Simulink Modelling of the Transient Cases of Three Phase Induction Motors

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Abstract-- In this paper, a modular approach has been utilized for investigation of the dynamic behavior and analysis the transient cases for a three-phase induction motor. By using motors with various power ratings (low, medium, and high). Mathematical model has been utilized with Matlab/Simulink to investigate the behavior of induction motor in both transient and steady state. Motor variables, (e.g. voltage, current, flux, speed and torque versus time) were investigated. A q-d axis based model is proposed to analyze the transient performance of three-phase induction motor using stationary reference frame [11-16]. This model could also be used for a wide range of horse power needed in scientific research and numerical applications. We will considered as a model for the study and analysis under different operating conditions for a 5, 50, and 500 hp induction motors. The motor stator voltage, the stator and rotor currents, the developed torque and rotor speed were numerically calculated and plotted for normal operation, short circuit, and unbalanced voltage source for the induction motor.

Index Term-- Induction Motor, mathematical Modeling, Stationary Reference Frame, Matlab/Simulink.

INTRODUCTION

The induction machine is the most wide used in an industrial applications as a source of mechanical power, due to its robustness, reliability, and good self-starting capability. In an induction motor, usually studies the steady-state and transient cases which are very important to taken into account. The transient cases in an induction motors are electromagnetic transient cases that result from commutations process and mechanical transient cases as a result of fast changes of rotation speed of the motor. Speed faded of electromagnetic transient cases depends on the winding parameters of the motor, the inertia torque of mass and the value of motor loads. In order to investigate and calculated the transient cases in an induction motors, the effects of the electromagnetic will be neglected, with a help of static-starting characteristic. The mechanical transient cases would be calculated, during the starting process when instantaneous current flow through the windings of the motor. This current is considered that is correspond with [8, 14, 16], the motor speed. The mutual flux produces instantaneous torque which consider to be fixed during constant speed of the motor. Which is the best approach used to calculate starting, stopping and the other transient cases in an induction motors. Motor speed in transient cases, change as a result of windings current effect and the values of rotating torque. However, as the motor speed increasing, the mechanical characteristic differs from the static characteristic. It can be interpreted as follows: Any change in the motor speed the rotor current will be changed as well. As a result of increased time constant for the winding, the rotation torque inertia of the rotor mass decreased. The dynamic-mechanical characteristics of the motor depends on the winding parameters and the load parameters (torque inertia mass and the value of the load). The change in torque inertia or in resistance torque leads to change dynamic-mechanical characteristic. The motor appears, only one static characteristic and an infinity number of dynamic-mechanical characteristic. To analyze and study the transient case and determine the behavior of any induction motor the dynamic differential equations (5,6) and the equivalent circuit see figure(1) will be used. The behavior of the induction motor in the transient cases will be described. There are non-linear equations will be used in mathematical model of induction motor (IM). Matlab/Simulink tool box will be utilize to solve and analyzed these equations [1-7]. As this software can be
utilize for high accuracy, and a very short time period for transient cases on a form of vibrations cartographic curves.

**MODELING OF INDUCTION MOTOR**

To determine the performance and the behavior of the IM we need to the dynamic equivalent circuit, and the dynamic equation that can describe the performance of the IM in the any transient cases. In this paper to described the dynamic behavior of IM we can using mathematical (dynamic) model of IM which is derived by using (d - q) variables axis in a synchronously rotating reference frame, and the dynamic performance of IM when feed the induction motor from a balanced voltage source at starting, or under short circuit or at unbalanced voltage source fault conditions for each low, middle and high power motors. In the windings of the rotor and in stator arise electromagnetic transient cases. When the motor is operated at any of these systems the electromagnetic torque, currents and rotational speed of the motor are determined as a function of time or of speed (as per unit). Under balanced condition the sum of stator currents as well as rotor currents is zero. The dynamic model of induction motor can be developed by utilizing differential equations for voltage and torque of the poly phase windings and the parameters of the induction machine are transferred to arbitrary reference frame d-q mode. This model is uses two windings for each stator and rotor. A transformation of variable to an invariant two-axis and defined as the following. 3-phase to 2-phase (abc- dq) conversion: To convert a 3-phase voltage to the 2-phase synchronously rotating frame, they are first converted to 2-phase stationary frame (α, β) using (1) and then from stationary frame to the synchronously rotating frame (d-q; where d is the direct axis, q is the quadrature axis) using (2). In place of voltage there may be currents or flux linkage.

![Image](204x465 to 383x516)

\[
\begin{pmatrix}
V_a \\
V_b \\
V_c
\end{pmatrix} = \begin{pmatrix}
1 & \frac{1}{\sqrt{3}} & -\frac{1}{2} \\
\frac{1}{\sqrt{3}} & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \frac{1}{2}
\end{pmatrix} \begin{pmatrix}
V_d \\
V_q
\end{pmatrix} \quad \text{(1)}
\]

\[
\begin{pmatrix}
V_d \\
V_q
\end{pmatrix} = \begin{pmatrix}
\cos \gamma & \sin \gamma \\
-\sin \gamma & \cos \gamma
\end{pmatrix} \begin{pmatrix}
V_a \\
V_b
\end{pmatrix} \quad \text{(2)}
\]

Where \((\gamma)\) is the transformation angle.

**2-phase to 3-phase (dq-abc) conversion:** This conversion does the opposite of dq-abc conversion for the current variables using (3) and (4) respectively by following the same implementation techniques as before.

\[
\begin{pmatrix}
i_\alpha \\
i_\beta
\end{pmatrix} = \begin{pmatrix}
\cos \gamma & \sin \gamma \\
-\sin \gamma & \cos \gamma
\end{pmatrix} \begin{pmatrix}
i_d \\
i_q
\end{pmatrix} \quad \text{(3)}
\]

\[
\begin{pmatrix}
i_d \\
i_q \\
i_c
\end{pmatrix} = \begin{pmatrix}
1 & 0 & \frac{1}{\sqrt{2}} \\
0 & \sqrt{2} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0
\end{pmatrix} \begin{pmatrix}
i_\alpha \\
i_\beta
\end{pmatrix} \quad \text{(4)}
\]

The dynamic equations in arbitrary reference frame which is rotating at speed \( (\omega) \) in the same direction of the rotator. The dynamic equations in arbitrary reference frame which is rotating at speed \( (\omega) \) in the same direction of the rotator.

1) When \( (\omega) \) is equal to zero, the reference frame (q-d) is fixed in the stator.

2) When \( (\omega) \) is equal to \( (\omega_e) \) the reference frame is fixed on the synchronously rotating.

3) When \( (\omega) \) is equal to \( (\omega_r) \) the reference frame is fixed in rotor and is rotating at speed of \( (\omega_r) \).

**The dynamic equation used:**

\[
\dot{V}_s = R_s i_s + \frac{1}{\omega_b} \frac{di_s}{dt} + \omega e M \left( \frac{1}{\omega_b} \right) \lambda_s \quad \text{... ... ... ...(5)}
\]

\[
\dot{V}_r = R_r i_r + \frac{1}{\omega_b} \frac{di_r}{dt} + (\omega e - \omega_r) M \left( \frac{1}{\omega_b} \right) \lambda_r \quad \text{... ... ... ...(6)}
\]

**Flux linkage-current relations:**

\[
\lambda = \begin{pmatrix}
\lambda_s \\
\lambda_r
\end{pmatrix} \quad \quad \quad \quad \quad \quad \quad \quad i = \begin{pmatrix}
i_d \\
i_q
\end{pmatrix}
\]
\[
\lambda_s = L_s i_s + L_m i_r \\
\lambda_r = L_m i_s + L_r i_r \quad (7)
\]

Where:

\[
L_s = L_m + L_{s1} \\
L_r = L_m + L_{r1} \quad (8)
\]

Mechanical system equations:

\[
T_{em} = 2H \frac{d\omega_{mec}}{dt} + B_m \omega_{mec} + T_L \\
T_{em} = 2H \frac{d\omega_{mec}}{dt} + B_m \omega_{mec} + T_L \]

Where:

\[
\omega_{mec} = \frac{2}{p} \omega_r \quad (9)
\]

\[\hat{V}_s, \hat{V}_r\] - voltages space vector of the stator and rotor. \[i_s, i_r\] - currents space vector of the stator and rotor. \[\lambda_s, \lambda_r\] - flux linkages space vector of the stator and rotor. \[L_s, L_r\] - magnetization inductance. \[T_{em}\] - electromagnetic torque. \[T_L\] - load torque. \[B_m\] - viscous friction coefficient. \[p\] - Number of poles. \[i_a, i_b\] - stator and rotor currents α, β frame. \[\omega_e\] - angular velocity of the reference frame. \[\omega_r\] - angular velocity of the rotor. \[\Omega_mec\] - mechanical angular velocity inertia of the rotor. \[V_{\alpha}, V_{\beta}\] - stator and rotor voltages α, β frame.

**Figure (1)** d-q of the dynamic equivalent circuit

**Figure (2)** Induction machines parameters.

**SIMULINK MODEL OF INDUCTION MOTOR:**

The dynamic model of induction motor in d-q variable axes which is represented by equations (5, 6, 7, 8, 9) for flux linkages, it can be used as a variable state. In this paper the flux linkages are chosen as a state variable and it was verified by Matlab/Simulink software environment. Figure (4) shows the block diagram of three phase induction motor supplied by a 3-phase voltages. The variable \(\omega = \omega_s\) represented the synchronous speed of the common reference frame used. This speed is an arbitrary speed. This block
(a) 3-phase voltages pu and frequency pu are represented in the
(block. (b) abc-dq axes block, realizes the transformations of variables
defined by (1) and (2). Figure (5) shows the IM-dq model, this block diagram
represent the induction motor using d-q variables axes in an
arbitrary reference frame. The IM-dq model of the motor is
represented using equations (5) and (6) with flux-currents
relations block. Figure (5) shows the sub-block diagram of flux Linkage-currents
relations using equations (7 and 8). It is used to compute the
four d-q currents using the four flux linkages and the inverse
inductance matrix. The dq- abc block realizes the
transformations of variables defined by equations (3) and (4).
Figure (6) shows the mechanical system block determines the
electromagnetic torque using equation (9) transformations of
variables defined by equations (3) and (4).

Fig. 3. Block diagram of induction motor model in the arbitrary frame
Simulation at normal operation:

The number of pulses (inrush) electromagnetic torque increases dramatically. The line voltage, speed, load and torque are used at rated values as a per-unit (1pu). The electromagnetic torque characteristic during normal operation can be expressed through the relationship between the electromagnetic torque and the rotational speed of the motor as shows in figure (7). The result analysis is performed by using the curves cartographic utilizing Matlab/Simulink. At starting moment of the motor under load, at the transient case will appear a strike current the arising electromagnetic torque and the current flowing in the motor's windings during the transient cases contains two components. The first is a direct current component (DC), and the second is an alternating current component (AC). This explains the significant effect of the electromagnetic transient cases because its two components are formed as a result of I-sub-transient, I-transient and I-steady state currents which corresponding values of X'' sub-transient and X' transient reactance and X-direct axis reactance respectively. These currents flowing in the motor's windings during a transient cases at starting, braking or short circuit cases. The DC component will be faded to zero at the end of the electromagnetic transient cases depending on the time constant. And we can say that when increasing the moment of inertia or a flywheel or the HP, the number of the inrush (pulses) of the electromagnetic torque whenever dramatically increased at starting, will disappear faster during a short period time as shown in figure (7).

Analyze effect of the motor parameters on the transient cases gives a perception of the quality and the values to change characteristic of transient and situations that define the pick value or a torque strike and the length of the transient case . Reducing the active resistance of the stator windings reduces the faded of the windings coefficient and the electromagnetic transient cases slowly faded, as well increasing the active resistance of the stator windings leads to faded the electromagnetic transient cases quickly and their effect on the electromechanical transient cases is less and this leads to a reduction in pulses torque curve and smoother in the increasing the speed.

If the value of the active resistance of the rotor windings is small, (e.g) starting motor at no-load there will be a rush into the motor speed and the motor speed will exceed the synchronous speed. The faded of the windings coefficient of the rotor will be decrease . Whenever the motor speed exceeded of the synchronous speed, the rotor current and torque will not equal to zero, and it will be reflected direction of current flow and the rotation torque, becomes the torque, braking torque which leads to reduce speed of the motor to a state of stability at rated value. At the end of transit cases, by
increasing the active resistance of the motor rotor, the torque-speed curves are increasing. From the speed signal for each motor as shown in figure (8-a, 8-b, 8-c). The motor accelerates up to reach synchronous speed, because the rotational losses are not represented at initially as in figures (8) through a time \( t = 0.3 \) sec for a 3HP and 50 HP, and through a time \( t = 1.05 \) sec for a 500HP, from this we note that the speed reach up synchronous speed in a few moments. For a 3HP and 50 HP, and through a time \( t = 1.05 \) sec for a 500HP .At the instant \( t = 1.5 \) sec the motors has been loaded by the rated torque and speed decrease to the rated speed. And this clear from the speed signal for each motor as shown in figure (8-a, 8-b, 8-c).

The number of currents inrush (pulses) that arises in motor at starting moment as a result of the effect of AC and DC currents components, will increases whenever increased the HP and changing in rotation speed of the rotor. The DC component faded to zero at the end of the electromagnetic transient cases, when a speed of motor reaches to rated value. The values strikes of the currents dramatically increased at starting .We can say that when increasing the moment of inertia or a flywheel or the HP, the inrush (pulses) of the currents dramatically increasing, and will disappear faster for a low HP, during a short period time. Fading of the frequencies are variable, depending on the rotation speed rotor .If the speed of the rotor is high; the fading will decrease very quickly. But at low speed will be very few

At the end of the transient cases arise no-load currents and the load currents. These currents are illustrated in fig. (9-a, 8-b, 8-c). But the vibration of the speed and electromagnetic torque near the synchronous speed are decreasing figure (10) voltage signals 3hp machines with reduced the voltage until the machine has reached 60% to 80% of synchronous speed where upon full voltage is applied. Although the offset in each of the stator currents, depends upon the values of source voltages and at the time of application. Instantaneous torque is independent of initial values of balanced source voltages, because the machine is symmetrical.
The figure(10) shows the voltage signals on the axes (a,b,c), (α, β) and (d,q) in PUs of the machines another noticeable difference between the dynamic and steady-state torque speed characteristics occurs in the case of the 500 hp machines. In particular, the rotor speed over shoots synchronous speed and instantaneous torque and speed demonstrate decayed oscillations about the final operating point, however, in case of the 3- and 50 hp machines the rotor speed is highly damped and the final operation condition is attained without oscillations and that clear from the torque signal for each motor shown. It is noted from table (1) that the ratio of rotor leakage reactance to rotor resistance is much higher for the larger-hp machines than for smaller-hp machines point, however, in the case of the 3- and 50 hp machines the rotor speed is highly damped and the final operation condition is attained without oscillations and that clear from the torque signal for each motor shown. It is noted from table (1) that the ratio of rotor leakage reactance to rotor resistance is much higher for the larger-hp machines than for smaller-hp machines.

Induction motor under fault condition:

when a 3-phase short circuit fault occurs or fail voltage whose feeds the motor during work, to electrically close to the motor no electrical energy can be enter or leave the motor It is obvious that current can still flow in both the stator and rotor windings, thus torque can be produced, as a result of the EMF and energy stored in the magnetic field, and therefore be dissipated either as mechanical energy or as heat due to copper losses in the motor. At instant occurrence fault, there is a large negative transient torque associated with a large transient stator current with a high peak magnitude. It is not uncommon for motors to have maximum reverse torque impulses of up to 15pu. This torque impulse reaches its maximum within few cycles, but decays rapidly. Since the flux decays rapidly, removing the fault and subsequent re-establishment of the supply voltage produces transient of the same order as at start up but with a few impulses. However, if many motors are left connected to the system their combined effect could lead to a voltage depression due to large currents, and all the motor might not be able to the motor might not be able to accelerate back to full speed.

Dynamic performance of induction machines during a 3-phase short circuit fault:

Dynamic performance of 3hp, 50hp, and 500hp induction machines is shown respectively in fig. (12) Through (14) during a short circuit or fail voltage fault at terminals. Initially the motor is running and operating at steady state conditions with a constant load torque. Fault at the voltage terminals is simulated by setting the stator voltages to zero at time t=1sec. After 0.5 sec i.e. at t=1.5 sec the stator voltages are reapplied to motors. At that instant, the voltage passes through zero going positive. Fig.(12) through (14) shows that stepping the supply voltage to zero volts causes a large transient stator current who is peak magnitude of Dynamic
performance of 3hp, 50hp, and 500hp induction machines is shown respectively in fig.(12) through (14) during a short circuit or fail voltage fault at terminals. Initially the motor is running and operating at steady state conditions with a constant load torque. Fault at the voltage terminals is simulated by setting the stator voltages to zero at time t=1sec. After 0.5 sec i.e. at t=1.5 sec the stator voltages are reapplied to motors. At that instant, the voltage passes through zero going positive. Fig.(12) through (14) shows that stepping the supply voltage to zero volts causes a large transient stator current who is peak magnitude of approximately 14 pu for a 3hp, and 10 pu for a 50hp and 9 pu for a 500hp as shown in fig.(12), and a large negative torque peak of approximately 9 times for a 3hp, and more 6 times for 50hp, and 5 times for 500hp of the rated steady state torque and the rotor speed and frequency also are decreases once the supply voltage is removed as shown in figures (15, 16).

Fig. 12. Dynamic performance of 3-hp, 50hp and 500hp IM respectively during short-circuit fault

Fig. 13. Dynamic performance (torque–speed characteristic) for a 3-hp, 50hp and 500hp IM respectively during fault

Fig. 14. Dynamic performance (stator current pu and β,α –voltage) for a 3-hp, 50hp and 500hp IM respectively during fault
The magnitude of the worst torque peak and the interruption duration, which occurs is a result of the function of motor and load inertia, larger inertia system causes the rotor speed to decreases more slowly. i.e. lower the magnitude of the negative torque impulse higher the load inertia. In the case of 3-hp and 50-hp motors, both the stator and rotor transients are highly damped and subside before the fault is removed and the voltage are reapplied. When the voltages are reapplied the transients again occur in the stator currents, with a few impulses but with a peak highest than the initial, and rapidly decay.

CONCLUSION
In this paper, an implementation and dynamic modelling behavior of a various three-phase induction motors using Matlab/Simulink is presented in a step-by-step manner. The model has been tested by 3 hp, 50hp and 500 hp induction motors [5, 6]. The simulated machine has given a satisfactory response in terms of the torque, which is dependent on the time constant and on electromagnetic torque. Because the formed transient currents contains from direct current (DC) component and alternating current (AC) component. These currents flowing in the motor windings during a transient cases at starting, braking or short circuit cases. Where the strikes (in-rushes) values of the transient torque at starting is increasing to 12.35 PU for a 3HP motor with a few impulses, and to 8.15 PU for a 50 HP motor with a more impulses, and to 2.5 PU for 500HP motor with many impulses. From above when increasing the moment of inertia or a flywheel or the HP at starting, the number of the strikes (pulses) of the electromagnetic torque and current will dramatically increases, and disappear faster during a short period time as shown in figure (7), and when speed of the motor increases to a higher than the synchronous speed, the torque becomes braking torque and the motor operated as a generator. Which lead to decreases the speed and returns again to operate as a motor with speed less than synchronous speed as shown in figure (7-c). In the motor’s during the transient period.

The strike (in-rush) currents flowing in the motor’s windings during the transient period at starting case, as a result of the effect of the changing in rotation speed of the rotor and the result of effect the currents which formation in a transient cases, as a result of (DC) and (AC) components, increases to 14PU for 3HP with a few impulses, and to 10PU for 50HP with more impulses, and to 8PU for 500HP with a large number of impulses as shown in figures (9). Therefore, in generally practice used different ways to start a large-HP.

From the calculation results the DC component faded to zero, through a period time (0.21sec) for a 3HP, and through a period time (0.38sec) for a 50HP, and through a period time (1.05sec) for a 500HP. Increasing loads lead to increasing vibrations during the period of time that increases the motor speed to reach 0.2-0.25 of the synchronous speed for a large power motors and to reach 0.4 - 0.5 for the low and middle power motors as shown in figure (7). At the end of the transient case appears a few of fluctuations with increasing loads, and then decreased and disappear.

The DC component will be faded to zero at the end of the transient cases which is depending on the time constant and on the rotation speed of the rotor. If the speed of the rotor is high; the fading coefficient of the DC components will decrease very quickly. But at low speed the faded coefficient of the DC components will be very few so when increases the moment of inertia, the motor is running at low speed and thus the fading of the coefficient can be slow which leads to more slowly transient cases with increasing moments of inertia. With a high inertia torque, the number in-rushes of the torque at initial transient cases, will be increases greatly and when the motor is starting, on the shaft of the motor arises non useful weight, as well as the changing electromagnetic torque carries electromagnetic vibrations of a very large amplitude with slowly faded. If the inertia torque drops, the amplitude of the electromagnetic torque will be increasing at the beginning of the transient cases and suddenly the vibrations of the torque are increased and motor speed will be near the synchronous speed. This effect leads to change quickly in the speed of the rotor if the flywheel mass of the rotor is few the motor has a high acceleration which occurs in time to reach the peak value of the torque pulse. Of the motor increases to a high speed when the flywheel mass is little, when a large flywheel mass the rotor speed slightly changing.

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