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FEM Analysis of Squirrel Cage Induction Motor Fed with Raised Sine Wave Supply

Balakrishnan MS[1], Theagarajan R[2]
[1]Sathyabama University, Chennai, India
Department of Electrical and Computer Engineering, Arba Minch Institute of Technology, AMU, Ethiopia
[2]Department of Electronics, National Institute of Technical Teachers Training and Research, Chennai, India

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ABSTRACT

AC motors are used frequently for many industrial applications such as material handling, traction, electric vehicles etc. A novel non-sinusoidal modulation technique employing Raised Sine Wave (RSW) for the PWM inverter is proposed in this paper. Squared Sine Wave has a distinct advantage of reduced rate of change at zero crossing of each half cycle, and eliminates the need for dead band. An Finite Element Analysis (FEM) is carried out to study its suitability for AC Induction Motor. The results show that the operation has a constant startup torque for all load conditions, thus providing a smooth start from zero speed to full rated speed. This feature makes it most suitable for applications requiring frequent startup such as traction. The operation of the conventional Variable Frequency Drives using Conventional Sine Wave (CSW) is compared with the results obtained with RSW supply.

Corresponding Author:

Balakrishnan. M.S.,
Research Scholar, Sathyabama University, Chennai, India.
Department of Electrical and Computer Engineering,
Arba Minch Institute of Technology, Arba Minch University,
Post Box No 21, Arba Minch, Ethiopia.
Email: b.9841110567@gmail.com

1. INTRODUCTION

AC Motor drives are frequently employed in industries for a wide applications such as material handling systems, traction and transportation, electric vehicles etc. These systems require a speed control and torque control which is currently available for the different PWM techniques [1]-[2]. High Frequency carrier based Pulse Width Modulation (PWM) schemes have become very common in many methods of control such as Sine PWM, Space Vector Modulation. These recent technological development in the field of power electronics and digital signal processors and micro controllers has made it possible to design power converters that can generate any form of power output. The high frequency carrier based Pulse Width Modulation (PWM) techniques have led to implementation of various modulation schemes. High processing speed of digital systems and high resolution timer blocks, have resulted in better accuracy in controlling the pulse width of ON and OFF intervals of inverter switches. Software based design of digital implementation of PWM schemes is possible for any technique of implementing these PWM schemes. In the classical analog system of sine-triangle modulation (SPWM), also known as natural sampling modulation (NSPWM), high frequency triangular carrier is compared with the sine wave modulating signal for each phase of the inverter to generate the gate pulses for the power switches in the inverter.

In its equivalent scheme with microprocessor based digital technique, the modulating signal is periodically sampled at predetermined intervals using the high frequency triangular signal, at each period (symmetric regular sampling) or at every peak (asymmetric regular sampling). This scheme is popularly referred to as the Regular Sampled PWM (RSPWM) [3]. Each crossing of the triangular carrier signal with the modulating sine wave determines the on-time and off-time of the pulses used for controlling the power switches of the inverter. The digital implementation of the same using synthesised signals and digital timers/counters is similar to the NSPWM [4].

In contrast to the above mentioned synthesis methods, the Space Vector PWM (SVPWM) method considers all three phases as single entity and are simultaneously generated within the two dimensional reference plane (dq plane) [5]. The performance of a three phase voltage source inverter (VSI) feeding three phase star connected loads can be improved by using appropriate zero-sequence or non-sinusoidal waveforms along with the modulating signals. A comparison between continuous PWM (CPWM) and discontinuous PWM (DPWM) is made in [6]. In what is known as discontinuous PWM, or bus-clamping modulation, zero sequence signals are added to the modulating signals. The turn-on and turn-off sequence of a generalized discontinuous modulation scheme for three phase VSI is presented in [7]. Further modification to these were carried out to improve the quality of power converters such as reduction of voltage harmonics in [8].

All these and many more other schemes of PWM modulation, generates a Conventional Sine Wave (CSW) power output that is very much similar to the utility supply sine wave or a discontinuous sine wave which is also very much similar to the CSW. In this paper we propose the generation of Raised Sine Wave (RSW) power supply for operation of an induction motor. The in-depth analysis of its application for driving a squirrel cage induction motor is done with the help of Finite Element Method (FEM). The recent developments in the possibility to use high frequency carrier pulses for generation of gating pulses forms the basis of this proposed Raised Sine Wave (RSW) power output using the standard full bridge PWM inverters. The generation principle of using high frequency carrier modulation for power output using VSI inverter is presented by the authors in [9].

Further to the generating principles, the analysis of the operation of inductive loads such as induction motors, is analysed using many practical and simulation methods. The designing of electrical motors frequently use analytical and numerical methods e.g. Finite Element Methods (FEM). This FEM analysis were widely used for failure analysis e.g. broken rotor bars [10], stator winding turn fault [11], analysis of IM under voltage harmonics [12], etc. Performance analysis and modeling of existing and new designs are also effectively performed using FEM [13]-[15]. An analytical method was used with MatLAB simulation for analysis of Induction Motor supplied with RSW power in [16].

2. RSW POWER SUPPLY

Operation and control for induction motor loads, employing various schemes exist in both analogue and digital methodology. Good amount of research and development has been achieved in both voltage & current control and in control of motors. Also a wide range of developments in control are reported in the applications of motors to improve performance and efficiency.

The operation of an induction motor with RSW power supply is presented here with reference to the well known AC fundamentals with sine wave operation of inductive loads. The RSW voltage of one (reference) phase for ac load applications is defined as.

$$\begin{aligned} V_{Positive-Half-Cycle} &= V_{max} sin^2(\omega t) \\ V_{Negative-Half-Cycle} &= (-1) * V_{max} sin^2(\omega t) \end{aligned} \quad (1)$$

Mathematically the 3 phase voltage vector can be represented as in Equation (2) and Equation (3)

$$\begin{aligned} v_{1+} &= V_{max} sin^2(\omega t) \\ v_{2+} &= V_{max} sin^2(\omega t + 2\pi/3) \quad for \quad 0 < \omega t < \pi \\ v_{3+} &= V_{max} sin^2(\omega t - 2\pi/3) \end{aligned} \quad (2)$$

$$\begin{aligned} v_{1-} &= -V_{max} sin^2(\omega t) \\ v_{2-} &= -V_{max} sin^2(\omega t + 2\pi/3) \quad for \quad \pi < \omega t < 2pi \\ v_{3-} &= -V_{max} sin^2(\omega t - 2\pi/3) \end{aligned} \quad (3)$$

The basic waveform of the RSW supply is shown in Figure 1, to enable the reader to visualize the waveform of the proposed systems in comparison to the conventional sine wave.

Current flow through inductors are obtained by differentiating the voltage waveform. Normalizing the magnitude to unity and analising further we get the differential of the RSW as shown in Fig 2 for one (reference) phase, as an analytical result of the current flow in the inductive load due to RSW voltages. Applying the fundamental equations of operation of inductive loads with AC supply to RSW power supply, the current flow through the motor is therefore:

$$i_L = \frac{V_m}{2L}\left(\omega t - \frac{\sin(2\omega t)}{2}\right) \quad (4)$$

The RSW cannot be defined mathematically with a single equation; rather each half cycle has to be defined separately to clearly show the polarity change as in Equation (2) and Equation (3). Hence the transient analysis for each half cycle is better suited instead of the steady state analysis.

Applying Equation (4) for each half cycle, we can see that the current flow is governed by the factor $2\omega t$ and the phase reverses by 180 deg for every alternate half cycle. The phase reversal is controlled by changeover in the arms of the inverter bridge.

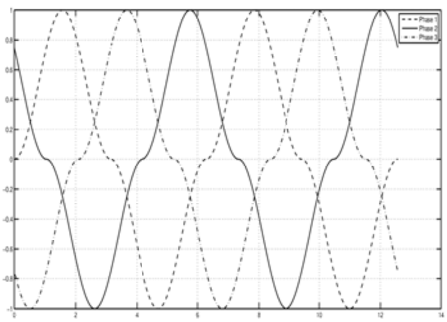

Figure 1. Waveform of proposed 3 phase RSW supply

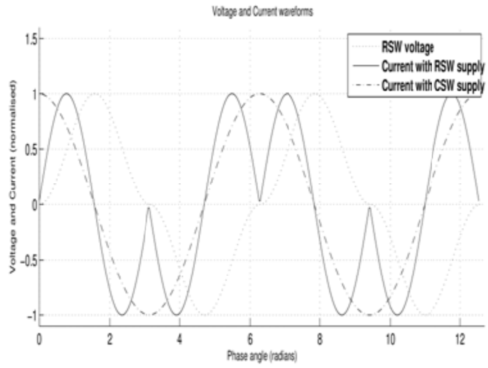

Figure 2. Voltage and Current waveforms for one phase

3. FINITE ELEMENT METHODS MODELLING

FEM analysis has been established as an efficient method for analysis of performance of induction motors under various conditions. A comparison between the classical circuit method and FEM is made in [17] wherein the procedure for FEM analysis is also presented in detail.

The model of a 2 HP 3 phase AC motor, used for the Finite Element Magnetics analysis, is shown in Figure 3. The technical specification of the motor model used in this analysis is given in Table 1. The analysis is done using time stepping transient analysis using an soft Maxwell software for both Conventional Sine Wave supply and the proposed Raised Sine Wave supply. The sources in the stator coils are defined using functions based on the CSW supply and the proposed RSW supply (Equation 2 and 3).

The solver is run with various load torque settings in the mechanical setup of the preprocessor. the stationary and rotating parts of the motor is defined with a 'band' in the air gap. The time stepping analysis involves many iterations allowing the rotor to dynamically change its position with respect to the shaft axis. A visual marker is inserted (with same material description as the rotor core) in the rotor core to visually interpret the rotor rotation and its position during each time step. The solver is run from 0 to 5 sec of the motor operation from startup with initial speed of zero rpm.

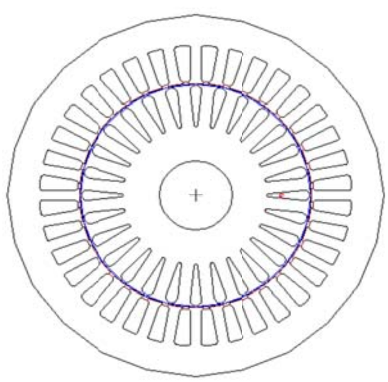

Figure 3. Model of IM used for FEM analysis

Table 1. Specification of Motor Model

Parameter	Value
Motor type	3 phase induction motor
Supply Voltage	440v Ph-Ph
Motor Current	2.2 amps - full load
Stator Slots	36
Rotor Bars	24
Winding	4 pole 44 turns each coil

4. POST PROCESSOR RESULTS

The post processing of the FEM analysis gives the results for transient analysis and the static field analysis. During the solution setup, the software is set to save static results for every 0.1 sec step of the motor running. The field map of the motor for two different time step (a) 1 sec after start-up and (b) 5 sec after start-up (full speed) is shown for operation with CSW supply in Figure 4 and for operation with RSW supply in Figure 5.

The drag in the magnetic field i.e., the radial angle difference between the points of peak magnetization in the stator core and the rotor core, indicating high slip, is clearly visible in Figure 4(a) and Figure 5(a), when the motor has not reached full speed. When the motor has reached full rated speed, the radial angle is very small, showing that there is almost no slip in Figure 4(b) and Figure 5(b). The effect of this field is conceivable in the acceleration of the motor from zero speed to full speed.

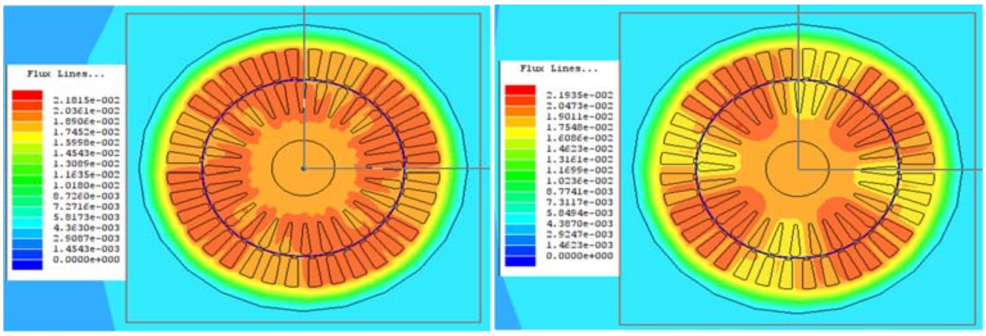

Figure 4. Field with CSW Supply (a) after 1 sec (b) after 5 sec

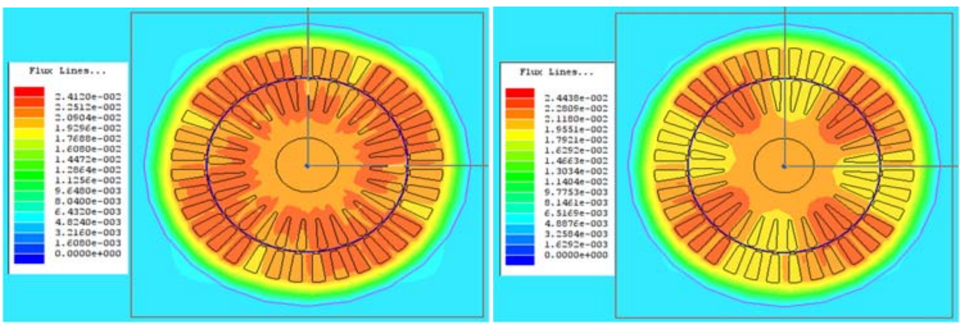

Figure 5. Field with RSW Supply (a) after 1 sec (b) after 5 sec

4.1. Acceleration at start up

The interesting conceivable factor in the comparison of variation in speed during start-up. Emphasis is made in this paper to this factor to highlight the advantages of RSW power supply over CSW supply. The acceleration at various loads is compared in the Table 2, in terms of time taken to reach full speed at startup. The acceleration graph, as obtained from the post processor transient analysis, is shown in Figure 6 for a load of 0.2 N-m and in Figure 7 for a load of 0.5 N-m.

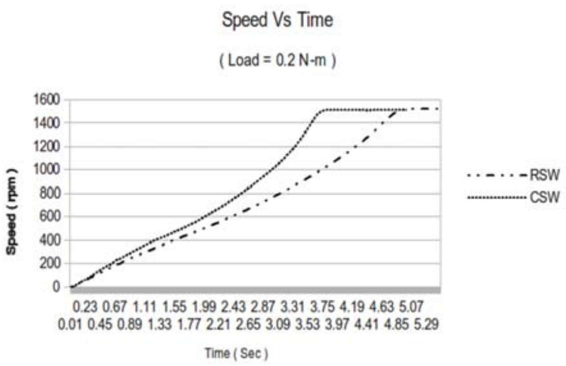

Figure 6. Acceleration at Startup for load of 0.2N-m

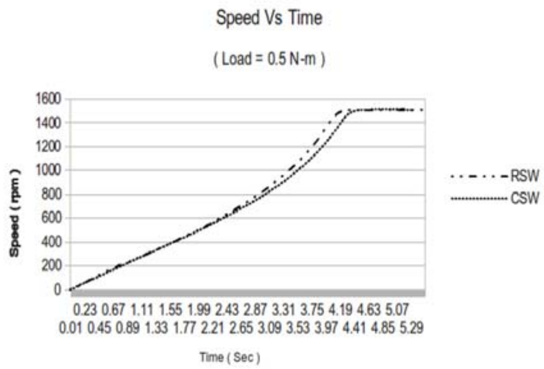

Figure 7. Acceleration at Startup for load of 0.5N-m

Table 2. Comparison of startup time between CSW and RSW supply

Load	CSW Supply	RSW Supply
No-load	1.25 sec	1.25 sec
0.1 N-m	2.25 sec	4.0 sec
0.2 N-m	3.6 sec	4.6 sec
0.5 N-m	4.5 sec	4.2 sec

5. DISCUSSION

The acceleration at all loads is almost constant and start-up time is also constant when operated with RSW power supply except at no-load. This constant acceleration is useful in applications such as elevators and traction giving a smooth operation under all load conditions. Also the peak starting current with RSW supply is found to be less than that with CSW supply. Thus the ratio of peak current to load current is less, placing a less demand on the utility supply bus. Most important is the very low current during the instants of zero crossing of the voltage in the load. This low transient currents reduces the stress on the power switches in the inverter and improves the reliability of the inverter.

6. CONCLUSION

The RSW power supply for Motor Drive application is suitable in terms of reduced starting currents and constant acceleration. From the current wave form in Figure 2, the peak currents of each cycle is at $\pi/4$ radians before and after the peak voltage (at $\pi/2$). Also the current cycle is in phase with the current cycle of the CSW supply. So the fundamentals of AC operation is not violated and is in concurrence with the basics of CSW operation with reactive loads.

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BIOGRAPHIES OF AUTHORS

Balakrishnan M.S., is a research Scholar at Sathyabama University, Chennai, India. He got his Bachelor Degree from Institution of Engineers (India) in 1986, and Masters Degree from Osmania University, Hyderabad, India in 2003. He is currently pursuing his PhD in the field of Power Electronics. His major interested areas are motor drives and industrial automation. He is currently employed as Sr Lecturer at Arba Minch Institute of Technology, Arba Minch University, Arba Minch, Ethiopia.

Dr.Theagarajan R. is HOD, Department of Electronics, at National Institute of Technical Teachers Training and Research, Chennai, India. The institute is functioning under the Ministry of Human Resources, Government of India. He is actively involved in training of technical teachers in pedagogical aspects of technical teaching. He has specialized in development and use of Media Resources and has developed many technical films and teaching materials.