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Development of Generalized Model of 3-Phase Induction Motor for Performance Study During Different Distorted and Unbalance Voltage

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***Abstract*—**Due to the introduction of FACT devices in power supply system and complicated control in power industry, presence of harmonics in power supply system is a common problem. It increases day by day and it distorts and unbalances the supply voltage. Due to unequal transformer tap settings, open delta connected transformer banks, unbalanced distribution of single phase loads supply voltage unbalance may occurs. Three phase induction motor is the main workhouse of modern industries. Due to the application of such a polluted supply voltage the performance of three phase induction motor may be affected seriously and this may affect the load connected with the drive system. To take correct measure during torque and speed control, it is required to know the performance during voltage unbalance and distorted supply due to different harmonics. To mitigate this, an attempt has been made to develop a generalized model of a three phase induction motor for online performance study of torque and speed during different distorted and unbalance supply voltage. In doing this, Matlab/Simulink has been used to develop a model based on generalized theory of induction motor. Finally, using the model, performance has been studied during application of different distorted and unbalanced supply and reported.

***Keywords*—**Modelling of Induction Motor, Torque and speed monitoring, Harmonics and unbalance voltage detection

I. INTRODUCTION

Induction motors are the main workhorse of modern industry. For a long time power companies, manufacturers and customers have long bothered due to harmonic pollution problems in the power system [1] [2] [3] [4] [5]. Once the power system gets polluted harmonics due to installation of FACT devices in the power supply system and complicated control in power industry, the operational characteristics of induction motors is affected first. When an induction motor is driven by a polluted source, the motor generates pulsating torque that may cause torsional vibration during its steady state operation and introduces stress into the mechanical system connected with the shaft. The shaft couplings may be destroyed prematurely due to fatigue in shafts caused by excessive torsional vibration. The damage caused by the vibrations may be responsible for catastrophic failure. Voltage unbalance may be created due to various reasons but the large negative sequence may generate due to small unbalance voltage. This can lead to increase the heat in the stator winding and rotor bar. Unfortunately, the generated heat is not producing the useful power and reduces efficiency [6] [7]. Torque (and thus the speed) produced by the motor becomes fluctuating in this condition [8] [9]. The torque can be measured, when the induction motor is running [10] [11] [12]. More vibration can be created in the gear box or the equipment connected to it due to these sudden changes in torque. The produced noise and vibration damages the equipment and also reduces the equipment efficiency. Signal processing, artificial intelligence and other offline techniques were used previously to identify voltage unbalance [13] [14] [15] [16] [17] and feature extraction techniques are used for different fault detection [18]. Continuous monitoring is important than offline monitoring, to protect the motor from excessive vibration and heat caused due to harmonic pollution problem and voltage unbalance problem. On line condition monitoring technique is used to determine if a fault exists in a machine while it is operating [19] [20] [21] [22] [23] [24].

The block diagram of general approach is shown in Fig-1. Online condition monitoring technique is used to stop the machine when the pre-set safety limit is exceeding to avoid catastrophic accident and it reduces both unexpected failures and maintenance costs. This technique is essential to monitor the condition of motor if voltage unbalance has occurred in any of three phases of the induction motor.

In this work, for online monitoring of the performance of three phase induction motor a model has been developed and designed on Matlab/Simulink platform by applying generalized theory of induction motor. This model can generate pulsating torque and speed in different distorted and unbalance supply voltage. The output of torques and speeds have been shown here at balanced supply voltage and supply voltage with 3-rd harmonic, combination of 3-rd and 5-th harmonics and combination of 3-rd, 5-th, 7-th harmonics condition. Inspecting the nature of speed and torque, an expert can identify which harmonic has introduced in the supply, in addition any voltage unbalance in any phase can be identified by observing the nature of speed and torque. In this work the output of 20% voltage unbalance in a phase (over and under voltage) has been shown but it is able to generate output in every voltage unbalance conditions. Observing the nature of output the expert can take decision that the system can be operated in this abnormal condition or not to avoid unscheduled shutdown of the machine and to increase the motor lifetime.

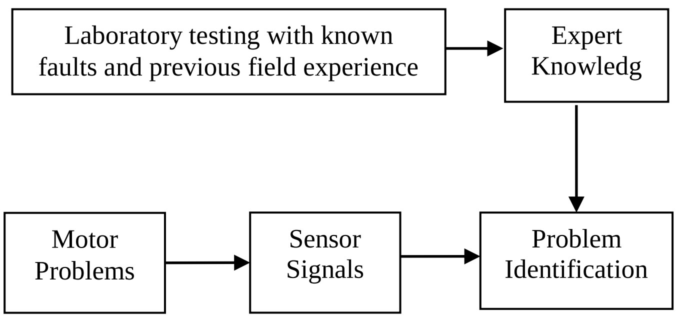

Figure-1. The online condition monitoring process

II. EFFECTS OF DISTORTED AND UNBALANCE VOLTAGE IN INDUCTION MOTOR

The harmonics distort the voltage which is consequently affects the performance of the other loads; especially electric motors. Generally, the three-phase non-sinusoidal, distorted voltage can be expressed as:

$$V_R = \sqrt{2}[V_a \sin(\omega t) + V_h \sin(h\omega t + \theta_h) \text{ ... ...} \quad (1)$$

$$V_Y = \sqrt{2}[V_a \sin(\omega t - 120^0) + V_h \sin(h\omega t + \theta_h) \text{......} (2)$$

$$V_B = \sqrt{2}[V_a \sin(\omega t + 120^0) + V_h \sin(h\omega t + \theta_h) \text{......} (3)$$

where V_a is the *rms* value of the fundamental; '*h*' is the harmonic order; V_h is the *rms* value of the *h*-th harmonic voltage; ω,Φ_h are the frequency (rad) of fundamental and the phase angle of the *h*-th harmonic respectively.

The *h*-order space harmonic wave is equivalent to a machine with the number of poles equal to (*h* x number of poles of the stator)**.** Therefore, for the *h*-th order space harmonic the synchronous speed will be

$$N_{s(h)} = \frac{N_s}{h} = \frac{120 f}{h \times p} \text{ ....} \quad (4)$$

A. Torque calculation in supply voltage harmonic

The developed torque in the induction motor due to the interaction between the magneto motive forces (*mmf*) produced by the stator (*F1*)and the rotor (*F2*) [25]may be expressed as:

$$\vec{T} = (\vec{F}1) \times (\vec{F}2) \text{ ....} \quad (5)$$

The phasor diagram of the induction motor and magneto motive forces diagram is shown in Fig-2, where I_m and Φ are the magnetizing current and flux respectively and E_r is the rotor induced *emf*. The stator produced *mmf* is proportional to the magnetic rotating flux and the rotor produced *mmf* is proportional to the rotor current. From equation (5) and Fig-2 it can be written as

$$T = F1.F2.\sin(\alpha) = K.\Phi.I_r.\sin(\alpha) \text{ ....} \quad (6)$$

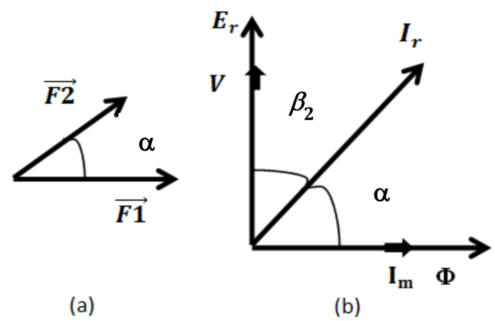

Figure-2. (a) Mmf diagram (b) Phasor diagram

Thus, the produced torque due to the fundamental components of the stator flux and of the rotor current can be expressed as

$$T = K\Phi_N I_{r(N)} \cos(\beta_2) \text{ ---------------} \quad (7)$$

The harmonic torque produced by the fundamental flux and the rotor harmonic currents can be obtained by

$$T_h = K\Phi_N I_{r(h)} \sin(\alpha) \text{ -----------------} \quad (8)$$

with $\alpha = 2\pi ft$

The produced harmonic torque due to the stator harmonic fluxes and the rotor fundamental current can he expressed as

$$T_{(h)} = K\phi_{(N)}[V_h/(hV_1)]I_r \sin(\alpha) \text{ ....} \quad (9)$$

In the same way, the produced harmonic torque due to the stator harmonic fluxes and rotor harmonic currents can be expressed as

$$T_{(h)} = K\phi_N [V_{(h)} / (hV_1)] I_{r(h)} \sin(\alpha) \quad \text{……………} \quad (10)$$

B. Torque calculation in supply voltage unbalance

The researchers have done a wide variety of research on modeling of unbalanced condition in study of induction machines. In the unbalanced voltage operating condition the torque can be written as [26] [27] :

$$T = \frac{P}{\omega} = \frac{P_d + P_2}{\omega} = T_d + T_2 \quad \text{……………....} \quad (11)$$

where, T_d is the *dc* torque and T_2 is the torque component of which frequency is twice the supply frequency. Assuming the induction motor as a R-L load in a simpler way the torque can be expressed as:

$$T = \frac{\eta \times V \times I}{\omega} \quad \text{……………………………….…} \quad (12)$$

Here, V and I are input voltage and current of each phase respectively. Assuming the sinusoidal waveforms for current and voltage this equation can be rewritten as:

$$T = K\cos(2\Pi f + \beta)\cos(2\Pi f + \alpha) \quad \text{………..} \quad (13)$$

So, $T = K[\cos(\beta - \alpha) + \cos(4\Pi f + \alpha + \beta)]$.. (14)

Equation (14) shows the resulting torque consists of a dc term and a term corresponding to the frequency is twice the fundamental frequency of the applied voltage. This additional torque component can be utilized to detect the unbalanced supply voltage.

III. THREE PHASE INDUCTION MOTOR MODEL

A. Mathematical Model

The generalized model of three phase induction motor may be referred to as dynamic model and may be explained by an electrical sub-model for implementation of three-phase to two-axis (3/2)transformation of voltage and stator current calculation. The torque sub-model calculates the developed electromagnetic torque in the motor and a mechanical sub-model to yield the rotor speed.

With the help of differential equations for voltage and torque the generalized dynamic model of induction motor can also be developed. For dynamic analysis, poly phase windings are transformed into two phase windings (*q-d*). In other words; the parameters of an induction machine are transferred to another *d-q* model which remains stationary.

The analysis of three phase circuit is simplified using direct-quadrature (*d-q*) mathematical transformation. Applying *d-q* transformation for balanced three phase circuits reduces the ac quantities can be reduced three to two [28].

The stator inductance is the sum of the magnetizing inductance and stator leakage inductance ($L_{ls} = L_s + L_m$).The rotor inductance is the sum of the magnetizing inductance and rotor leakage inductance ($L_{lr} = L_r + L_m$).

The equation for three-phase source is applied to conventional model of an induction motor are

$$V_R = \sqrt{2}V_a \sin(\omega t)$$
$$V_Y = \sqrt{2}V_a \sin(\omega t - 120^0)$$
$$V_Y = \sqrt{2}V_a \sin(\omega t + 120^0)$$

where V_a is the *rms* value of the fundamental voltage. 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 equations:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = [A] \times \begin{bmatrix} V_R \\ V_Y \\ V_B \end{bmatrix} \quad \text{……………………………} \quad (15)$$

where, matrix $[A] = \begin{bmatrix} 1 & -(1/2) & -(1/2) \\ 0 & (\sqrt{3}/2) & -(\sqrt{3}/2) \end{bmatrix}$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \int_{\tau=0}^{t} \left\{ [B] \times \left(\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} - [C] \times \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \right) \right\} d\tau \quad \text{….} \quad (16)$$

Here, $[B] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}^{-1}$ and

$$[C] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & (\frac{P}{2})\omega_0 L_m & R_r & (\frac{P}{2})\omega_0 L_r \\ -(\frac{P}{2})\omega_0 L_m & 0 & -(\frac{P}{2})\omega_0 L_r & R_r \end{bmatrix}$$

In the electrical model as described by equation (16), the three-phase voltage [V_R, V_Y, V_B] is the input and the current vector [i_{ds}, i_{qs}, i_{dr}, i_{qr}] is the output vector. The cage rotor winding is short circuited, so the rotor voltage vector is normally zero, *i.e.*, V_{dr}=0 and V_{qr}=0. The electromagnetic torque$T$ is given in the two-axis stator reference frame by

$$T = \frac{PL_m}{3}(i_{dr}i_{qs} - i_{qr}i_{ds}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

Neglecting viscous friction and from the torque balance equations the rotor speed $\omega_0$can be written as

$$\omega_0 = \int_0^t (T - T_L)/J \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

whereT_L is the load torque and J is the moment of inertia of the rotor and load.

B. Simulink Model

In Matlab/Simulink platform, model of three-phase induction motor has been developed and presented in Fig-3. Here oscillograms of speed and torque can be viewed at healthy and different supply voltage unbalanced condition. Matrix [A] in equation (15) and matrix [B] of equation (16) have been implemented by the "Matrix Gain" block of Simulink, while matrix [C] has been implemented by four "Fcn" blocks of Simulink. This system has been applied for online monitoring of system performance. This system is able to show the nature of torque and speed when different harmonics exists in the supply voltage due to FACT devices power supply system and complicated control in power industry. Three phase voltages are converted to generalized two phase voltages (V_{ds} and V_{qs}) and using the motor equivalent circuit parameters the i_{ds} and i_{qs} are also calculated. The torque and speed are also calculated using i_{ds} and i_{qs} and applying mathematical equation. Torque and speed oscillations in the torque-time and speed-time characteristics are recorded in the scope when harmonics (3-rd harmonic, combination of 3-rd and 5-th harmonics and combination of 3-rd, 5-th and 7-th harmonics) are introduced in the supply voltage and using the nature of waveform it can be identified that which harmonics are present in the supply voltage. The model is also able to generate abnormal torque-time and speed-speed oscillograms in unbalanced supply condition (under and over voltage unbalance).The Matlab functions check the percentage of supply voltage unbalance occurred in the phases. In this work torque-time and speed-time oscillograms have been shown for 20% over and under voltage unbalance condition but this model is able to generate output in any unbalance conditions. Observing the nature of torque-time and speed-time characteristics in the scope(Figures-4 to 9)one can diagnosis the type of problems occurred in the supply and can take it decision about whether the system can be operated in this condition or not.

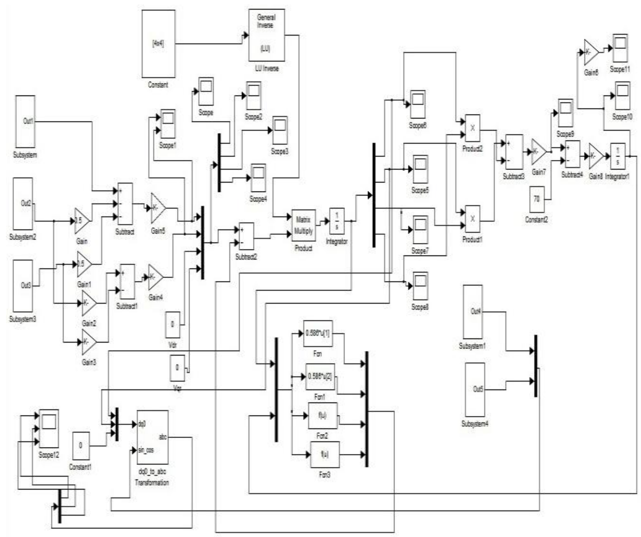

Figure-3.Matlab/Simulink based model of induction motor

IV. RESULT AND DISCUSSION

The three phase, star connected 7.5 *k*W, 6-pole, Squirrel cage induction motor [29] used for the simulation has the parameters R_s=0.288 V/ph, R_r=0.158 V/ph, L_s= 0.0425 V/ph, L_m = 0.0412 V/ph, L_r = 0.0418 V/ph, J = 0.4 kg-m^2, J_L = 0.4 kg-m^2

To illustrate the transient operation of the induction motor the direct-on-line starting is demonstrated for simulation study. The motor, previously de-energized at t=0, and it is connected to a 220 V, 50 Hz three-phase supply through a cable at standstill condition. T_L is the load torque and it is kept constant at 20 N-m. The torque-time and speed-time oscillograms in different conditions are presented in figures 4-6.

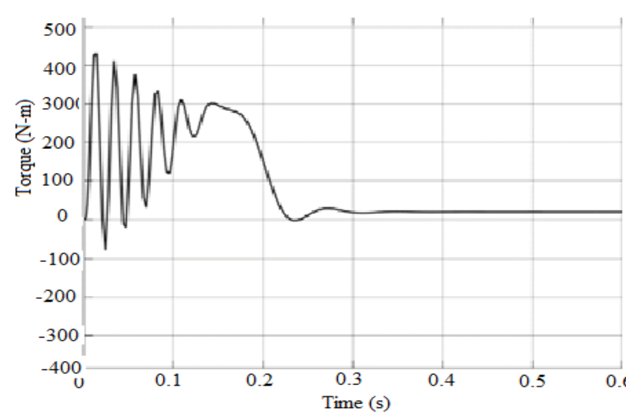

Figure-4.(a) Torque-time characteristic of Induction Motor at balanced supply voltage

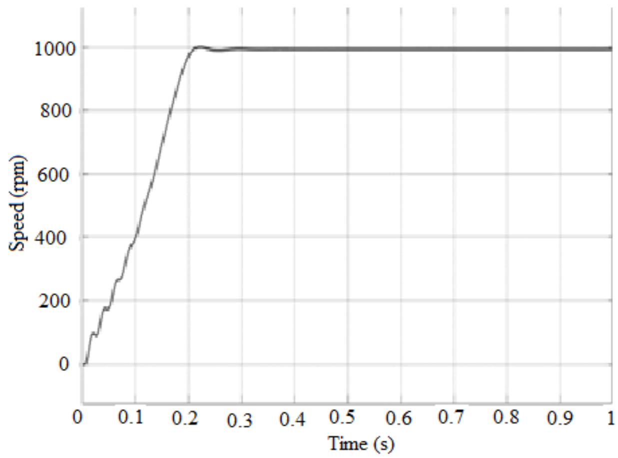

Figure-4.(b) Speed-time characteristic of Induction Motor at balanced supply voltage

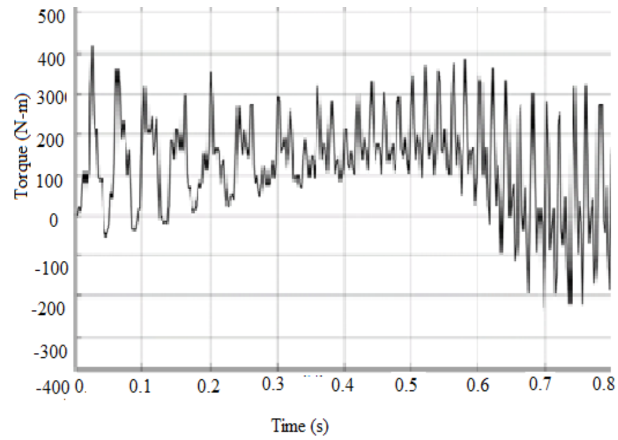

Figure-6. (a) Torque-time characteristic of Induction Motor at supply voltage with 3-rd and 5-th harmonic

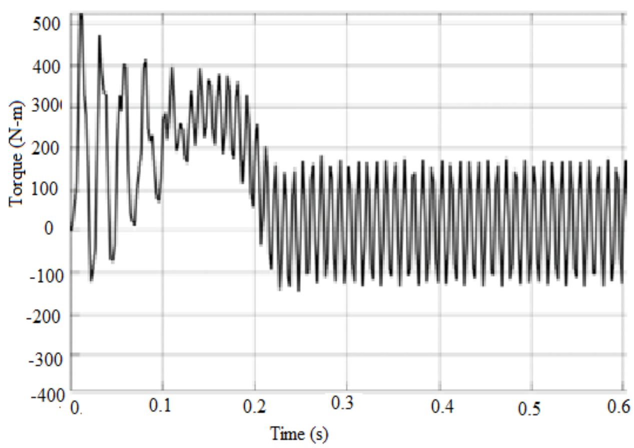

Figure-5. (a) Torque-time characteristic of Induction Motor at supply voltage with 3-rd harmonic

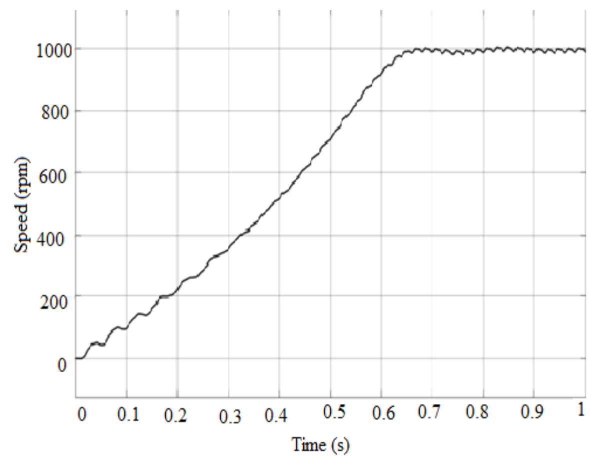

Figure-6.(b) Speed-time characteristic of Induction Motor at supply voltage with 3-rd and 5-th harmonic

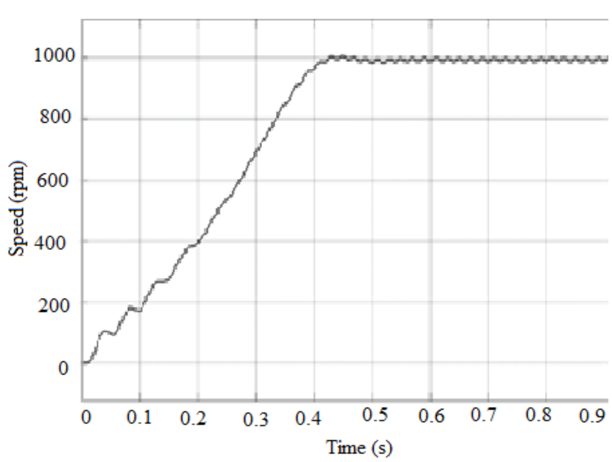

Figure-5. (b) Speed-time characteristic of Induction Motor at supply voltage with 3-rd harmonic

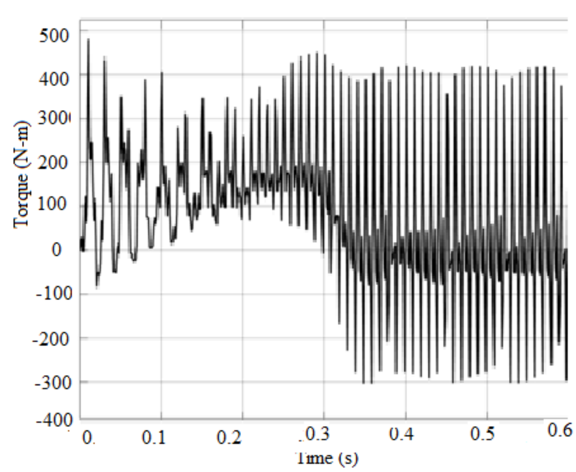

Figure-7. (a) Torque-time characteristic of Induction Motor at supply voltage with combination of 3-rd, 5-th and 7-th harmonics

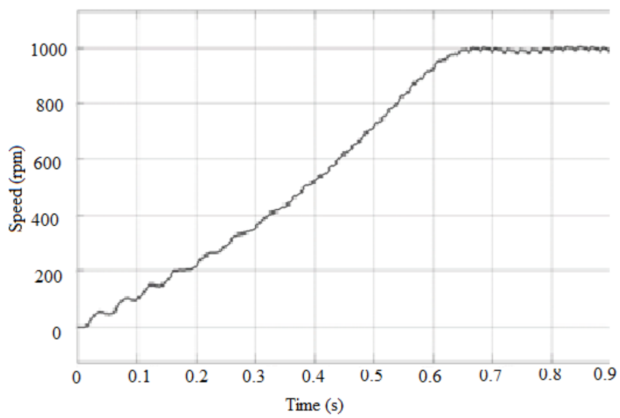

Figure-7. (b) Speed-time characteristic of Induction Motor at supply voltage with combination of 3-rd, 5-th and 7-th harmonics

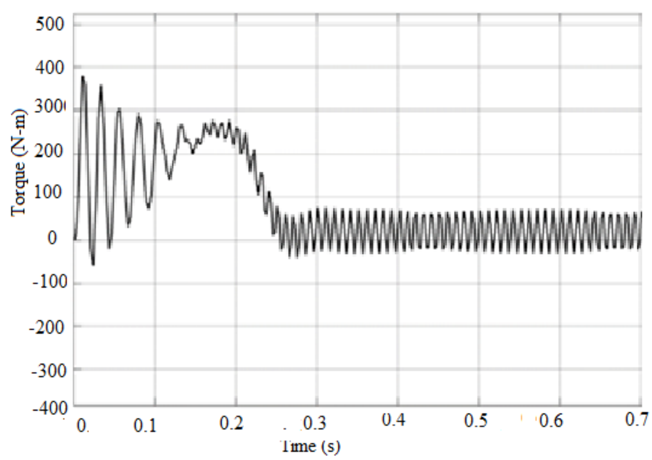

Figure-8.(a) Torque-time characteristic of Induction Motor at single phase voltage unbalance at 20% under voltage

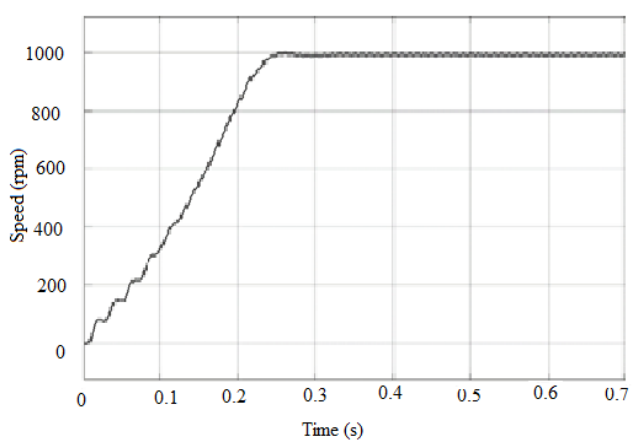

Figure-8.(b) Speed-time characteristic of Induction Motor at single phase voltage unbalance at 20% under voltage

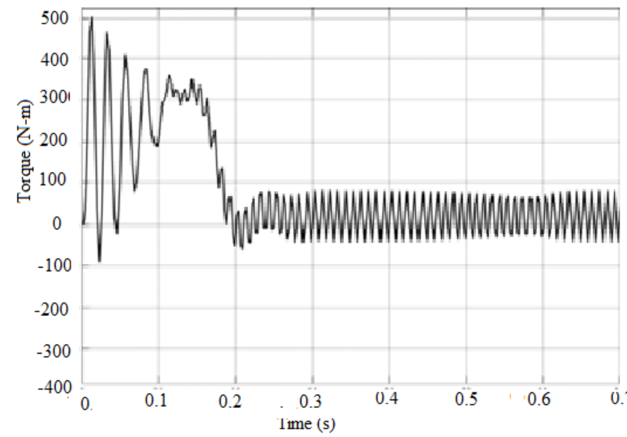

Figure-9.(a) Torque-time characteristic of Induction Motor at single phase voltage unbalance at 20% over voltage

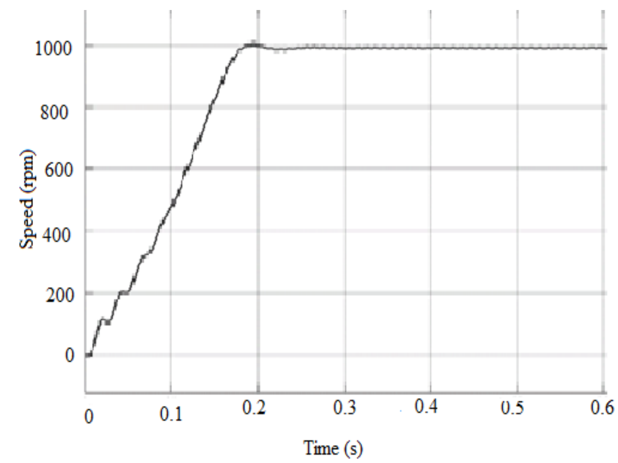

Figure-9.(b) Speed-time characteristic of Induction Motor at single phase voltage unbalance at 20% over voltage.

V. CONCLUSION

It is not always possible to detect the problems accurately in online condition monitoring system. The designed generalized model of induction motor using Matlab/Simulink has ability to detect and identify and type of the voltage unbalances occurred and also the supply voltage harmonics by inspecting the abnormal torque-time and speed-time characteristics. The results have been obtained without the help of complicated differential equations. This model can be applied in online condition monitoring system. In this work studied have been made for 20% over and under voltage unbalance conditions but it is capable to identify any voltage unbalance and to protect the machine from excessive heat occurs due to supply voltage unbalance. Observing the abnormal torque-time and speed-time oscillogramsan engineerscan easily identify which types harmonics have introduced in the supply voltage and also the voltage unbalance.

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