# V/I CON [illegible] ND ITS ANN IMPLEMENTATION FOR MAXIMIZING ATTAINABLE EFFICIENCY OF INDUCTION MOTOR

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## ABSTRACT

Induction Motor (IM) drives are widely used in industrial, commercial, domestic, and other applications due to their simple robust construction, safe-long trouble free operation with minimum maintenance and wear and tear etc. Maximum efficiency of an IM usually occurs at near full load operation at rated voltage. But in many applications these motors are required to operate at other than rated load, where, the efficiency is much less than the maximum attainable efficiency. To achieve the maximum attainable efficiency at loads other than rated values, it is necessary to regulate the flux level by changing the voltage/frequency suitably at any given motor load. Large IMs usually are fairly highly efficient, compared to small IM. Low efficiency leads to uneconomic use of power in industrial installations. Maximum attainable efficiency operation of an IM at partial loads may be obtained by using a controller which can search for the maximum attainable efficiency condition at the given partial load and then operate the IM at that condition. The controllers reported in literature arrive at maximum efficiency point by minimizing the power or minimizing the current or maximizing power factor or optimizing the slip.

In this thesis, a technique based on V/I maximum attainable efficiency method is proposed for operating an IM with V/f controller at maximum attainable efficiency at partial loads. The technique requires estimation of V/I reference value $(V/I)_{ref}$, corresponding to maximum attainable efficiency at a given load using IM equivalent circuit parameters. Analysis and theoretical validation of the technique has been carried out using IM equivalent circuit. Experiments were carried out in the laboratory using a PWM inverter fed fractional horsepower SCIM with a V/f controller (specially developed and fabricated) at a few selected loads at rated frequency. The supply voltage to the SCIM was varied for the selected loads and the corresponding V/I values were calculated by measuring V and I at stator terminals. The efficiency for various values of V/I were plotted for the selected loads. It has been found from the graphs that for a given load, the maximum attainable efficiency

occurs at a value of V/I closer to the calculated $(V/I)_{ref}$. The results thus validate the concept proposed.

To validate the feasibility of online application the technique to VVVF drives, a online V/I maximum attainable efficiency control software using Visual Basic 6.0, V/I_GUI has been developed and incorporated in the motor V/f controller. The V/f controller was designed developed and fabricated using MC3PHAC AC motor controller module. The experiments were repeated at the selected loads for selected frequencies below the rated frequency. The efficiency versus V/I plots for different loads at each selected frequency have confirmed that maximum attainable efficiency can be achieved at V/I values ( $(V/I)_{online}$ ) closer to $(V/I)_{ref}$ value in the frequency range of 0.7 p.u to 1.0 p.u. of rated frequency. This confirms the applicability of the proposed V/I maximum attainable efficiency method for online IM control also.

The control software developed using Visual Basic 6.0 was found to result in some drawbacks with respect to flux regulation and response time due to searching for the optimum control variables corresponding to the maximum attainable efficiency, in multiple steps. To overcome the deficiency, the V/I_RBFNN, an improved control software using Radial Based Function Neural Network (RBFNN) was developed and incorporated in the V/f controller. The data obtained using the previous control software was used to train and test the proposed V/I_RBFNN. The functioning of the improved control software was verified by simulation using MATLAB 10. It was found that the improved control software using RBFNN predicts with considerable precision the optimum control variables corresponding to maximum attainable efficiency in one single step. Due to technical complexities involved and limitation in the required facilities, the implementation of V/I_RBFNN proposed in a online V/f drive could not be carried out experimentally. However, the proposed method is applicable to any variable frequency drive when the proposed and developed control software based on RBFNN is incorporated into its V/f controller. The theoretical analysis, experimental and simulation methodology and the results obtained are described and discussed in the thesis.

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| | |
|---|---|
| AC | Alternating Current |
| AI | Artificial Intelligent |
| ANN | Artificial Neural Network |
| ANSI | American National Standard Institute |
| ASD | Adjustable Speed Drive |
| BJT | Bipolar Junction transistors |
| BS | British Standard |
| CSA | Canadian Standards Association |
| CSI | Current Source Inverter |
| DAS | Data Acquisition Interface System |
| DAQ | Data Acquisition |
| *DAQv* | Voltage Signal at A/D Converter |
| DC | Direct Current |
| DOL | Direct Online |
| DSP | Digital Signal Processing |
| DTC | Direct Torque Control |
| EMI | Electromagnetic Interference |
| EPAct | The Energy Policy and Conversation Act |
| EPRI | Electric Power Research Institute |
| $f$ | Supply Frequency |
| FL | Fuzzy Logic |
| GA | Genetic Algorithm |
| $G_{amp,v}$ | Voltage Gain from amplifier |
| $G_{f,I}$ | Current Gain from Low-pass Filter |
| $G_{f,v}$ | Voltage Gain from Low-pass filter |
| GTO | Gate Turn-off (GTΘ) Thyristor, |
| HTML | Hypertext Mark-up Language |
| $I_1$ | Stator Current |
| $I_2$ | Rotor Current Referred to Stator, |
| $I_l$ | RMS Phase Current |

| | |
|---|---|
| $I_{1,max}$ | Maximum Fundamental Phase Current |
| $I_{phase}$ | Phase Current Signal |
| $I_{sense}$ | Sensed Current Signal |
| IC | Integrated Circuit |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electric and Electronic Engineering |
| IGBT | Insulated Gate Bipolar Transistor |
| IM | Induction Motor |
| JEC | Japanese Electrotechnical Committee |
| LED | Light Emitting Diode |
| LPF | Low-pass Filter |
| $m$ | Modulation Index |
| MOSFET | Metal Oxide Silicon Field Effect Transistor |
| MSQ | Mean Squared Error |
| NEMA | National Electrical Manufacturer Association |
| $N_r$ | Rotor Speed |
| $N_{r,\eta\_max}$ | Rotor Speed at Maximum Attainable Efficiency |
| PC | Personal Computer |
| *Pcl* | Primary copper losses |
| Pin | Power in |
| PWM | Pulse Width Modulation |
| RBFNN | Radial Based Function Neural Network |
| RPM | Revolution per minute |
| s | slip |
| SCADA | Supervisory Control and Data Acquisition |
| SCIM | Squirrel Cage Induction Motor |
| SLL | Stray Load Losses/Stray Losses |
| $R_1$ | Stator Winding Resistance |
| $R_2$ | Rotor Resistance |
| $T_1$ | Time at First Zero Crossing |
| $T_2$ | Time at Second Zero Crossing |
| $T_3$ | Time at Third Zero Crossing |

| | |
|---|---|
| $V_1$ | Stator Voltage |
| VB | Visual Basic |
| V/f | Voltage/frequency |
| $(V_1/I_1)$ | Measured Value of V/I |
| V/I | Voltage over Current |
| V/I_GUI | V/I Graphic User Interface |
| $(V/I)_{online}$ | Online Value of V/I |
| $(V/I)_{ref}$ | Reference Value of V/I |
| $V_1$ | RMS Phase Voltage |
| $V_{1,max}$ | Maximum Fundamental Phase Voltage |
| $V_{boost}$ | Voltage Boost |
| V/I_RBFNN | V/I Radial Basis Function Neural Network |
| $V_m$ | Maximum Voltage |
| $V_{phase}$ | Phase Voltage Signal |
| $V_{sense}$ | Sensed Voltage Signal |
| VSI | Voltage Source Inverter |
| VVVF | Variable Voltage Variable Frequency |
| WRIM | Wire Wound Induction Motor |
| $X_1$ | Stator Winding Leakage Reactance |
| $X_2$ | Rotor Leakage Reactance |
| $X_m$ | Magnetizing Reactance |

# CHAPTER 1

# INTRODUCTION

## 1.1. General

Induction motors (IMs), especially squirrel cage induction motors (SCIMs), are widely used in almost all industrial applications. According to a recent survey, more than half of the electricity generated is consumed by the electric motors of SCIM type (Boglietti et al, 2008; Bonnett, 1993). Traditionally, AC machines with constant frequency sinusoidal power supply have been used in applications requiring nearly constant speed operation, whereas, DC machines have been preferred for variable-speed drives. DC machines have the disadvantages of higher cost, higher rotor inertia and maintenance problems with their commutation system. Commutation in conventional DC machines limits the machine speed and peak current, causes electromagnetic interference (EMI) problems and does not permit machine operation in hazardous and explosive environments. IMs on the other hand, do not have the disadvantages mentioned above. With the advances made in semiconductor technology, the development of variable speed IM drives using static inverters, particularly the voltage source inverter (VSI) is found feasible. As a result, inverters fed IMs are now replacing conventional DC machines in many industrial applications.

## 1.2. Developments in IM Drives

Issues of controlling the speed and the torque of IM have drawn attention of the researchers for many decades. As a result, from the simple scalar control of IM to complex vector control incorporating intelligent control, have been attempted. Many types of AC motor drives have been developed in the past for the control of speed, torque, and position of mechanized systems (Abe et al., 1993; Cardoso; 1998; Danial et al, 2005; Ebrahim, 2006; Ferreira, 2005; Bensalem, Y. and Abdelkrim, 2009). The principle of direct torque control (DTC) was proposed in 1995 (Holtz, 2002). Though, IM drives, in general, are simple in construction and operation, they are more complex to control than their DC counterparts. The complexity in control increases substantially, if high performances are demanded. In spite of being singly excited, the reasons for the increased complexity are the need for variable-frequency harmonically optimum converter power supplies, complex dynamics, variation in machine parameters and difficulties in processing feedback signals in the presence of harmonics (Bose, 1996; Boglietti, 2007). Though the control of IM sometimes may become costly, industries still favour IMs over DC motors due to simple construction of the motor, easy maintenance, longevity and due to their capability to operate in harsh and hazardous environments. Continuous and high market demands make it desirable that IMs replace high performance motors like separately excited DC motor drives. This calls for controllers to be employed in an energy efficient way.

Integrating energy efficiency schemes in IM drives is very important and is a continuous process. They get attention from various communities starting from engineers, researchers, utilities and governments (Gray, 1996). One major problem associated with IMs is that the efficiency of IM drops when it operates with load lower than rated values (Kim et al, 1984; Kirschen, 1985) as more losses occur during such operation. Studies conducted by the Electric Power Research Institute (EPRI) revealed that over 60% of industrial motors operate at less than 60 percent of their rated load. Idling, cyclic/lightly loaded or oversized motors consume more power than required even when they aren't working (Fernando, 2008). These motors waste energy, generate excessive utility costs and unnecessary motor wear and tear (Bose, 2004).

From mid 1980 to 2000 many control schemes for energy management in scalar or vector or direct torque controlled IMs have been reported. Due to the advances in the application of artificial intelligence (AI) in power electronics and drive systems, to face the continuous crisis of increased fuel price and to conserve fossil fuel reserve, energy optimization management of IM remains a subject of further improvement (De Almeida et al, 1997; De-Keulenaer et al, 2004; Ferreira et al, 2005; Boglietti et al, 2008; Wang, 2010). Production of efficient and premium efficient motors (Peter et al, 2007; Kwang, 2009) which comply with the National Electrical Manufacturer Association (NEMA) and European CEMEP protocols are being undertaken. These motors themselves are now very efficient and are able to work at variable voltage variable frequency (VVVF). As the VVVF motors have become available, the researchers have also been concentrating on inventing and producing new VVVF controllers which are better in energy efficiency aspect than the direct online (DOL) controllers (Feldman, 2009). For example, volt/hertz (V/f) is the most simplest and widely use VVVF controller in industries. The combination of premium efficient VVVF motors and VVVF controllers will not only save energy but also prolong the life of the motors. These inventions have not closed the door for more improvement of the VVVF motors and drive controllers (Bose, 2002). At the beginning, the researches to improve the strategies to control and to increase efficiency were done separately. However, due to advances in power electronics technology, sensing technology, data acquisition and interfacing technology, and computer software and hardware, it has been realized that integrating the control and efficiency increasing strategies of the IM drive is possible. Researches done to improve the efficiency of IM drives (Bonnett, 1993; Brethauer, 1994) include: 1) the use of high-efficiency (premium efficiency) motors instead of standard motors, 2) replacement of constant speed mechanically controlled processes with variable or adjustable speed control, and 3) replacement of DC motor drives with IM adjustable speed drives (ASD) in industrials processes where necessary (as in conveyors, textile and paper industries, and machine tools). As the AI, power electronics and drive systems technology progressed, the focus is given on optimizing the efficiency, along with improving the torque and control characteristics of drives.

The VVVF SCIM drives incorporating AI are preferable to replace the old drive systems. Especially, the premium or high efficiency VVVF motor drives with intelligent maximum attainable efficiency schemes are more desirable (Bose, 2000; Jianye et al, 2010) for both low performance and high performance drives. The reason is that, a significant amount of energy is saved (up to 60%) by such incorporation (Jingli et al, 2008). These replacement strategies not only save energy, but they also improve the reliability of the system having less failure, repair and maintenance time, thus reducing maintenance cost and increasing productivity. It also improves work environment and safety in the area where these drives exist.

Many motors can be controlled by a single supervisory control system. Achieving maximum attainable efficiency in IM is directly related to the choice of the flux level. The higher the flux level, the larger the iron losses are. However, extreme minimization causes greater copper losses. Thus, there is an optimal flux level that guarantees loss minimization. Choosing the optimum flux level in the IM remains an open problem from the perspective of motor efficiency. Many researchers continue to work on this problem. In general, most of the researchers have attempted IM control for maximum efficiency through optimum current control, optimum power factor control, optimum slip control, minimum power control etc. (Abrahamsen, 1997; 2000; Benbouzid, 1997; Bose, 1999; 2002; Feng, 2003; Cacciato , 2006; Chakraborty, 2002; Gamboa, 2007; Ahmed, Ebrahim ; 2009) . These methods have one or more of the following disadvantages: need for large computational effort, sensitivity to machine parameter variations (especially due to high temperature), need for extra sensors on the rotor side, working in parallel with speed control loop resulting in complex controller configuration.

## 1.3. Thesis Objectives

The objectives of the thesis are:

1. To study and develop a new method which overcomes the deficiencies of the existing methods for maximizing the attainable efficiency of IM drives at a given load. The method is based on the use of V/I reference value (specific for each motor) calculated using motor constants.

2. To validate the method experimentally in the laboratory using a three-phase PWM inverter fed low power induction motor and develop the required hardware and software effective for online implementation of the method in variable voltage variable frequency IM drives with V/f controller.

## 1.4. Main Contributions of the Thesis

The main contributions of the thesis are:

1. The continuous crisis of increased fuel price and the need to conserve fossil fuel reserve, energy optimization management of induction motors remains a subject of great concern and further research. This thesis proposes a new method for achieving maximum attainable efficiency of IM drives even at partial loads (lower than full load) and thus contributing to energy saving. The method called "V/I Maximum attainable efficiency method" shall provide a new approach in the control of modern induction motors. The method can be implemented on three-phase induction motors (squirrel cage or wound rotor) with VVVF drive system.

2. The conventional V/f IM drives are provided with open-loop control. A new online closed-loop control method and related software for incorporating V/I maximum attainable efficiency method have been proposed and developed for V/f IM drives for applications where the speed control requirement is not very stringent.

3. A new effective intelligent method called "V/I_RBFNN maximum attainable efficiency method" for online implementation of "V/I maximum attainable efficiency method" in VVVF IM drives is proposed and the relevant control software has been developed. The method has been validated by MATLAB simulation.

The research publications based on the thesis are listed at the end of thesis.

## 1.5. Thesis Organization

This thesis consists of seven chapters. The content of each chapter is outlined as below:

**Chapter 1** of the thesis introduces the subject matter with a brief review of IM control methods, modern control and efficiency improvement techniques for IMs. Then the objectives and contributions of the thesis are presented.

**Chapter 2** deals with literature review, where, the previous works related to the subject are briefly discussed. This includes the conventional and intelligent IM drives and controllers and various types of losses and techniques of evaluating efficiency of IM. The motivation for the research work carried out in this thesis has been outlined.

**Chapter 3** describes basic principle of the proposed method of maximizing attainable efficiency of IM drives using V/I control method. The derivation of $(V/I)_{ref}$ corresponding to maximum attainable efficiency using IM equivalent circuit parameters is discussed. The related mathematical analysis is presented.

**Chapter 4** describes the development of experimental setup for V/f SCIM drive using SCIM system in the laboratory and latest AC motor controller module available in the market for the implementation and verification of the proposed method. The experimental validation and results are presented and discussed.

**Chapter 5** describes the design, development and integration of software and hardware in the online implementation of the proposed method, and study of the performance for a given operating condition (voltage, load, speed, and temperature). The development of a closed-loop V/f controller and development of the required GUI software for incorporating the proposed method using Visual Basic 6.0, are discussed. The results obtained from the laboratory implementation are presented and discussed.

**Chapter 6** presents a method of using RBFNN for online implementation of V/I control method in industrial environment. The development of two RBFNN based intelligent control variable estimator with relevant software has been discussed. The verification of the method by MATLAB simulation and simulation results are presented.

**Chapter 7** summarizes the achievements of this research and the recommendations for future work.