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Investigation of Effect Of Harmonicson Air Gap Flux Density And Torque Performance Of Asynchronous Machine Invariable Speed Drive Systems

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Abstract–Application of Variable speed drives in industrial applications has reached to highest percentage in the global industry sector. Even though many analytical and digital techniques available till today, still there is need for improvement of VSD system performance along with protection of supply voltage and current profiles. Theeffect of harmonics on air gap flux density of rotating machine and itsfurther effect on torque performance, harmonics injected by power electronic switching converters intothe rotating magnetic devices are investigated in this paperby considering generalized model of electrical machine [1] as a prerequisite for later work on optimization of Variable Speed Drive (VSD) system. Investigation of harmonics carried out on Induction Motor fed by ac-dc-ac converter system and fed by pure sinusoidal ac supply system. The special harmonic analyzer [5, 6] proposed by the authors comprises of investigation of harmonics using FFT analysis used for harmonic analysis of both converter and induction motor. The aim of proposed work is to investigate converter level harmonics and its effects on air gap flux density and further torque performance issues. The MATLAB Simulink models of Induction Motor is used for analysis and machine with typical parameters used for the purpose of practical measurements. A general switching converter circuit along with PWM inverter is in the induction motor drive. The results obtained from these methods show good agreement with the practical methods.

Index Terms - *Circuits, Harmonics, Variable Speed Drives (VSD), Finite-element analysis, Magnetic devices.*

I. INTRODUCTION

The increased use of Variable Speed Drives (VSDs) in industry coupled with complaints about VSD shutdowns, together with the various problems like overloaded neutral conductors, overheating and failure of motors and transformers, frequent tripping of circuit breakers and capacitor failures, were often met with unacceptable answers and limited solutions. Above stated problems resulted in VSDs becoming one of the first targets as a cause of supply harmonic problems. It is easy to see why VSDs were blamed for harmonic problems, as they are normally high power devices, which inject high magnitudes of harmonic currents into the connected rotating machines.

To investigate further effects of these harmonics entering in to rotating machinery connected in the drive system. There are various methods presented previously, among them numerical modeling of magnetic devices, it often requires that the effect of power electronic circuits be considered. This is not just because of the fact that magnetic devices are combinations of magnetic components and circuitry, but also because of the need for designers to perform system level simulation. If we take geometric complexity, nonlinearity, induced eddy currents, mechanical movement, and electric circuits with general topologies into account, it is necessary to couple and study the magnetic device along with power converter circuit analysis. For accuracy and details, it is essential to use FEM [4] modeling of magnetic device and coupling it with power converter to be used in the VSD. Since FEM modeling involves long simulation time depending on the size of the VSD. This paper is proposed to investigate various harmonics entering in to magnetic devices and further distortions in air gap flux density and torque performance of the machine using conventional d-q transformation technique. This primary work will depict need for the coupled simulations and range of the VSD for which conventional flux calculation methods are suitable.

In this proposed work AC drive systems selected to analyze and investigate harmonics as they have been widely accepted for industrial applications. In general, they take the advantages of a higher power density and a higher efficiency than DC drive systems. AC drive systems [10] are composed of two major groups, namely the induction drive systems and synchronous drive systems.Among the induction drive systems, the cage-rotor is almost exclusively used for industrial applications.Among the synchronous drive systems, the permanent magnet (PM) brushless AC drive system (usually termed PM synchronous drive system) is becoming popular, whereas the synchronousreluctance drive system is receiving attention. In this paper, chaos is investigated in the asynchronous drive system, namely a cage-rotorinduction drive system.

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In this work the drive system is practically tested and recorded various parameters to come to the conclusion on total air-gap flux density in the rotating machines. Simulations of all this modelis carried out in the MATLAB Simulink environment and observations on injection of harmonics into magnetic devices due to switching converters are observed using harmonic analyzer [5].

The block diagram of Simulink model of harmonic calculator [5] is as in figure.1 & 2. The Fourier calculator was designed based on extraction of non-stationery sinusoid tracking algorithm and phase-dictated sinusoid tracking algorithm. A simple GUI based MATLAB program also can be run in order to plot frequency spectrum and total harmonic distortion wave.

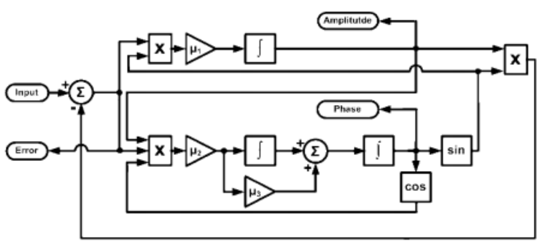

Figure.1 Block diagram of the sinusoid tracking algorithm

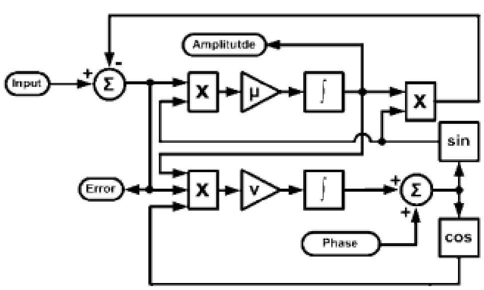

Figure.2 Block diagram of the phase dictated sinusoid tracking algorithm

II. EQUATIONS OF INDUCTION MOTOR

Driving the model equations can be generated from the dq0 equivalent circuit of the induction machine shown in figure 1. The flux linkages equations [1,2] associated with this circuit can be found as follows:

$$\frac{dqs}{dt} = \omega_b[Vqs - \frac{\omega e}{\omega b}\psi_{ds} + \frac{Rs}{Xls}(\psi_{mq} - \psi_{qs})] \ldots\ldots\ldots \quad (1)$$

$$\frac{dds}{dt} = \omega_b[Vds + \frac{\omega e}{\omega b}\psi_{qs} + \frac{Rs}{Xls}(\psi_{md} - \psi_{ds})] \ldots\ldots\ldots \quad (2)$$

$$\frac{dqr}{dt} = \omega_b[Vqr - \frac{(\omega e - \omega r)}{\omega b}\psi_{dr} + \frac{Rr}{Xlr}(\psi_{mq} - \psi_{qr})] \ldots\ldots \quad (3)$$

$$\frac{ddr}{dt} = \omega_b[Vdr + \frac{(\omega e - \omega r)}{\omega b}\psi_{ds} + \frac{Rr}{Xlr}(\psi_{md} - \psi_{dr})] \ldots\ldots \quad (4)$$

Where

$$\Psi_{mq} = X_{ml}[\frac{qs}{Xls} + \frac{qr}{Xlr}] \ldots\ldots\ldots\ldots \quad (5)$$

$$\Psi_{md} = X_{ml}[\frac{ds}{Xls} + \frac{dr}{Xlr}] \ldots\ldots\ldots\ldots \quad (6)$$

$$X_{ml} = 1/(\frac{1}{Xm} + \frac{1}{Xls} + \frac{1}{Xlr}] \ldots\ldots\ldots \quad (7)$$

Then substituting the values of the flux linkages to find the currents;

$$i_{qs} = \frac{1}{Xls}(\psi_{qs} - \psi_{mq}) \ldots\ldots\ldots\ldots \quad (8)$$

$$i_{ds} = \frac{1}{Xls}(\psi_{ds} - \Psi_{md}) \ldots\ldots\ldots\ldots \quad (9)$$

$$i_{qr} = \frac{1}{Xlr}(\psi_{qr} - \psi_{mq}) \ldots\ldots\ldots\ldots \quad (10)$$

$$i_{dr} = \frac{1}{Xlr}(\psi_{dr} - \Psi_{md}) \ldots\ldots\ldots\ldots \quad (11)$$

Based on the above equations, the torque and rotor speed can be determined as follows:

$$T_e = \frac{3}{2}(\frac{P}{2})\frac{1}{\omega b}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \ldots\ldots\ldots \quad (12)$$

$$\omega_r = \int \frac{p}{2J}(T_e - T_L) \ldots\ldots\ldots\ldots \quad (13)$$

Where P: number of poles; J: moment of inertia (Kg/m2). For squirrel cage induction motor, the rotor voltages Vqrand Vdrin the flux equations are set to zero since the rotor cagebars are shorted. After driving the torque and speed equations in term of d-q flux linkages and currents of the stator, the d-q axis transformation should now be applied to the machine input (stator) voltages.

The three-phase stator voltages of an induction machine under balanced conditions can be expressed as:

$$V_a = \sqrt{2}V_{rms}\,\text{Sin}\,(\omega t) \ldots\ldots\ldots\ldots \quad (14)$$

$$V_a = \sqrt{2}V_{rms}\,\text{Sin}\,(\omega t - \frac{2\pi}{3}) \ldots\ldots\ldots\ldots \quad (15)$$

$$V_a = \sqrt{2}V_{rms}\,\text{Sin}\,(\omega t + \frac{2\pi}{3}) \ldots\ldots\ldots\ldots \quad (16)$$

These three-phase voltages are transferred to a synchronously rotating reference frame in only two phases (d-q axis transformation). This can be done using the following two equations.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \ldots\ldots\ldots\ldots (17)$$

Then, the direct and quadrature axes voltages are

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (18)$$

The instantaneous values of the stator and rotor currents in three-phase system are ultimately calculated using the following transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (19)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (20)$$

III. ENERGY CONVERSION INVOLVING HARMONICS FROM AC-DC-AC SYSTEM

An asynchronous machine with a non-sinusoidal voltage at its terminals may serve as a classical example for the study of the proposed work. A general example of the non-sinusoidal voltage source for an induction motor is an ac-dc-ac high frequency converter with the PWM inverter. Assuming the induction machine to be ideal means no additional harmonics in the air gap. It is safe to view the picture as the one truly reproducing the harmonics spectrum of the applied voltage. An ideal machine does not generate noise, and so for the harmonic spectrum of magnetic field **B** to be defined, it is enough to expand the phase voltages in to a harmonic series. The directions of rotation and amplitude of time harmonics depend on the number of phases in the machine and the ordinal number of each harmonic, and is easy from the set of equations. It is assumed that each of the 'm' harmonics making up the field in the air-gap is set up by two pairs of windings on the stator or rotor along the d and q axes or $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ axes. The model of such a machine has two sets of m windings on the stator and rotoralong $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ axes rather than **n** and **m** windings on the stator and rotor respectively [1,2]. This model is analogous to the model of the generalized energy converter.

The developed circular field in the air gap can exist only in an idealized rotating machine. In real machines, the air gap exhibits an infinite spectrum of harmonics differing in amplitude and frequency along with the fundamental harmonic. These harmonics revolves in the directions of both forward and the backward with respect to the revolving fundamental harmonic. These harmonics attain the angular velocities of higher and lower than that of the fundamental component and amplitudes of them can vary in rotation. These harmonics exist in the air gap may be divided into two types; they are time and space harmonics.

Time harmonics enter in to the air gap of the machine from the outside. Space harmonics will be developed in the air gap on account of the design and internal structure of the machine. If we consider machine has two ports, it has two inputs one on the side of electrical terminals and the other on the side of mechanical terminals. Time harmonics usually arise from non-sinusoidal, asymmetric voltages and non-linear changes in the amplitude and frequency of voltages due to use of high frequency converters for the VSD system. Time harmonics also result from the non-linear changes in the torque and speed. Briefly time harmonics appear from the simultaneous action of non-linear factors at two input terminals. These harmonics may also get in to the air gap of an electrical machine further changing machine parameters deteriorating performance of the machine.

Non sinusoidal voltages which enhance rise of time harmonics may basically result from non-linear elements such as saturable reactors and power electronic converters as semiconductor elements exhibits nonlinearity ahead of the motor. If the supply voltage contains a constant component, a harmonic spectrum emerges, which includes an infinite range of even along odd harmonics. The proposed work will investigate for the observation of variation of time harmonics due to various switching states of VSD system based on real time application. In the absence of time harmonics in the air gap of a machine, space harmonics will originate from the non-sinusoidal distribution of turns and other internal design structures.

IV. SIMULATION OF VSD USING MATLAB/SIMULINK

In the proposed work Induction motor drive is simulated using Simulink model of ac-dc-ac converter system and generalized model of induction motor is coupled to this high frequency converter as the input voltage source.This drive is meticulously observed for various steps of dc link voltage and input supply voltage. The generalized induction motor model implemented using Simulink with a m-file parameter initialization prior to run the simulation. Harmonic calculator utilized to measure numerical values of harmonics by connecting it to both ac-dc-ac converter and induction motor.

The uncontrolled diode bridge is used for ac-dc conversion as a rectifier and PWM inverter is used for dc-ac conversion as shown in the fig.3. Analysis has done with typical induction motor parameters for two different carrier frequencies of PWM controller and observed injection of harmonics with decrease of carrier frequency keeping modulation index (m) constant at 0.8. Wave forms of all these observed parameters of both power electronic converter and induction machine are as shown in figures from fig.4 to 9.

Parameters of a typical induction machine

Rs- Stator resistance =6.03
Rr- Rotor resistance=6.085
Ls- Stator inductance=489.3e-3
Lr- Rotor inductance=489.3e-3
M- Mutual inductance=450.3e-3
P=4 Poles
J=0.00488 Inertia

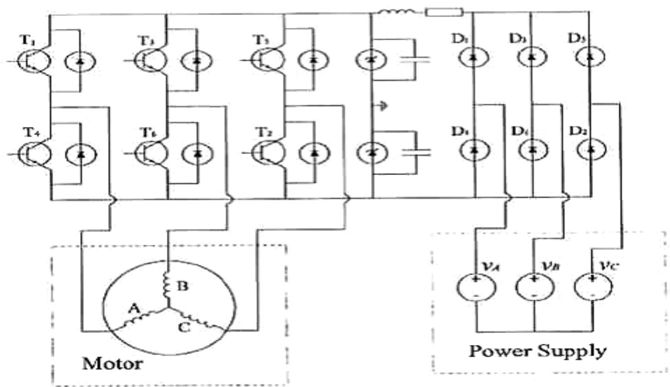

Fig.3 Simulink block diagram model of Induction Motor drive

When carrier frequency of PWM controller is 1800Hz

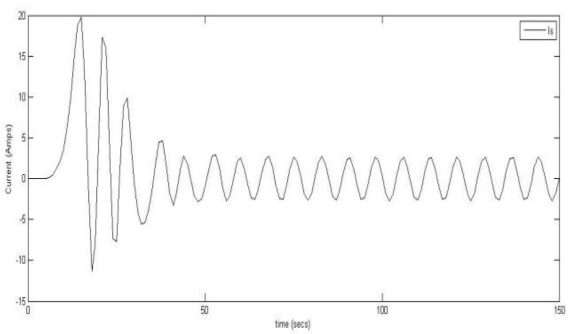

Fig.4 Supply voltage waveform fed by pure ac source

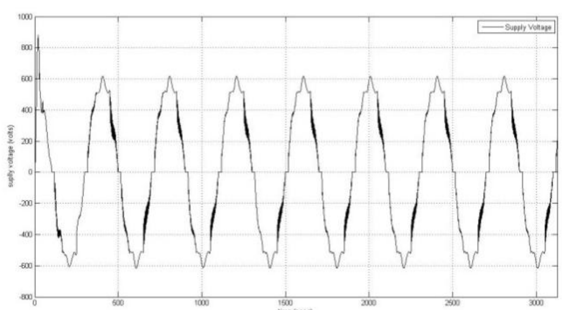

Fig.5 Supply voltage waveform fed by ac-dc-ac converter

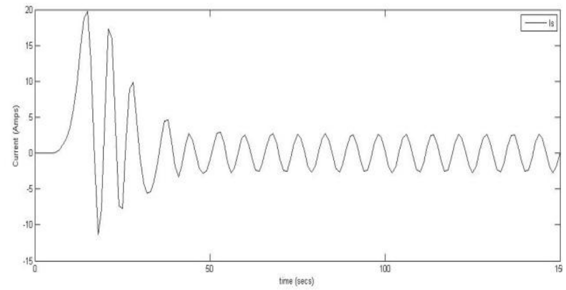

Fig.6 Stator current waveform fed by pure a.c supply

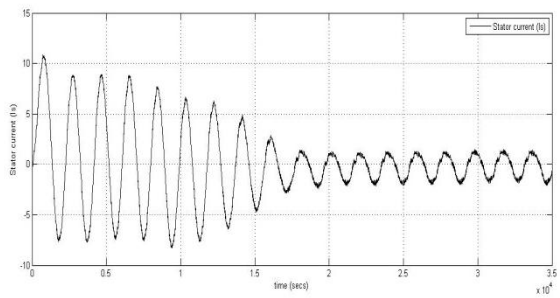

Fig.7 Stator current waveform fed by ac-dc-ac converter

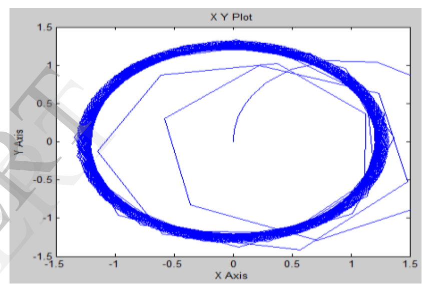

Fig.8 Phase angles of ids *V*siqs fed from pure a.c supply

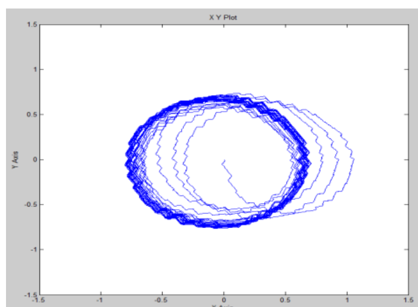

Fig.9 Phase angle of ids *V*siqs fed by ac-dc-ac converter

Supply currenti.e drawn from the mains, PWM inverter output voltage and Stator current of Induction motor drive fed by PWM inverter at carrier frequency of 1608 Hz. Figures 10 to 12 shows waveforms of the supply current, Input Voltage of Motor and Current drawn by the motor (Stator current).

When carrier frequency of PWM controller = 1608Hz

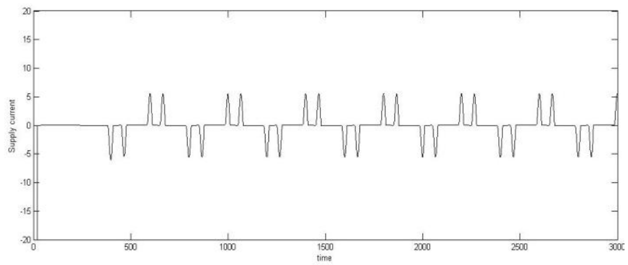

Fig.10 Supply current waveform fed by ac-dc-ac converter

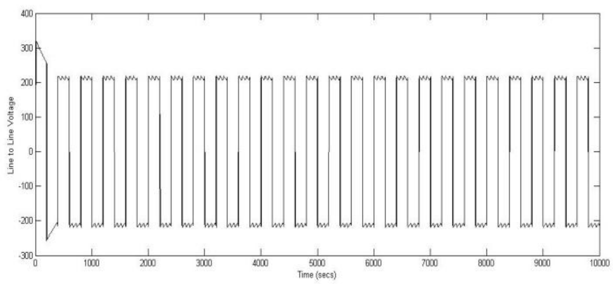

Fig.11 Output voltage waveform of PWM inverter

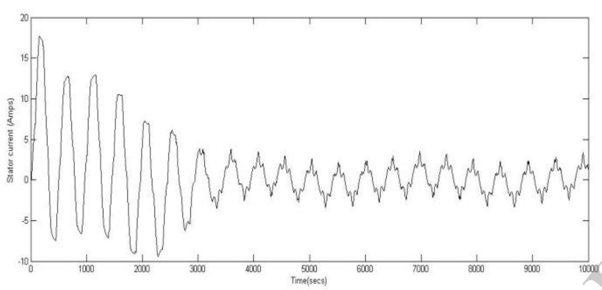

Fig.12 Stator current waveform of Induction Motor

V. CONCLUSIONS

Presented investigation on the torque performance of induction motor drive by studying stator current supplied by PWM inverter, disturbances in a.c. mains supply current and electromagnetic torque developed by the motor depicts that continuous changes in the load, application of variable speed technique and use of power electronic converters playing vital role in the creation of disturbance in the air gap injecting various orders of time harmonics. These harmonics even though eliminated from power electronic converter side by implementing PWM technique in dc-ac converter up to some extent, variation of the frequency by the switching converter will further increases the possibility of harmonics in to the air gap of the machine. This work has finally provided use full information and some conclusions to authors that conventional **α** and **β** transformation technique [1,2] should be limited up to the extent of low voltage machine drives. With increase in size of the VSD more rigorous and analytical calculations are unavoidable in the improvement of performance of the machine. Authors concluded that improvement of ac-dc-ac converter performance and induction motor performance individually will not solve the problem of optimization of the VSD system. Analysis of combined VSD system must be required in order to optimize the VSD system performance. This combined study will be possible with coupled simulations. Coupled simulations [11-18] will provide in depth knowledge on harmonics in the air gap for various changes in the switching circuit parameters. In continuation to this work other methods will be used to verify the flux density and torque of the motor namely conventional analytical calculation, finite element calculation and practical measurements in the later stage.Investigation of additional time harmonics in the air gap of motor due to switching converter will be the future scope of this paper. And future work will be using finite element analysis or coupled simulations for studying harmonics in the airgap of induction motor later on system optimization of the VSD using coupled simulations.

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