CHAPTER - 1

INTRODUCTION

1.1. Introduction

In present days due to increased population and their utilities, the existing power generation is not sufficient to meet the load demand. This problem is rectified by increasing the generation and effective control. The power generation will depend on so many factors such as decentralization etc.

The effective control of power generation can be achieved by decreasing the wastage and by using low power consumption load equipment’s. While dealing about load equipment’s i.e., the industrial, commercial, agricultural etc., are inductive in nature and hence the induction motor are widely in usage because of their multiple advantages i.e., simplicity, ruggedness and easy maintenance etc.

With the use of power electronic devices a wide range of speed control methods are possible. But power electronic devices introduce some power quality problems. In general the power quality problems are like voltage swells, voltage sags, shortages, distortion and harmonics. Speed control of induction motors is possible with variable voltage, frequency. These supplies are available with various types of inverters (Voltage, Current) etc. But by using these types of inverters produces distortions at the output stage.

This work deals with EZ - Source (Embedded Z - Source) Inverter for AC electrical drives. EZ - Source Inverter can be applied to the entire spectrum of power conversion. It is used for Boost - Buck conversion, where capacitor
and inductors are used. The EZ - Source inverter is considered in place of Impedance Source (Z - Source) Inverters, Conventional Inverters (Voltage Source Inverter (VSI) and Current Source Inverters (CSI)). By using the EZ-Source Inverter many problems can be overcome, which are existed in Impedance Source (Z - Source) Inverters and in Conventional inverters, and also it results in higher efficiency.

Conventionally there are two types of inverters: namely Voltage Source Inverter (VSI) and Current Source Inverter (CSI). Each inverter has six switches in the main circuit. These switches are power switches with anti-parallel diodes. These diodes provide bi-directional current flow and voltage blocking capability. Conventional Source Inverters have the following problems,

- There can be either a boost or a buck inverter operation and cannot be a buck-boost inverter operation.

- Their output voltage range is limited to either greater or smaller than the input voltage.

- Their main circuits cannot be interchangeable. In other words: the Voltage Source Inverter (VSI) cannot be used for the Current Source Inverter (CSI), vice-versa.

- They are vulnerable to EMI noise in terms of reliability.

The three-phase squirrel cage induction motor is the most popular electric motor used in industry by utilities. It is popularly used because of several factors: ruggedness, simplicity of construction and suitable in all areas,
make the induction motor a reliable, long-run and easy to maintain and low cost solution, while its ability is to start and operate directly from the grid without any extra hardware. Energy efficient speed control of the Induction Motor is possible by adjusting the frequency of the supply voltage, which is usually done by means of a frequency converter. In the most common type of frequency converters, the line voltage is first rectified into DC voltage, which is subsequently inverted into an adjustable AC voltage using Pulse Width Modulation (PWM) techniques.

The control strategies of the Inverter - Motor combination may be classified into two broad categories: Open-loop Scalar control strategies [24] for application with moderate static and dynamic performance requirements and Closed-loop Vector strategies for high-performance applications. In Vector control, the flux linkage magnitude and the electromagnetic torques are controlled independently (by analogy with the DC machine) [30] - [31]. The independent control is possible by dividing the stator current vector into two components, parallel and perpendicular to the flux linkage vector. The division can be made only if the direction of the flux linkage vector is known, as demonstrated by Blaschke, who is credited for his pioneering work in the vector control of induction motors [34] - [37]. Usually it is either the stator flux linkage or the rotor flux linkage that is selected for control.

The key to Vector control is thus the correct observation of the orientation of the flux linkage (which is often called the field orientation) and thereafter, the independent control of the mutually perpendicular stator current
components. However, if there is an error in the orientation, a cross-coupling between the flux and torque control leads to poor dynamic performance and may increase the power losses in the motor. Moreover, a flux level considerably lower than the desired may cause the motor to lose the required torque producing capability. The field orientation is an assumption of constant rotor speed often made in order to simplify the analysis of the flux dynamics of an Induction Motor.

The constant speed assumption linearizes non-linear system. It is reasoned that the currents of a winding can change almost instantaneously, while the acceleration is limited by the moment of inertia in the system. The mechanical dynamics are thus excluded from the treatment of the flux dynamics, and the speed merely enters the voltage equations of the motor as a disturbance. However the moment of inertia in the system is not always large enough to justify the assumption of constant speed. In fact, if nominal torque is applied and the moment of inertia of the rotor alone is considered, a typical Induction Motor accelerates from zero to nominal speed in a time interval comparable to the rotor time constant. In such an extreme case, there is no justification for a two-time scale approach to separate the flux dynamics from the mechanical dynamics.

The work presented here is motivated by the difficulty in achieving speed sensorless vector control of an Induction Motor when the stator frequency is close to zero. The objective is to develop such a Vector control, with the following attributes:
1. There is no speed sensor in the system.

2. The control is based on the known stator currents and stator voltages.

3. At low speeds, the system is stable in steady state, under all load torque conditions up to rated torque, in all four quadrants, including zero frequency and zero speed.

4. The system is adequately robust against errors in motor parameter estimates for a practical application.

5. The dynamic performance of the system is comparable to that of speed-sensor vector control.

6. The system is widely applicable with respect to motor size, design, and application.

7. The system is easy to implement.

The sensorless zero-frequency Vector control of an Induction Motor cannot be achieved by using pure DC quantities, some kind of signal injection method should be considered. However, the control should preferably be a simple, generally applicable to motor model.

The work presented in this thesis is based on the ideal motor model, which is augmented with the equation of motion in order to take the mechanical dynamics into account. In addition, a fast stator current control, which removes the dynamics of the stator winding from the dynamics of the rest of the electromechanical system, is assumed. Thus, the stator voltage is considered to be an output of the current-fed motor.
Adding a low frequency AC current signal (about 25 Hz) to the stator current creates a specific response from the electromechanical system that can be extracted from the stator voltage. This phenomenon is analyzed in this work, and it is observed that the response conveys information about the rotor flux direction, provided that the total moment of inertia is not too high. Based on the result, a method for determining the direction of the rotor flux in a speed sensorless Induction Motor Drive is developed. Experimental results indicated that the method is capable of tracking the rotor flux direction at all low speed operating conditions, including zero frequency. The method is also known to be insensitive to errors in motor parameter estimates.

Early work introduced the Two-Reaction Theory (Park 1929) for Synchronous Generator which laid down general principles for the analysis of AC machines. Stanley (1938):

1. Balanced rotor windings are assumed for all cases, and the three-phase machine equations are derived from the additional assumption that the stator winding are also balanced.
2. It is assumed that the co-efficient of mutual inductance between any stator winding and any rotor winding is a Co-Sinusoidal function of the electrical angle between the axes of the two windings.
3. It is further assumed that the rotor is smooth and that the self-inductances of all the windings are independent of the rotor position.
4. The effects of saturation, Hysteresis and Eddy currents are neglected.
The assumptions yield the selection of constant parameter, fundamental wave model, for a three phase Induction Motor. The assumptions also guarantee that the spatial distribution of the air gap field in the motor is always sinusoidal, even if the timely behavior of the currents in the individual windings is not. Thus the fundamental wave model is also applicable in dynamic analysis.

Space vectors provide an efficient and convenient tool for the analysis of three phase systems. They were originally developed by Kovacs and Racz (1959). The space vector representing the three phase quantities \( x_a, x_b \) and \( x_c \) is a complex quantity \( X^s \) defined by

\[
X^s = \frac{2}{3}(x_a + e^{2\pi/3} x_b + e^{4\pi/3} x_c)
\]

where the phase quantities may vary arbitrarily in time. The factor \( \frac{2}{3} \) in (1.1) is chosen so that if \( x_a, x_b \) and \( x_c \) form a symmetrical three-phase system, the magnitude of \( X^s \) equals the amplitude of the sinusoidal phase quantities. The superscript “s” indicates that the space vector is expressed in the stationary reference frame, the real axis of which is attached to the magnetic axis of phase a. The space vector can be expressed by its real and imaginary parts as \( X^s = X_\alpha + jX_\beta \). The reference frame is often chosen differently by attaching its real axis to the space vector of a suitable quantity in the motor, usually the space vector \( \psi \) of a flux linkage. In this reference frame, the flux linkage \( \psi \) reduces to a real quantity \( \psi \). Moreover, the steady - state space vectors of the electrical quantities are constant in this reference frame.
The fundamental wave model of the three-phase Induction Motor is fully determined by five parameters in the commonly used T-equivalent circuit of the motor: the magnetizing inductance $L_m$, the inductances $L_\sigma$ and $L_\alpha$ of the stator and rotor windings, respectively, and the resistances $R_s$ and $R_r$ of the windings. The dynamic T-equivalent circuit of the induction motor is given in the stationary reference frame. The variables are the stator voltage $u_s^s$, the stator current $i_s^s$, the magnetizing current $i_m^s$, the rotor current $i_r^s$, the rotor flux linkage $\psi_r^s$ and the angular speed $\omega_m$ of the shaft in electrical radians per second.

In this work the dynamic \( n \)-equivalent circuit is adopted, with all leakage referred to the stator side (De Donekor and Novotny, 1994). The circuit, expressed in the stationary reference frame, is fully determined by only four parameters: the magnetizing inductance $L_M$, the total leakage inductance $L_\sigma$, stator resistance $R_S$ and the rotor resistance $R_R$.

The relationships between these quantities \( n \) that is different from each other in the T- and \( n \)-equivalent circuits. The equations governing the \( n \)-equivalent circuit are the voltage equations for the stator and rotor

\[
\begin{align*}
u_s^s &= R_s i_s^s + L_\sigma \frac{d}{dt} i_s^s + L_M \frac{d}{dt} i_M^s \\
0 &= R_E i_E^s + L_M \frac{d}{dt} i_M^s - j \omega_m \psi_R^s
\end{align*}
\]

and the flux equations of the stator and rotor

\[
\psi_s^s = L_\sigma i_s^s + L_M i_M^s
\]
1.2. Literature Review

DC-to-AC converters are called inverters. The function of an inverter is to change a DC input to AC output of desired magnitude and frequency. By varying input DC voltage and maintaining the gain of the inverter constant, one can obtain a variable output voltage. The output voltage waveforms of ideal inverters should be sinusoidal where practical inverters have nonsinusoidal waveforms. Inverters are widely used in industries such as, variable speed AC motor drives, induction heating, standby power supplies, U.P.S. The input may be a battery, fuel cell, solar cell etc. Inverters generally use PWM control signals for producing an AC output voltage, which are thyristor dependent applications. The inverters are fed from a voltage source and the load current is forced to fluctuate from positive to negative, and vice versa [M.H. Rashid, Power electronics. 2nd edition. 1993].

Voltage source DC-to-AC inverters are desired to accept DC voltage source as input and produce either Single phase or Three phase Sinusoidal output voltage at a low frequency relative to the switching frequency for current source inverters. These AC-to-DC inverters can make a smooth transition into the rectification mode, where the flow of power reverses to be from the AC side to the DC side. The Sinusoidal PWM switching scheme allows control of the boost converter in regulated DC power supplies, where a negative polarity output may be desired with respect to the common terminal of the input voltage, and the output voltage can be either higher or lower than the input voltage. [N. Mohan, W.P. Robbin and T. Undeland, 1998].
PWM techniques are extensively used for the control of Voltage fed inverters. It is possible to control the output voltage as well as to minimize the harmonics by performing semiconductor devices in a current fed inverter which must withstand reverse voltage, and therefore standard symmetric voltage blocking devices are used [B.K. Bose, 2002].

Impedance Source (Z - Source) Inverter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be obtained in the Conventional voltage-source (or voltage-fed) and current source (or current fed) inverters where capacitors and inductors are used respectively. Z - Source converter overcomes the conceptual and theoretical barriers and limitation of the Conventional Voltage Source Inverter (VSI) and Current Source Inverter (CSI) provides a novel power concept. The Impedance source (Z-Source) concept can be applied to all AC - to - AC, AC - to - DC, DC - to - AC, and DC - to - DC power conversion. To describe the operating principle Impedance Source Inverter for DC to AC power conversion needed in fuel cell application [Fang Z. Peng, 2002].

Limitations of the conventional Inverters, Impedance Source (Z-Source) Inverter for Fuel Cell, It has unique features of the inverter, concept, and Simulation and Experimental results are discussed [Fang Z. Peng, 2002]. The concept of Impedance Source (Z - Source) Inverter was proposed by Peng [1]. Comparison of conventional inverters and Impedance Source (Z - Source) Inverter was presented by Miaosen, Joseph & Jin [3]. The Pulse - Width
Modulation (PWM) of Impedance Source (Z - Source) Inverters was presented by Loh, Vilathgamuwa & Lai, Chua & Li [5]. Constant boost control of the Impedance Source Inverter (Z - Source) to minimize current ripple and voltage stress was presented by Shen, Wang, Joseph, Peng, Tolbert and Adams in [10].

A new family of simple topologies of single-phase PWM AC-AC converters with a minimal number of switches: voltage-fed Z-source converter and current-fed Z-source converter. By PWM duty-ratio control, they become “solid-state transformers” with a continuously variable turns ratio. All the proposed AC-AC converters in this project employ only two switches. Compared to the existing PWM AC-AC converter circuits, they have unique features: providing a larger range of output AC voltage with buck-boost, reversing or maintaining phase angle, reducing in-rush and harmonic current, and improving reliability. The operating principle and control method of the proposed topologies are presented. Analysis, simulation, and experimental results are given using the voltage-fed Z-source AC-AC converter as an example. The analysis can be easily extended to other converters.

Identification of an Effective control scheme for Impedance Source (Z-Source) Inverter was presented by Meenakshi and Rajambal, in [26]. Performance Analysis of Reduced switch Impedance Source (Z - Source) Inverter fed Induction Motor drive was presented by Srinivasan and Dash [27]. Comparison of Impedance Source (Z - Source) Inverter and Conventional two stage boost inverter in grid renewable energy generation is presented by Li and Liu [68].
The above literature does not deal with EZ - Source inverter controlled Induction Motor Drive. This work proposes EZ - Source for the control of three phase Induction Motor Drive.

1.3. Objectives

Objective of this work is to simulate and implement the hardware of EZ - Source (Embedded Z - Source) Inverter fed three phase Induction Motor Drive system. This inverter can be used to buck - boost the input voltage, minimize the component count, increase the efficiency and reduce cost, Harmonic Distortions. Proof of EZ - Source Inverter fed three phase Induction Motor Drive system is viable alternate to the existing systems.

1.4. Methodology

- Literature survey was done by referring to related material and collecting the needed information
- A detailed study of traditional inverters (VSI and CSI) and their problems
- A detailed study of impedance source inverter overcoming the problems of traditional inverters
- Simulation of impedance source inverter using MATLAB/SIMULINK
- Hardware implementation of the circuit

1.5. Conventional Inverters

There exist two Conventional Inverters: Voltage Source (or Voltage fed) and Current-Source (or Current fed) converters (or inverters depending on
power flow directions). Fig. 1.1 shows the conventional three-phase Voltage Source Inverter (abbreviated as VSI) structure. A DC voltage source supported by a relatively large capacitor feeds the main converter circuit, i.e., a three-phase bridge inverter system.

![Conventional Voltage Source Inverter (VSI)](image)

The DC voltage source can be a battery, fuel-cell stack, diode rectifier, and/or capacitor. Six switches are used in the main circuit each is traditionally composed of a power transistor and an antiparallel (or freewheeling) diode to provide bi-directional current flow and unidirectional voltage blocking capability. The V-source converter is widely used. It, however, has the following conceptual and theoretical barriers and limitations.
• The AC output voltage is limited below and cannot exceed the DC rail voltage or the DC rail voltage has to be greater than the AC input voltage. Therefore, the V-source inverter is a buck (step-down) inverter for DC to AC power conversion and the Voltage Source Inverter (VSI) is a boost (step-up) rectifier (or boost converter) for AC to DC power conversion. For applications where drive is desirable and the available DC voltage is limited, an additional DC-DC boost converter is needed to obtain a desired AC output. The additional power converter stage increases system cost and lowers efficiency.

• The upper and lower devices of each phase leg cannot be gated on simultaneously either by purpose or by EMI noise. Otherwise, a shoot-through would occur and destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noise’s misgating ON is a major problem to the converter’s reliability. Dead time to block both upper and lower devices has to be provided in the Voltage Source Inverter (VSI), which causes waveform distortion, etc.

• An output LC filter is needed for providing a Sinusoidal Voltage compared with the Current Source Inverter (CSI), which causes additional power loss and control complexity.
Fig. 1.2 shows the Conventional three-phase Current-Source Inverter (abbreviated as CSI) structure. A DC current source feeds the main converter circuit, a three-phase bridge. The DC current source can be a relatively large DC inductor fed by a voltage source such as a battery, fuel-cell stack, diode rectifier, or thyristor converter. Six switches are used in the main circuit each is traditionally composed of a semiconductor switching device with reverse block capability such as a gate-turn-off thyristor (GTO) and SCR or a power transistor with a series diode to provide unidirectional current flow and bi-directional voltage blocking.
However, the Current - Source converter (CSI) has the following conceptual and theoretical barriers and limitations.

- The AC output voltage has to be greater than the original DC voltage that feeds the DC inductor. The DC voltage produced is always smaller than the AC input voltage. Therefore, the I-source inverter is a boost inverter for DC-to-AC power conversion and the Current Source Inverter (CSI) is a buck rectifier (or buck converter) for AC to DC power conversion. For applications where a wide voltage range is desirable, an additional DC-DC buck (or boost) converter is needed. The additional power conversion stage increases system cost and lowers efficiency.

- The main switches of the Current Source Inverter (CSI) have to block reverse voltage that requires a series diode to be used in combination with high speed and high performance transistors such as insulated gate bipolar transistors (IGBTs). This prevents the direct use of low cost and high performance IGBT modules and intelligent power modules (IPMs).

In addition, both the Voltage Source Inverter (VSI) and the Current Source Inverter (CSI) have the following common problems.

- They are either a boost or a buck converter and cannot be a buck-boost converter. That is, their obtainable output voltage range is limited to either greater or smaller than the input voltage.
• Their main circuits cannot be interchangeable. In other words, neither the Voltage Source Inverter (VSI) main circuit can be used for the Current Source Inverter (CSI), nor vice versa. The objective is to develop an inverter system which can work at low voltage.

1.6. **Organization of the Report**

This thesis has been organized into six chapters. The details of the chapters are as follows

Chapter - 1: Describes the brief idea about EZ - Source and Z - Source inverters, Literature review that contains the different authors, the objective of this work and methodology.

Chapter - 2: Deals with Control and Estimation of 3 - phase Induction Motor Drive. Both Scalar and Vector control methods are discussed.

Chapter - 3: Illustrates the theory about the conventional Source Inverters (VSI & CSI). Modes of operation and comparison between these inverters are presented.

Chapter - 4: Explains the Impedance Source Inverter (Z - Source) with block diagram, equivalent circuit diagram, theoretical and mathematical analysis, Simulink details & results, Hardware fabrication details & results.

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Chapter - 5: Presents the simulation results of EZ - Source Inverter, its output voltages and current waveforms with Induction Motor, Simulink model & results, Hardware fabrication details & results, comparison with existed inverter fed system results.

Chapter - 6: Gives Conclusions and Scope for Further work.