

and

$$m_d = \frac{P}{2} \times \frac{L_m}{L_r} \times \psi_{dr} \times i_{qs}$$

If FOC is used, The obtained condition is

$$s\omega_s \psi_{dr} = R_r \frac{L_m}{L_r} i_{qs}$$

From above equations

$$i_{sqrated} = \frac{L_r}{L_m} \sqrt{\frac{m_d s\omega_s P}{R_r 2}} = 613.5615$$

$$\psi_{r_rated} = \psi_{dr_rated} = R_r \times \frac{i_{sqrated}}{s\omega_s} \times \frac{L_r}{L_m} = 1.7759$$

$$i_{sdrated} = \frac{\psi_{dr_rated}}{L_m} = 230.9391$$

The rated values of v_{sd} and v_{sq} can be obtained from Eq.(2.21) and Eq.(2.22) by substituting the rated values for the currents i_{sd} and i_{sq}.

$$V_{dsrated} = i_{ds} R_s^{'} + \sigma L_s p i_{ds} - \sigma L_s \omega_s i_{qs} - R_r \frac{L_m}{L_r^2} \psi_{dr} = -54.8453$$

$$V_{qsrated} = i_{qs}R_s^{'} + \sigma L_s p i_{qs} + \sigma L_s \omega_s i_{ds} + \frac{L_m}{L_r}\psi_{dr}\omega_r = 577.2290$$

where

$$R_s^{'} = [R_s + R_r\frac{L_m^2}{L_r^2}]$$

The controller parameters obtained for the 160kW machine from the above design are given in Table. 3.2

Table 3.2: Controller parameters

Controller	f_b (Hz)	K_p	K_i	U_{max}	U_{min}
i_{sd}	100	0.1892	13.3338	54.8453	-54.8453
i_{sq}	100	0.1892	13.3338	577.2290	-577.2290
ψ_{dr}	10	8.29e3	8.1706e3	230.9391	-230.9391
ω_m	5	52.3148	82.1759	613.5615	-613.5615

3.1.6 Phase voltage calculation

The estimation of the flux using either of the estimation schemes discussed requires the knowledge of the instantaneous phase voltages of the motor. This is calculated using the sensed value of the DC bus voltage and the d and q axis reference voltages to the inverter. If the inverter is assumed to be having a constant gain G_i, then the input d and q axis voltages of the motor can be obtained by multiplying the reference values with the gain. Knowing the values of these voltages, the phase voltages can be calculated using the following equations for transformation from the dq reference frame to the stator reference frame.

$$v_{sa} = \frac{2}{3}[v_{sd}\cos\rho(t) - v_{sq}\sin\rho(t)] \quad (3.21)$$

$$v_{sb} = -\frac{1}{3}[v_{sd}\cos\rho(t) - v_{sq}\sin\rho(t)] + \frac{1}{\sqrt{3}}[v_{sq}\cos\rho(t) + v_{sd}\sin\rho(t)] \quad (3.22)$$

$$v_{sc} = -\frac{1}{3}[v_{sd}\cos\rho(t) - v_{sq}\sin\rho(t)] - \frac{1}{\sqrt{3}}[v_{sq}\cos\rho(t) + v_{sd}\sin\rho(t)] \quad (3.23)$$

where v_{sa}, v_{sb} and v_{sc} denote the a, b and c phase voltages while v_{sd} and v_{sq} denote the d and q axis stator voltages.

3.1.7 AVR of alternator

The 1320kw, 604v, 50hz, 4 pole alternator has field resistance R_f=0.0003828, field inductance L_f=0.0001815, inertia J=33.01 and friction factor B=0.63
Based on the approximate model block diagram of exciter control parameters are determined. The exciter and alternator transfer functions are similar and time constant of exciter is high compare to alternator, so exciter is modelled as only gain. The approximate model is shown in figure 3.6. The low pass filter also neglected for finding parameters. Let the band width of the loop be f_b.

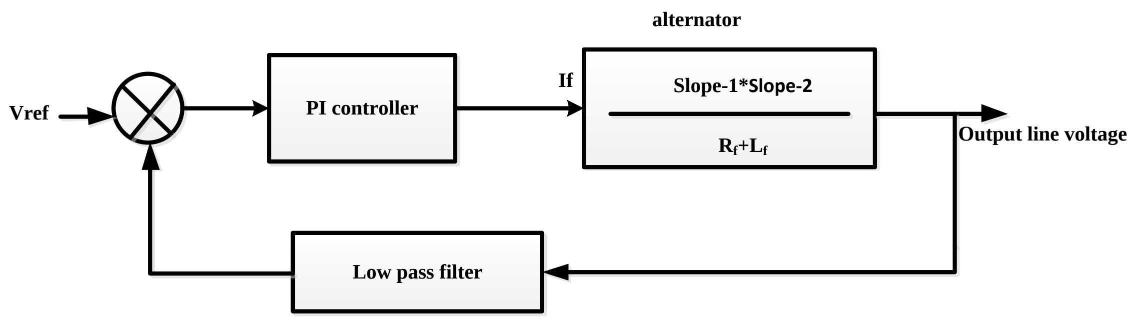

Figure 3.6: Approximate model of AVR

Similar to current and flux controller of induction drive, the parameters are calculated as follows.

$$\tau_b = \frac{1}{2\pi f_b} \tag{3.24}$$

Then the condition for the loop to have a first order response can be written as

$$\frac{K_p(1+sT_{id})}{sT_{id}} \times K \times \frac{1}{R_f(1+s\tau_s)} = \frac{1}{s\tau_b} \tag{3.25}$$

where K=slope-1*slope-2, $\tau_s = \frac{L_f}{R_f}$. By choosing $T_{id} = \tau_s$, then from Eqn. 3.25,

$$\frac{K_p K}{R_f \tau_s} = \frac{1}{\tau_b} \implies \boldsymbol{K_p = \frac{R_f \tau_s 2\pi f_b}{K}} \tag{3.26}$$

Now the integral gain of the PI controller can be obtained as

$$K_i = \frac{K_p}{T_{id}} \implies \boldsymbol{K_i = \frac{K_p R_f}{L_f}} \tag{3.27}$$

Bandwidth to be selected that it takes 1 to 2 seconds to regulate the output voltage of alternator, practically it takes some time to regulate. Let band width be 1 hz, slope-1=slope-2=10 then the control parameters are K_p=5.7019e-5 , K_i=1.2026e-4.

3.1.8 Speed loop of alternator

Diesel engine is used to rotate rotor of alternator, Irrespective of load engine have to rotate rotor with fixed speed. Based on the error speed controller gives fuel input to engine, engine provides torque as input to rotor of alternator. By figure 3.7 the parameters are determined as follows

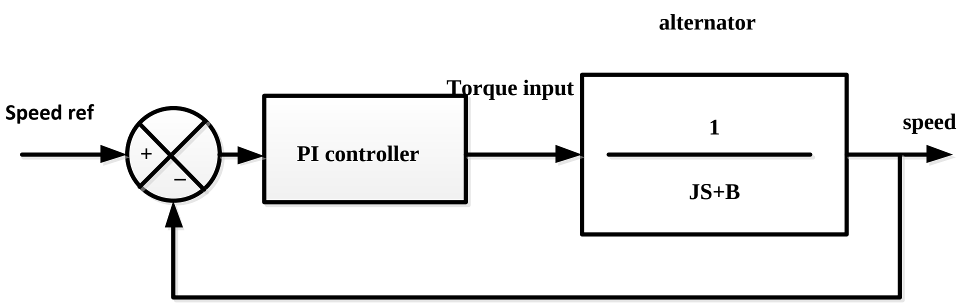

Figure 3.7: Speed loop of alternator

$$\frac{K_p(1 + sT_{id})}{sT_{id}} \times \frac{1}{B(1 + s\tau_s)} = \frac{1}{s\tau_b} \tag{3.28}$$

where, $\tau_s = \frac{J}{B}$. By choosing $T_{id} = \tau_s$, then from Eqn. 3.28,

$$\frac{K_p}{B\tau_s} = \frac{1}{\tau_b} \implies \boldsymbol{K_p = \frac{B\tau_s 2\pi f_b}{1}} \tag{3.29}$$

Now the integral gain of the PI controller can be obtained as

$$K_i = \frac{K_p}{T_{id}} \implies \boldsymbol{K_i = \frac{K_p B}{J}} \tag{3.30}$$

For alternator whose J=33.01,B=0.63 and bandwidth=1(should be less than 3.33 hz based on practical constraints), The control parameters are K_p=207.407 ,K_i=3.9584 .

3.2 Control design of strategy-2

In this strategy except Vdc controller all other design like current controllers, flux controller is already discussed in strategy-1. Only Vdc controller is the one which cause difference between two schemes. AVR, speed control of alternator are also not present in this method.

Design of Vdc control parameters is explained based on relation between the i_{sq} and capacitance c of capacitor which acts as a DC source. Three phase sinusoidal voltage is rectified by six pulse diode bridge rectifier. The output of rectifier is not pure DC, it is a pulsating DC. So capacitor is connected parallel to reduce the oscillations. That DC voltage is used in inverter.

$$-c\frac{dVdc}{dt} = i_{qs}$$

Change the above equation into laplace transform

$$-scVdc = i_{qs}$$

$$\frac{Vdc}{i_{qs}} = -\frac{1}{sc}$$

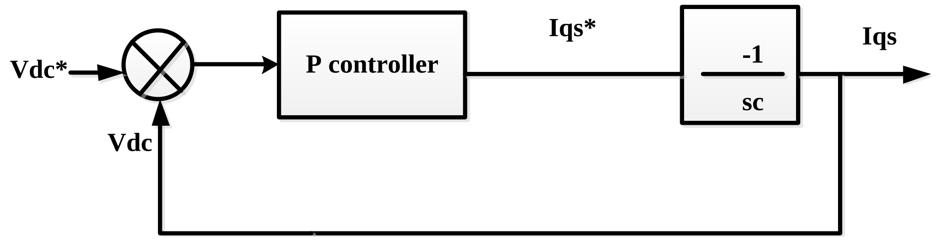

Figure 3.8: Model of Vdc control loop

The negative sign shows in block diagram can cause the negative torque which lead to rotate the rotor of induction motor in reverse direction, ignore that negative sign to study this control strategy of locomotive. Let proportional controller be as constant K, then the open loop transfer function is

$$OLTF = \frac{K}{sc}$$

$$CLTF = \frac{1}{1 + s\frac{c}{K}}$$

The bandwidth of this loop should be less than $\frac{1}{10}$th of bandwidth of current control loop. Current control band width is 100 hz, then Vdc loop band width is f_b=10 hz. Then

$$\tau_b = \frac{1}{2\Pi f_b}$$

$$\frac{1}{1+s\dfrac{c}{K}} = \frac{1}{1+s\tau_b}$$

$$\frac{c}{K} = \tau_b = \frac{1}{2\Pi f_b}$$

Then the proportional constant K can de written as

$$K = c2\Pi f_b$$

The capacitor value is c=1e-6, then the value of proportional constant K=6.2831e-5

3.3 Conclusion

This chapter presented the design of the control strategies. The design of the PI controllers and the various blocks for control, used in the vector control system, AVR is described in detail. In the next chapter the results obtained from the simulation will be presented and discussed.

CHAPTER 4

COMPARISON

4.1 Simulation results

Comparison of two theories will be explained based on simulation result. The simulation of control strategies is done in SIMULINK using the model of a 160 KW induction machine and 1320 KW alternator. The results obtained are presented in the following sections. The machines ratings and parameters are given in Table 4.1, 4.2, 4.3 and 4.4.

Table 4.1: Ratings for the 160 KW motor

Parameter	**Value**
Power	160 KW
Voltage	400 V
Current	288.67 A
Power factor	0.8
Connection	Star
Speed	1487 rpm
Rotor type	Squirrel Cage

Table 4.2: Ratings for the 1320 KW alternator

Parameter	**Value**
Power	1320 KW
Voltage	604 V
frequency	50 hz
Speed	1500 rpm
Rotor type	Salient type

Table 4.3: Induction motor parameters

R_s	$R_r^{'}$	L_{ls}	L_{lr}	L_m	J
0.01379 Ω	0.007728 Ω	0.000152 *mH*	0.000152 *mH*	0.00769 *mH*	2.9 $kg - m^2$

Table 4.4: Alternator parameters

R_f	L_f	P	B	J
0.0003828 Ω	0.0001815 *mH*	4	0.63 N.m.s	33.01 $kg - m^2$

The design of the controllers and the limiter values of strategy-1 have been done following the procedure outlined in previous Chapter for the 160kW induction machine and 1320KW of alternator. The values obtained from these are given in Table 4.5.

For strategy-2, the control parameters and the limiters are given in table 4.6.

Table 4.5: Controller parameters

Controller	f_b (Hz)	K_p	K_i	U_{max}	U_{min}
i_{sd}	100	0.1892	13.3338	54.8453	-54.8453
i_{sq}	100	0.1892	13.3338	577.2290	-577.2290
ψ_{dr}	10	8.29e3	8.1706e3	230.9391	-230.9391
ω_m	5	52.3148	82.1759	613.5615	-613.5615
$\omega_{alternator}$	1	207.407	3.6584	8403.38	-8403.38
v_f	1	5.7019×10^{-5}	1.2026×10^{-5}	45	-45

Table 4.6: Controller parameters

Controller	f_b (Hz)	K_p	K_i	U_{max}	U_{min}
i_{sd}	100	0.1892	13.3338	54.8453	-54.8453
i_{sq}	100	0.1892	13.3338	577.2290	-577.2290
ψ_{dr}	10	8.29e3	8.1706e3	230.9391	-230.9391
V_{dc}	10	$6.2831 10^{-5}$	–	613.5615	-613.5615

4.1.1 Strategy-1

Constant speed-varying load:

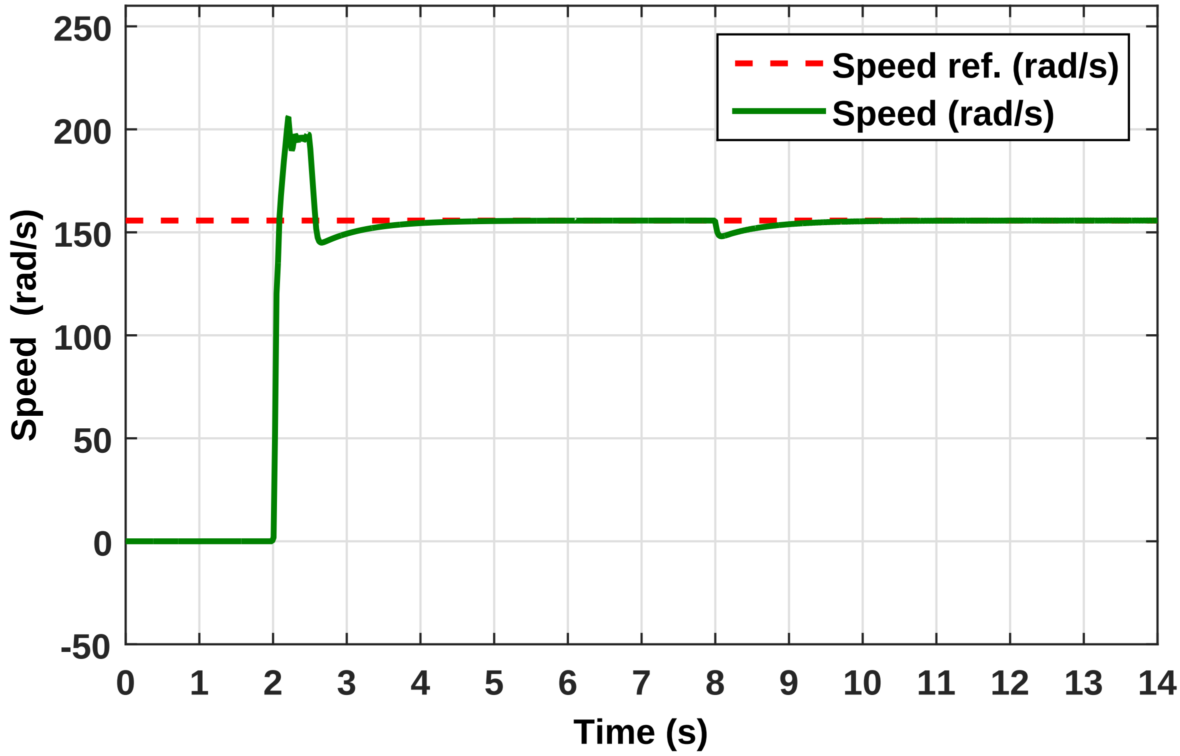

Figure 4.1: *Simulation result* : Speed response for sudden full load torque application *(Scale: X-axis: 1.0 s/div, Y-axis: 50 rad/sec /div)*

Fig. 4.1 shows the simulated speed response of induction motor, from t=0 s to t=2 s induction motor is not connected to alternator. In that time alternator generates the required DC voltage for induction motor. At t=2 s induction motor suddenly connected to rectifier voltage Vdc, because of high transient torque and selection bandwidth of controllers its takes time to enter into steady state rated speed. At t=8 s full load torque was applied to induction motor, because of already connected to Vdc its take less time to settle and speed is following the reference speed with a small dip.

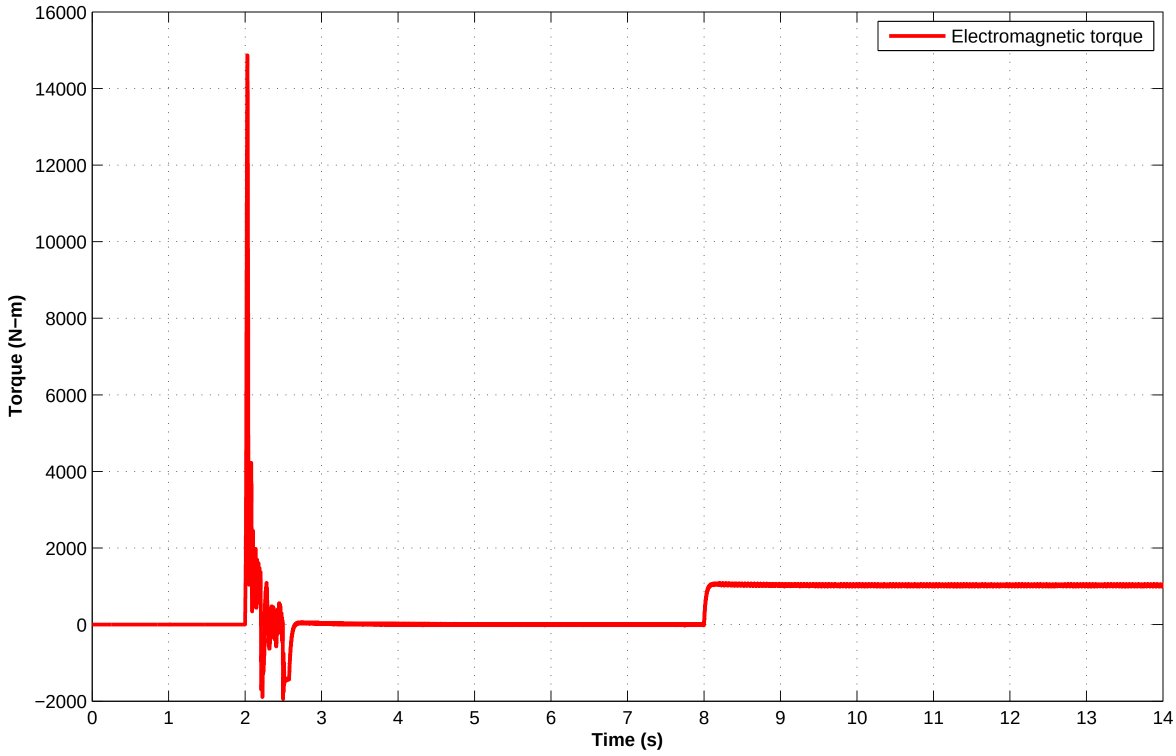

Figure 4.2: *Simulation result* : The electromagnetic torque response of motor for sudden full load torque application *(Scale: X-axis: 1.0 s/div, Y-axis: 2000 N-m /div)*

Fig. 4.2 shows the response of electromagnetic torque. From t=2 s to t=8 T_l=0, At t=2 s induction motor connected to alternator high torque obtained as in transient state. At t=8 s full load torque of T_l=1024 N-m was applied. If machine is able to withstand that load and engine have sufficient power to give to motor then only electromagnetic torque would reach the load torque. All controllers will work as expected when Torque developed by motor reached that full load value is clearly visible in zoom picture of this figure. If torque has unable to reach the respective load torque then speed of motor will goes to zero it means motor would stop. Zoom of this will show in fig. 4.3

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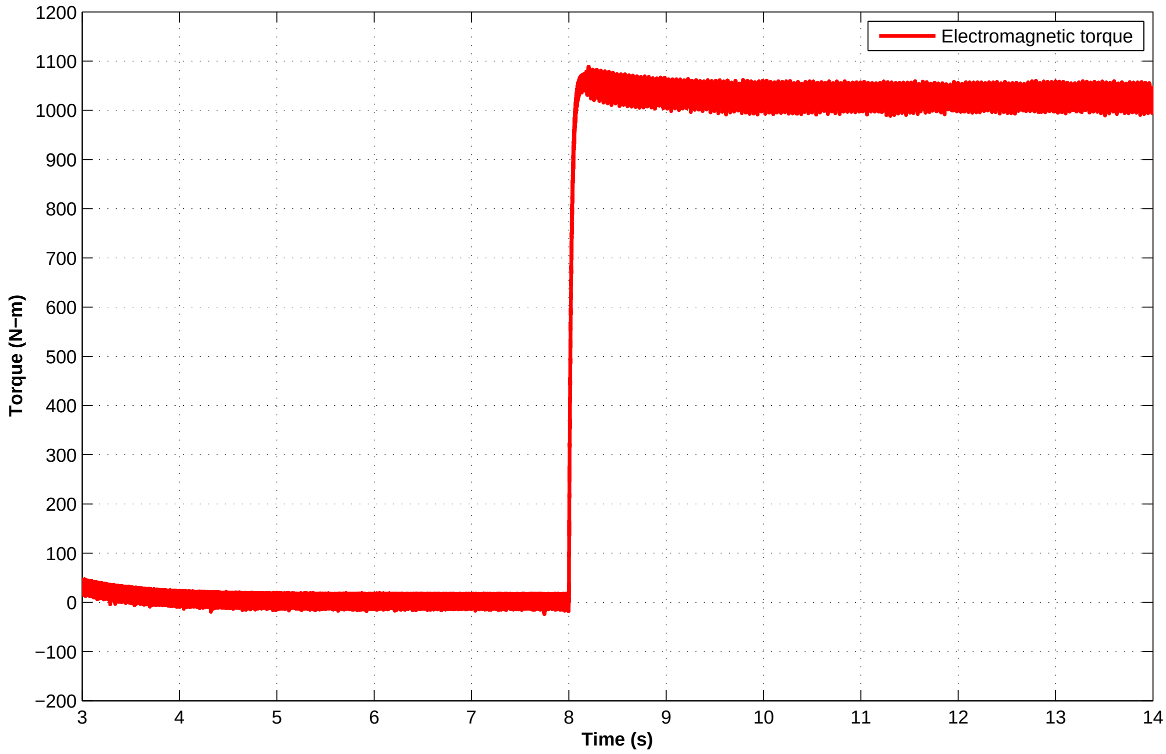

Figure 4.3: *Simulation result* : The zoom of electromagnetic torque response of motor for sudden full load torque application *(Scale: X-axis: 1.0 s/div, Y-axis: 100 N-m /div)*

Fig. 4.3 shows the developed torque was reached to load torque of value T_l=1024 Nm at t=8 s, with error of 50 N-m. As Vdc is constant the inverter generates AC supply to motor, controllers generate required waveforms to control the motor in a signal form and by using SPWM, inverter is able to generate those signals. Torque developed has reached to load torque with a error of 5% because of PWM techniques and that error is acceptable.

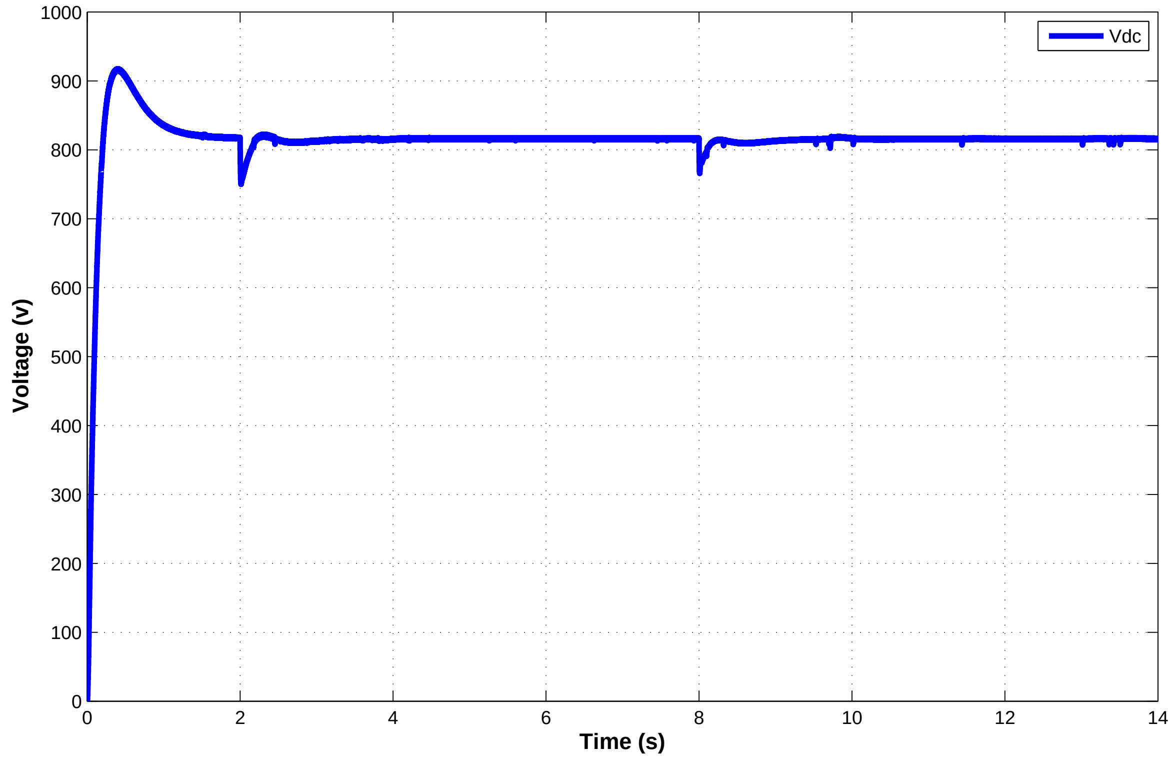

Figure 4.4: *Simulation result* : Rectifier output response for sudden full load torque application *(Scale: X-axis: 2.0 s/div, Y-axis: 100 v /div)*

Fig. 4.4 shows response of Vdc, the induction drive would work correctly only when this Vdc is constant. At t=2 s induction drive connected it act as load to the alternator and causing reduction in voltage. If AVR is not present then voltage is reduced and it settle to some value. AVR used as controller that to maintain constant voltage then small dip appeared as shown in figure. At t=8 s full load torque applied to induction motor, indirectly act as burden to alternator and AVR regulate voltage because of this again small dip of voltage obtained.

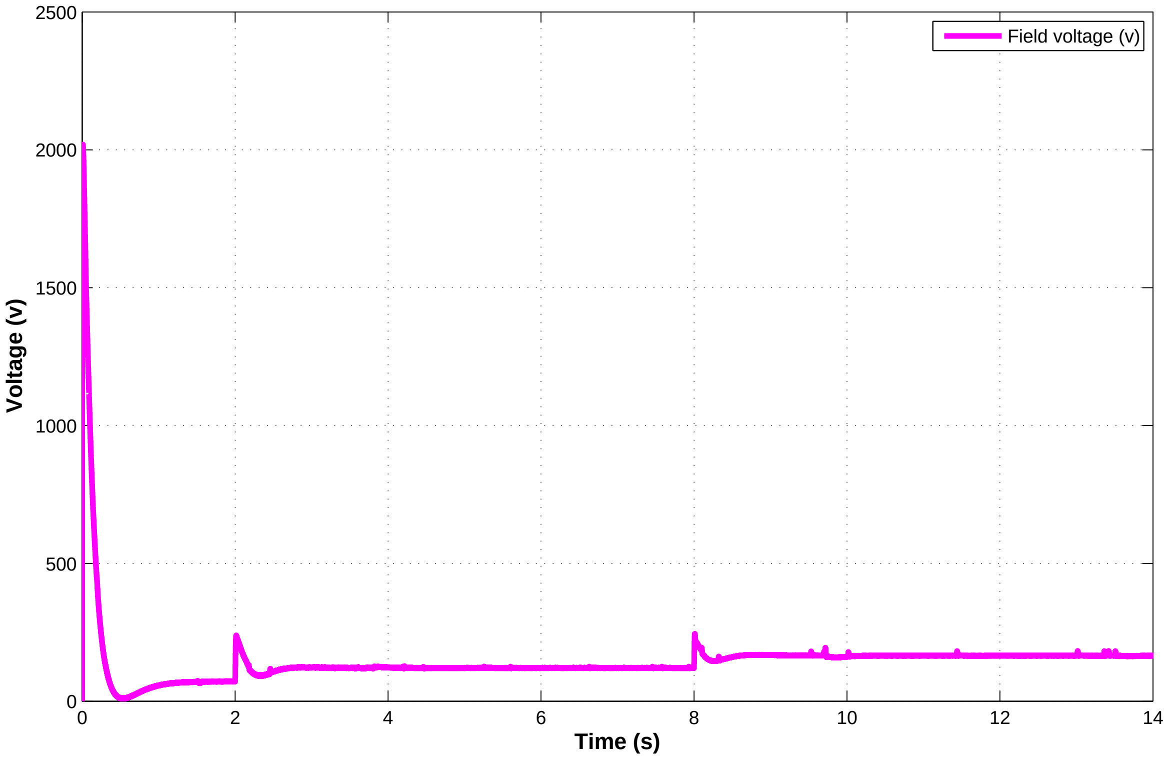

Figure 4.5: *Simulation result* : Exciter voltage response of alternator for sudden full load torque application *(Scale: X-axis: 2.0 s/div, Y-axis: 500 v /div)*

Fig. 4.5 shows response of field voltage. In fig. 4.4 instead of reducing the voltage Vdc, it was controlled by field voltage. At t=0 s speed of the alternator rotor is zero and AVR gives supply to field to maintain constant Vdc voltage, high voltage is required to give to field. As speed is increasing small field voltage is enough to get rated Vdc voltage that observed from t=0 s to t=2 s. The generated voltage of alternator depend on speed and field voltage.

At t=2 s induction motor was connected to alternator, indirectly its act as burden to alternator and causing reduction of voltage. To maintain that voltage is constant have to increase the field voltage that shown in figure. At t=8 s full load was applied to induction motor and same thing was happen like at t=2 s and AVR gives some more field voltage for regulating Vdc voltage that changes in field voltage shown in figure.

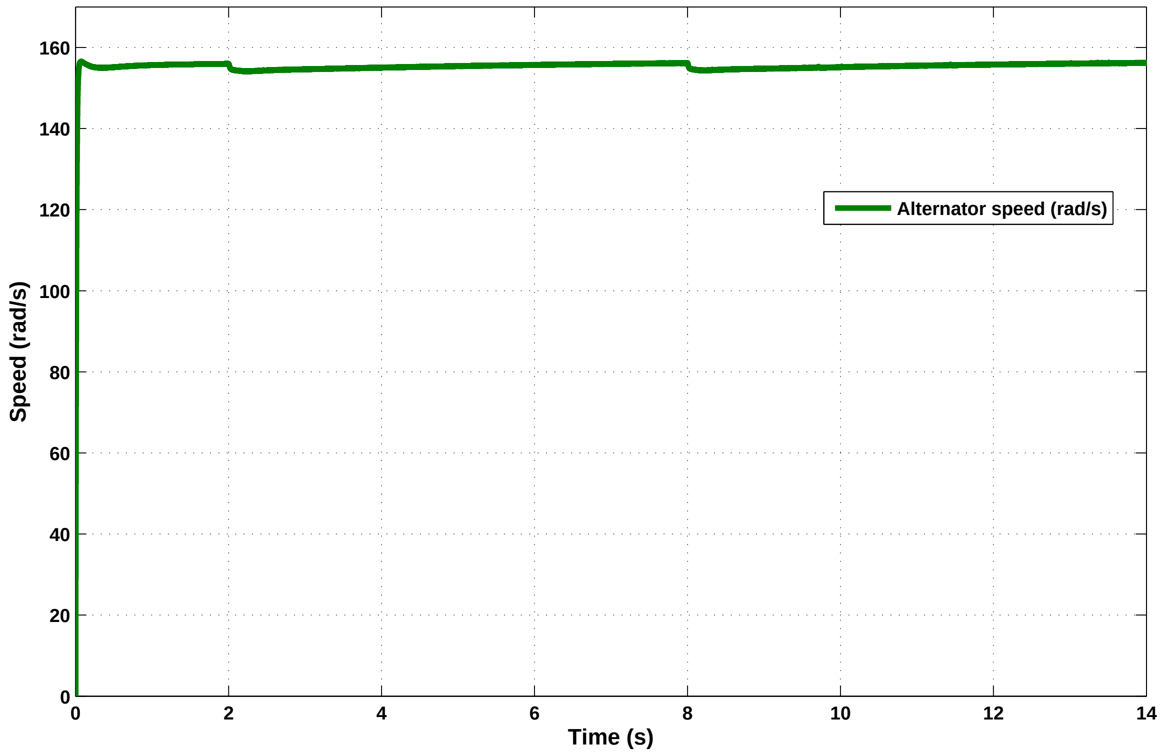

Figure 4.6: *Simulation result* : Speed response of alternator for sudden full load torque application *(Scale: X-axis: 2.0 s/div, Y-axis: 20 rad/sec /div)*

Fig. 4.6 shows the response of speed of alternator during loading condition. During loading condition rotor speed is reduced and require more torque to rotate the same speed. Diesel engine provides that torque to the rotor of alternator, during loading condition more fuel is required to give more torque to rotor for maintaining same speed. After speed was reached to rated at t=2 s motor connected to alternator then speed is reduced and asking for more torque, engine provides that by utilizing more fuel. At t=8 s again loading was happen, speed controller of alternator maintains same speed by allowing more fuel to engine as a result small dip of speed was observed and above response shows speed was regulated by speed controller of alternator.

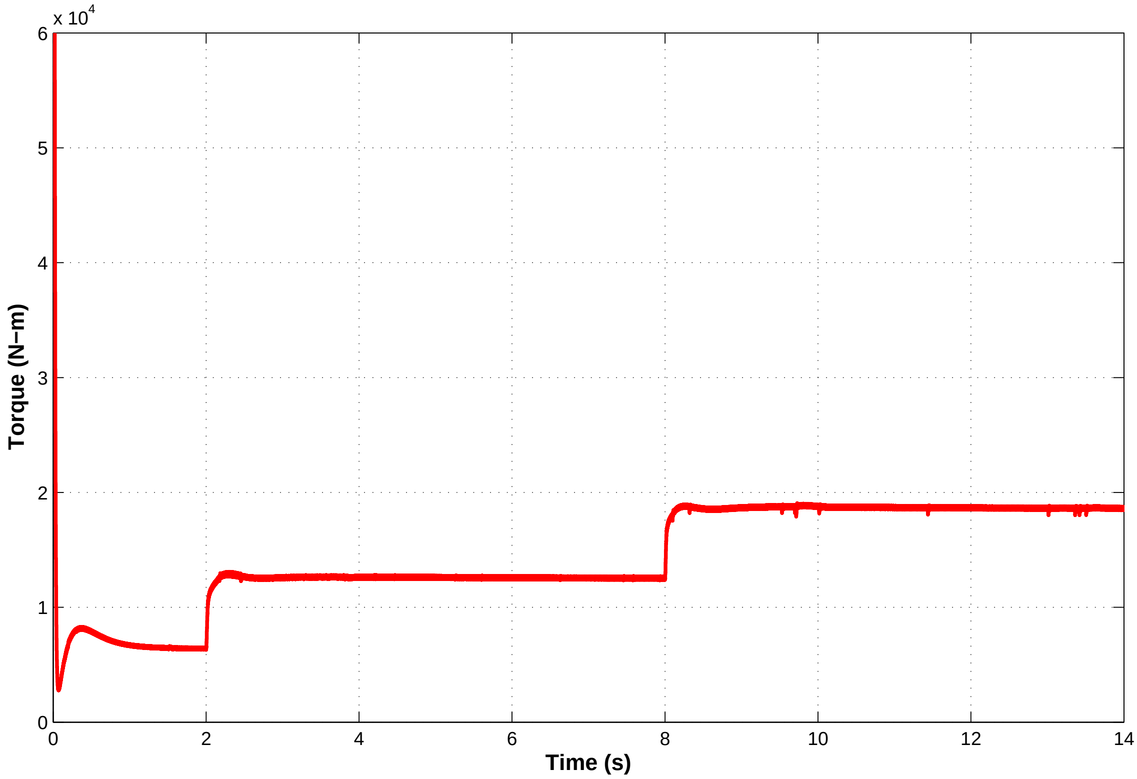

Figure 4.7: *Simulation result* : Response of input torque of alternator for sudden full load torque application *(Scale: X-axis: 2.0 s/div, Y-axis: 1*$\times$ 10^4 *N-m /div)*

Fig.4.7 shows the response of torque input given to alternator. At starting require more torque to rotate and as a speed is increasing requirement of torque is reducing for maintaining same rotor speed. From t=0 s to t=2 s as speed is constant torque given by engine is also constant. At t=2 s because of loading speed of rotor was reduced it wants more torque by engine to maintain same speed, increasing of torque can observed in figure. Again at t=8 s full load was applied to motor and to maintain same speed speed controller allows more fuel to engine that generates more torque as shown in figure. So the response shows that the alternator speed was controlled by varying torque.

Constant load-vary speed

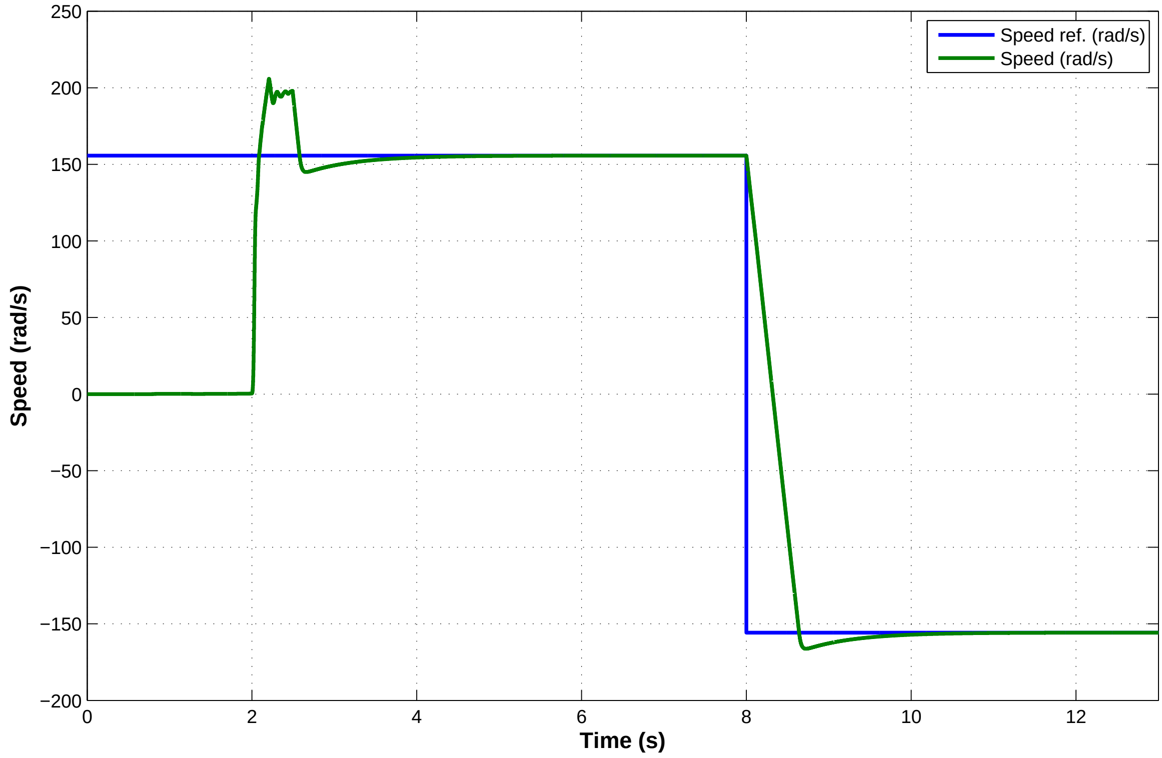

Figure 4.8: *Simulation result* : Speed response of induction motor during speed reversal operation *(Scale: X-axis: 2.0 s/div, Y-axis: 50 rad/s /div)*

Fig. 4.8 shows the simulated speed response for a speed reversal command from 157 rad/s to -157 rad/s at t=8 s. From t=0 s to t=2 s induction motor was not connected to alternator so the speed is zero. At t=2 s it was connected to alternator with AVR and speed control then the speed of motor starts increasing and it takes time to settle that was decided by bandwidth of controller. At t=8 s speed reversal command was given speed and flux controllers produce currents to get that reference speed and in this case load was not applied, the developed torque response is shown in fig. 4.9

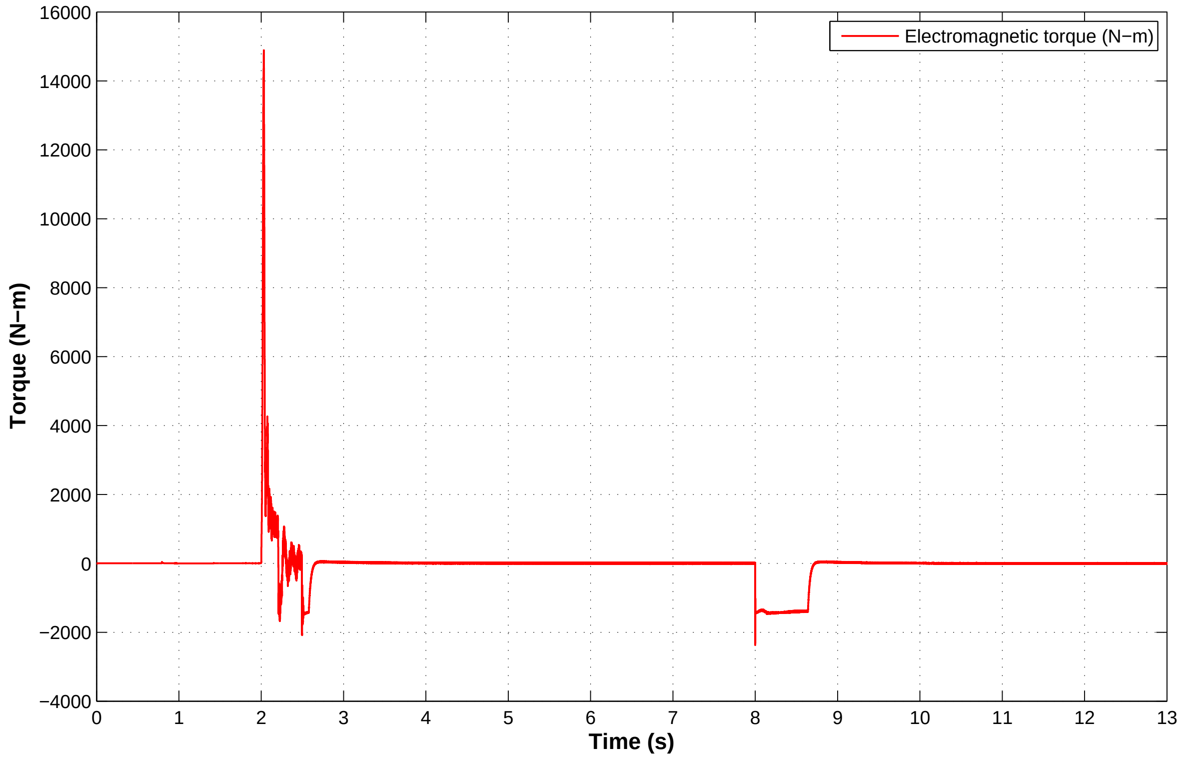

Figure 4.9: *Simulation result* :Electromagnetic torque response of induction motor during speed reversal operation *(Scale: X-axis: 1.0 s/div, Y-axis: 2000 N-m /div)*

Fig. 4.9 shows simulated response of developed torque of motor. During reversal torque goes to negative maximum value indicating that current i_{sq} is in negative direction. It indicates that drive is in regeneration mode. At t=2 s speed of motor is zero so high torque is required for rotating the driving wheels that was shown in figure. At t=8 s torque was in negative up to speed settled to reversal reference speed, after reaching that speed again developed torque reach to load torque. Load was not applied so developed torque settled to zero that can identified in above figure.

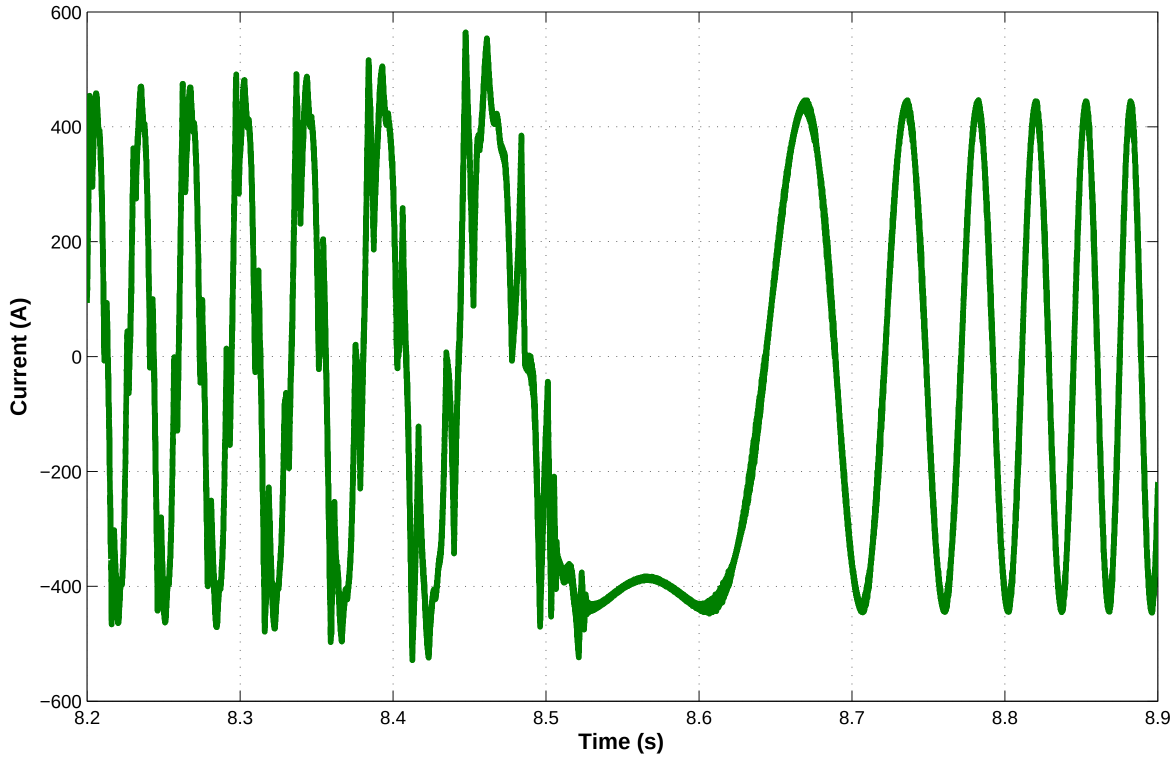

Figure 4.10: *Simulation result* : Phase current during speed reversal operation *(Scale: X-axis: 1.0 s/div, Y-axis: 2000 N-m /div)*

Fig. 4.10 shows the simulated waveform of the R-phase current during the speed reversal operation shown in Fig. 4.8. The change in frequency and phase sequence during the reversal can be observed. Remaining Vdc, field voltage, alternator speed waveforms are same as in first case.

4.1.2 Strategy-2

In this control method, at starting AVR and speed control of alternator were used upto the rectified voltage Vdc reaches the rated value (Vdc=816). After reaching, constant voltage given to field instead of AVR and constant torque given to rotor of alternator. Responses from the simulating of this method was shown in below figures as follows.

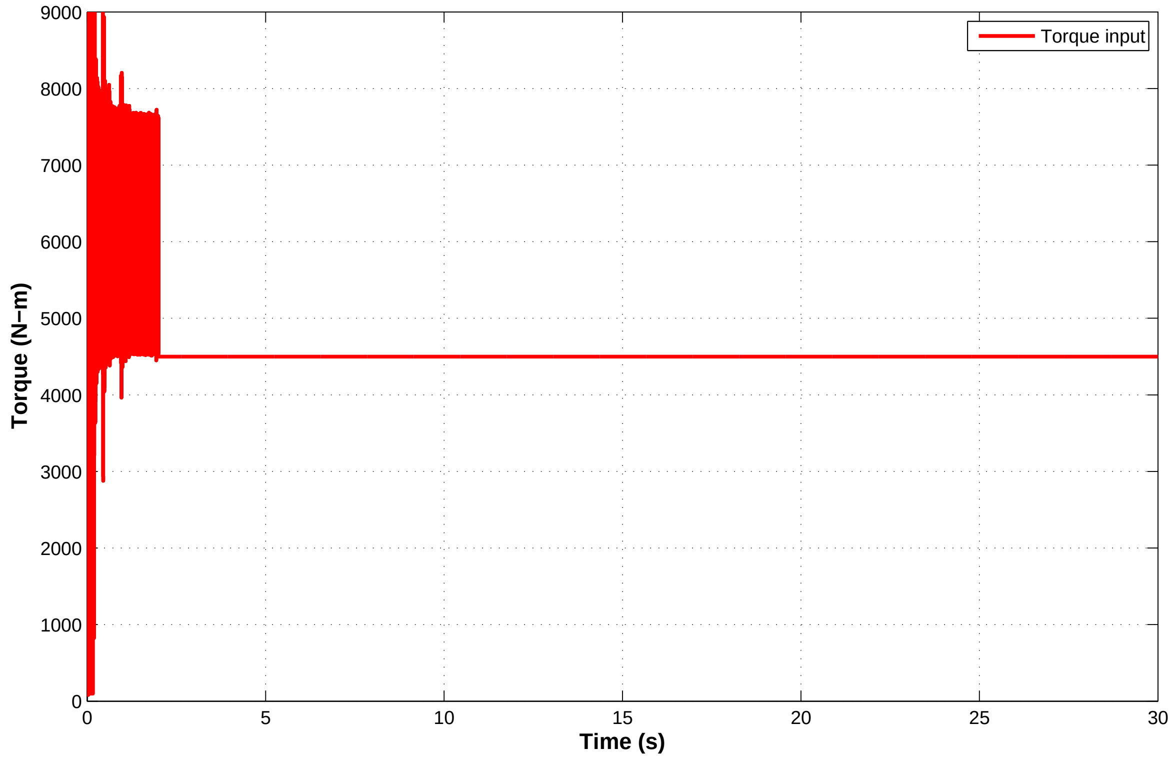

Figure 4.11: *Simulation result* : Torque response of engine given as input to alternator *(Scale: X-axis: 5.0 s/div, Y-axis: 1000 N-m /div)*

Fig. 4.11 shows the simulated torque response of Diesel engine which was given as input to alternator. From t=0 s to t=2 s torque was applied to rotor of alternator and AVR provide voltage to field for generating rated Vdc voltage. After that from t=2 s constant torque was given to rotor of alternator. At t=15 s full load was applied to motor that indirectly act as load to alternator, more fuel is required to maintain constant torque that given to rotor of alternator. For simulation study constant torque was applied that shown in figure but the fuel input was varying based on load that have to keep in mind.

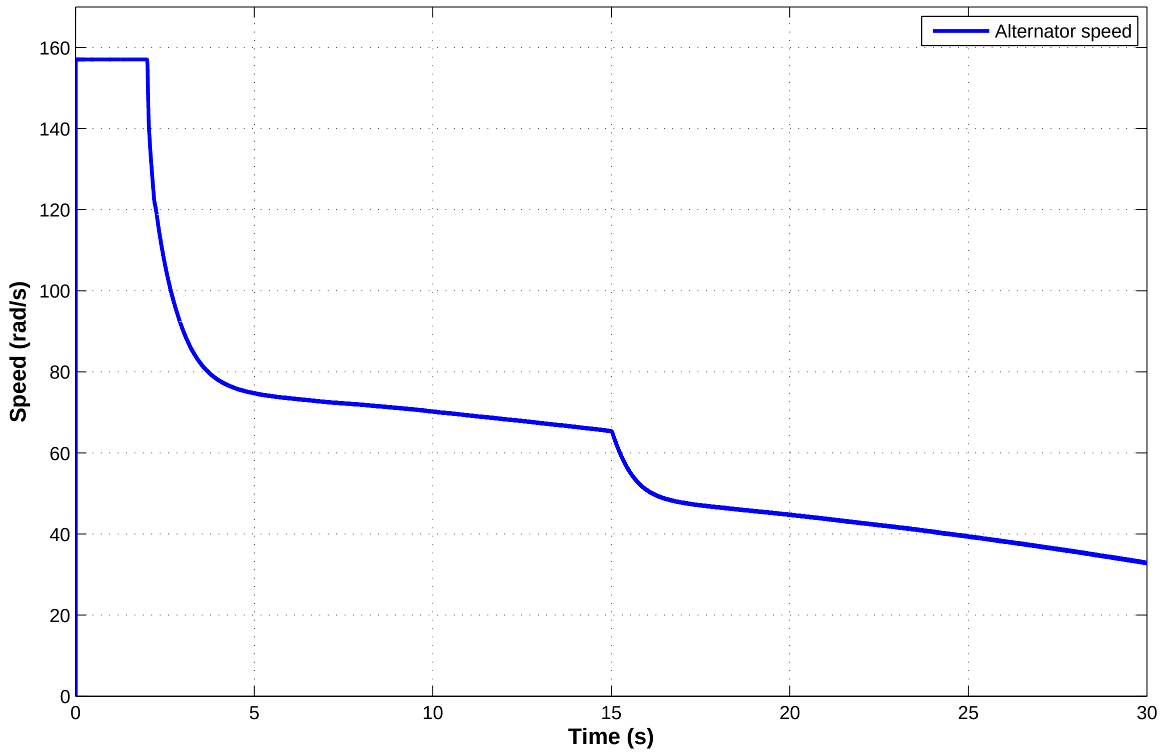

Figure 4.12: *Simulation result* : Speed response of alternator during loading condition *(Scale: X-axis: 5.0 s/div, Y-axis: 20 rad/s /div)*

Fig. 4.12 shows the simulated speed response of alternator. At t=2 s induction motor was connected but in this strategy constant torque and field were applied and AVR, speed controller of alternator are not used so the speed of alternator was reduced. At t=15 s full load was applied and the rotor speed reduced further. In order to maintain same speed during loading condition more torque is required to give to rotor. The settling time is around 10 s compare to previous strategy it is more, but it is a practical method using for locomotive. In previous methods its takes only 2 s that is too speed because of controllers, those are very costly mainly used for specific applications.

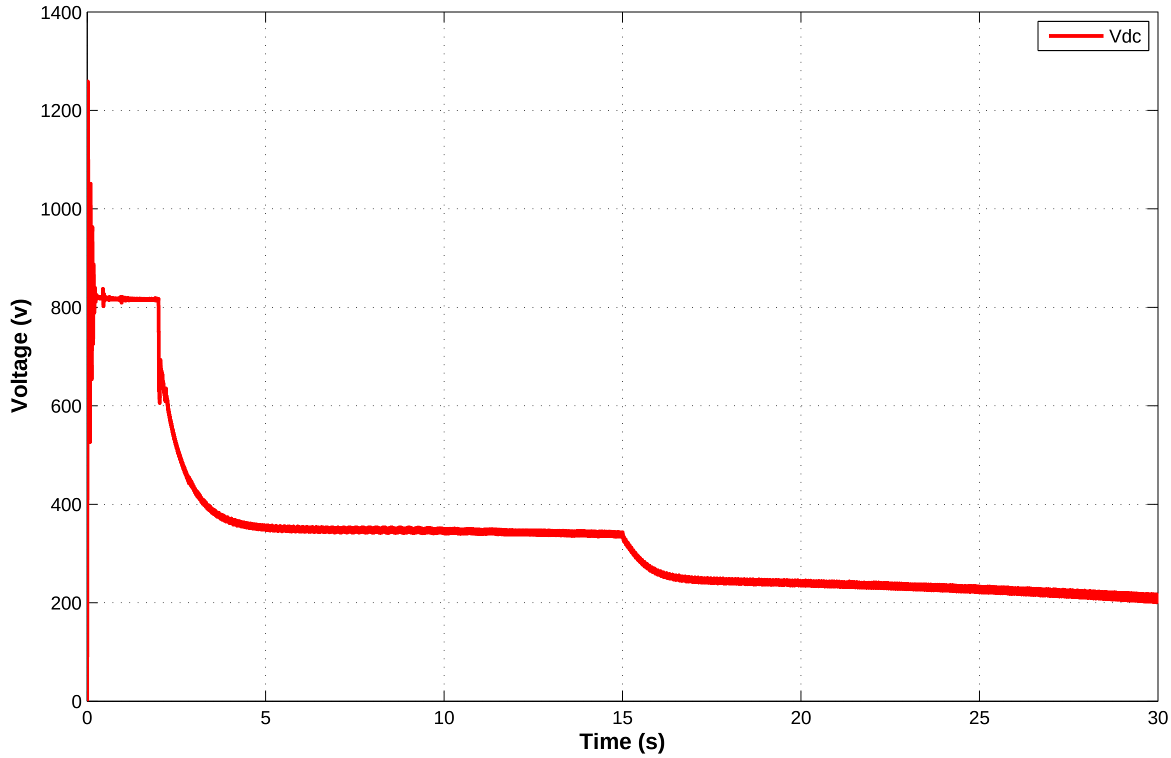

Figure 4.13: *Simulation result* : Rectified voltage response during loading condition *(Scale: X-axis: 5.0 s/div, Y-axis: 200 v /div)*

Fig. 4.13 shows the simulated voltage response of rectifier. It shows the reduction of rectified voltage(Vdc) During loading condition. In this method flux controller used for generating i_{ds} and based on the value of Vdc the current i_{qs} produced that cause developed torque. If Vdc is rated then speed of motor is high, as Vdc is reduced the Vdc controller produces more current so the speed of motor settle down otherwise it goes to zero. The rating of alternator is 1320 KW, it takes 15 s time to settle down based on rating of alternator this time is acceptable. In previous method excitation system used to control Vdc so it appears as a small dip. In this method there is no control of field then Vdc was reduced while loading.

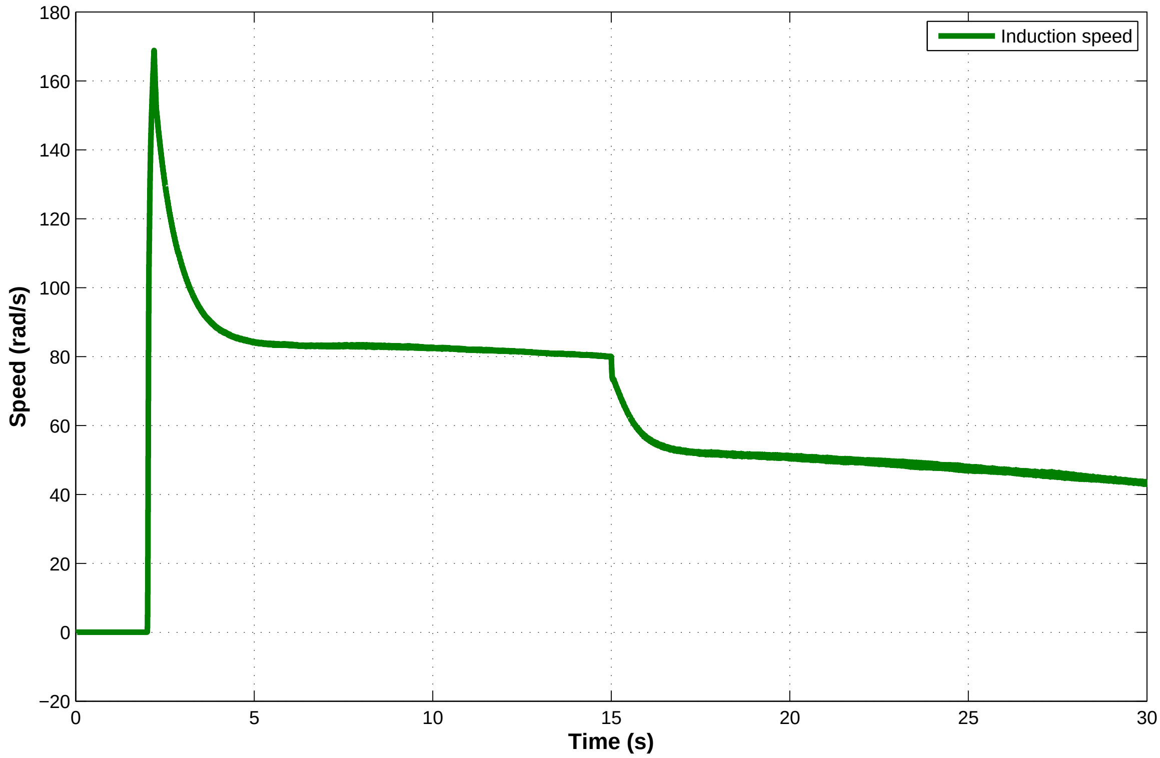

Figure 4.14: *Simulation result* : Phase current during speed reversal operation *(Scale: X-axis: 5.0 s/div, Y-axis: 20 rad/s /div)*

Fig. 4.14 shows the simulated speed response of induction motor. At t=2 s speed goes to high value that is because of Vdc controller, at starting the controller error is high its take time to settle. At t=15 s high load was applied, because of no AVR, speed control of alternator, and torque input to rotor of alternator is also a constant leads to speed of motor was reduced and it takes around 10 s time to enter into steady state. In previous method there is some reference speed to give and controller maintain that speed, but in this method based on the fuel input of diesel engine the motor speed could decided. As the fuel input is constant the torque given to rotor of synchronous machine is constant then the response of speed during loading was shown in above figure.

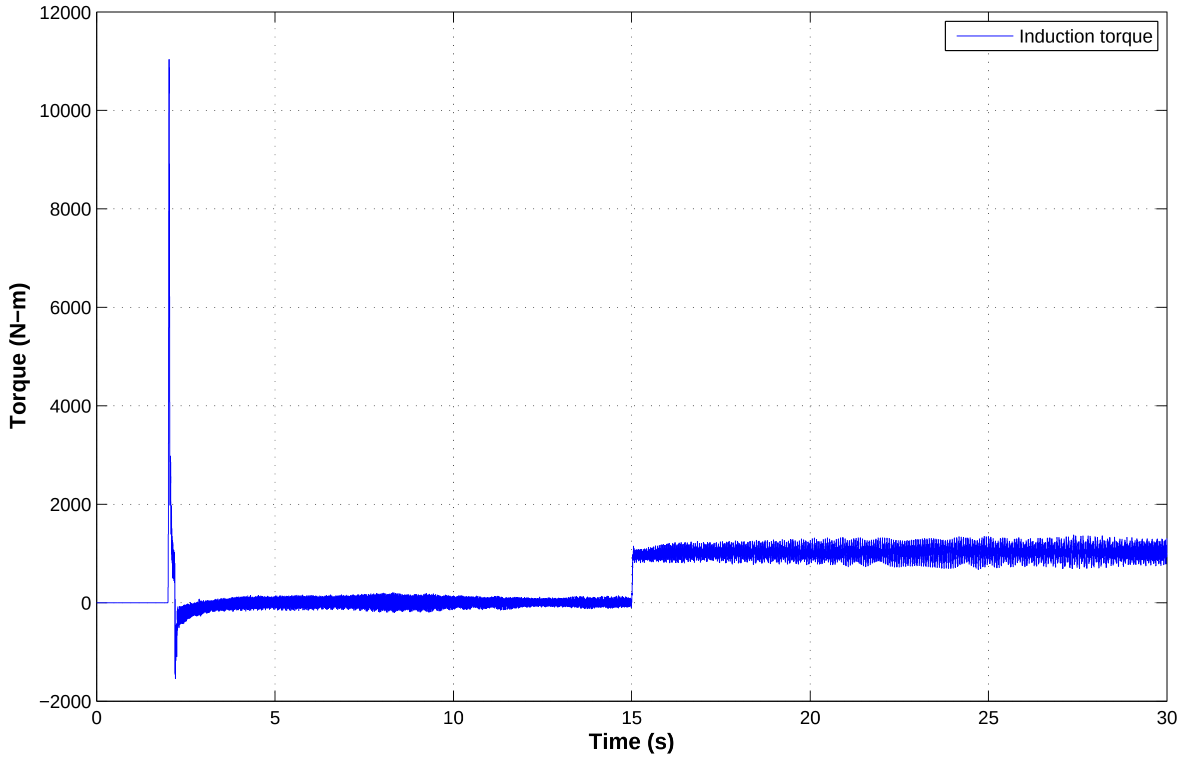

Figure 4.15: *Simulation result* : Electromagnetic torque response of induction motor during loading condition *(Scale: X-axis: 5.0 s/div, Y-axis: 2000 N-m /div)*

Fig. 4.15 shows the simulated response of electromagnetic torque of induction motor to a step change in load torque of rated value applied at t=15 s. The electromagnetic torque immediately rises to the rated value to meet the load torque demand. Inverter converts DC into AC that required waveforms would get by PWM techniques, it works good since Vdc is constant rated value because the modulation index, reference waveform limits are decided based on Vdc value. During loading condition Vdc is reduced, inverter couldn't generate as expected it resulting the error of the torque developed is around ± 10 % tht shown in above figure.

4.1.3 Conclusion

The results from the simulating the two control strategies for the 160 Kw induction motor and 1320 Kw alternator were presented in this chapter. In both schemes After Vdc reaching rated value i.e., Vdc=816, then only induction machine has connected to inverter with Vdc. Comparison of these two methods will be explained as follows:

- The controllers FOC, AVR, speed control of alternator were used for controlling of locomotive in method-1. Where as in method-2 no controllers were used except flux controller to decoupled torque and flux of motor, driver itself has to control the locomotive by varying the fuel input to diesel engine. So scheme-1 is automatic control and scheme-2 is the manual control

- During loading condition speed was suddenly reduced and hardly took 2 to 3 seconds to reach the reference speed in method-1. But in method-2 it has taken minimum of 15 second to reach required speed by driver of locomotive.

- By observing figures of induction torque in both methods, the oscillating error of torque waveform in method-1 is maximum as $\pm 5\%$ (± 50 N-m) and in method-2 is $\pm 10\%$ (± 100 N-m).

- As AVR is used in strategy-1, under loading condition Vdc was reduced and it regain to normal with in 2 to 3 seconds. No AVR is present in strategy-2, under loading condition Vdc was reduced and it takes minimum of 15 seconds to reach steady state and couldn't rise to rated Vdc.

- Speed reversal can be achieved by simply giving negative reference speed in scheme-1. In scheme-2 speed reversal is possible as applying negative Vdc by interchanging its terminals.

- In some regions where rail traffic is high, can be controlled by scheduling train speeds and exact speed is necessary irrespective of load, so method-1 is the best choice for this case.

  Regions where rail traffic is less, no need to drive locomotive with exact speed. Based on load driven use to control speed by varying fuel. Method-2 is suitable for this case.

- Controllers which are used in control method-1 are costly. Except this remaining locomotive cost is same for both cases. Some applications where exact and fast control of speed is mandatory, then method-1 is approachable.

These are the differences between two control strategies. The overall final conclusion of this report and future scope will be discussed in next chapter.

CHAPTER 5

CONCLUSION

5.1 Summary of the project work

Study of Diesel-electric locomotive and their control strategies were successfully implemented in a 160 KW induction machine and 1320 KW alternator. For the proposed control techniques proper theoretical analysis was presented. Objectives of control methods are obtained in simulation fully achieved. Different types of locomotives were studied and advantages of Diesel-electric locomotive over other were explained.

Basic structure and control study of Diesel-electric locomotive was analysed. Two control strategies were proposed for this locomotive. Indirect vector control of induction motor, automatic voltage regulator of alternator and other controllers are used in control strategies. The control of method-1 is fully automatic, where as method-2 is controlled by driver of locomotive. Design of various control parameters used in two methods was proposed and checked in simulink. Based on the results obtained from the simulation two methods were compared. Method-1 is prefer for high rail traffic areas where exact and fast speed control are the main objectives. Torque error is high in method-2 than method-1 and the advantages and disadvantages of each method were discussed. Overall view of Diesel-electric locomotive was studied in this entire report.

5.2 Future scope of work

There remains a good scope of extending this project by adding additional features to the induction drive. The implementation of a field weakening scheme can enable the drive to operate at speeds greater than rated, in a constant power mode.High inertia is the main feature of traction drive, so the required torque during starting is much higher that the steady state full load torque. So an induction machine drive with field weakening scheme is preferred choice for high speed applications.

Instead of using SPWM, use space vector pulse width modulation (SVPWM) and inverter should be operated in over modulation region to maximize the DC-bus utilisation.

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