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A comparative study for the performance operation of electric machine based on conventional and D-Q theories

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ABSTRACT

Induction motors are used widely in industrial applications, thanks to their high efficiency and reliability which nominates it as a good machine used in various application. Based on the application and accuracy, modeling processes of electric machines are carried out using different mathematical methods. The most common method for modeling electrical machines is based on solution of differential equations of voltages as well as calculating the time varying self-inductances and the mutual inductances based on the rotor angle. One of the most important features of this method is that the inductance is no long depend on the time varying voltage, which is the major problem facing the conventional model. But the D-Q modeling approach has several problems, the greatest of which is that the voltage applied on stator must be balanced in addition to the fact that the winding are sinusoidal distributed form. Herein this research is focused on build two models of a 3-Φ induction motor (IM) based on the two analytical approaches and compare them to clarify the difference. The results have been shown that the conventional model gives more accurate response when it is applied in both normal and upnormal operation. MATLAB/Simulink softare is used to construct the D-Q and classical abc IM models.

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1. INTRODUCTION

Induction machine with multi phases have many features compared with classical type, it has a low torque ripple, few harmonics components, low value of stator currents at same level of phase voltage, fault tolerant ability is greater and more reliable. In addition, it has the ability to start if there is an open or short circuit at one of the stator phases. Nowadays induction machines have been extensively used industrial applications due to the simple structure, reliability, high efficiency with accepted power factor in addition to its low price compared with permanent magnet and synchronous machines. Due to mentioned features it as a good machine used in various application Also it can be used in unpredictable or hug operating conditions and did not affected by corrosion and there are no spark losses due to absence of brushes in cage type rotors. The generated electromagnetic torque is calculated based on the derivative of the stored magnetic energy and relative to the angular location of the rotor. In addition, it is possible to evaluate the torque based on the relationship between the currents and inductances. This approach is called the electromagnetic coupled circuits [1]-[4].

Different approaches had been used to simulates the dynamic and steady state performance of electrical machines. One of the widely approaches used to construct the operation of electric machines under healthy and faulty conditions is the finite element method [5]-[8]. This method is applied to simulates the electrical and mechanical parts based on the geometrical dimensions and type of materials used to build the machine. It is also used to calculate the electrical parameters of electric machines accurate by solving nonlinear differential equations on a specified region [9]. Moreover, modeling method using the equivalent magnetic circuit is also utilized, which depends on the calculation of reluctances for possible magnetic flux paths within the electrical machine. But this method has several drawbacks like time consumption in solution the differential equations and required an accurate information about the electric machines, which make it using in design approaches.

The classical (abc) approach which is used to simulate the dynamic performance and calculates the main variables directly without affect by the asymmetry of currents, voltages and inductances [10]. The dynamic response of the induction machines under unstable and faults operation are simulated easily using D-Q transformation theory, where this approach is used to model and simulates the two-phase and short circuit condition on stator winding based on the same set of equations developed for normal operation [11]. A general purpose model is introduced to simulate the steady state, transient and unbalanced two-phase operation of the machines [12], [13]. In addition, the D-Q model is used as a computer aided design to simulate and realize the performance operation during start up, breaking, regeneration and also at open circuit and blocked rotor test of induction machine. For best understanding the operation of electric machines, it is necessary to consider the effect of saturation. Due to the magnetizing inductance is not introduced in most analytical methods, therefore the comparison between practical and simulated results has a big difference. Thus, in order to construct an accurate model, it is important to introduce all the non-linear characteristics of magnetic materials [14]. Calculation of varying inductance with time is the drawback of this approach which leads to increase the investigation based on D-Q theory. This approach removes the effect of time varying as well as simulates the machines under different operating conditions. The D-Q method is used to model the motor where both stator current and magnetic flux has a constant magnitude and it is easy to track their reference values [15]. D-Q transformation reference theory has the advantages of reduced the number of parameters which reduce the complexity accompanied with the use of traditional methods to simulate the multi-phase machine [16]-[19].

Induction motors (I.Ms.) are used widely in industry for up to 10MW in size. During start-up, I.Ms. draw large current, produce high voltage, torque oscillation as well as generate harmonics. Various models are developed to study the steady state, transient, healthy and faulty operating conditions of I.Ms. [20]. Then models are tested to be reliable and accurate.

Usually, the characteristics of the three phase induction machine such as the current, induced voltage and linkage flux are described based on the differential equations in which coefficients are time varying (except the stand still condition of the rotor), the mathematical model of such characteristics is very complex due to the continuous changing of the current, induced voltage and linkage flux values as the electric circuit in relative motion. Therefore, for this type of machines to solve the equations that contain time depending quantities, a model based on mathematical transformations are usually utlized to decouple parameters by referring it to a common reference frame such as using Park and Clarke transformation methods [21]. The quantities of the three phase induction motor (IM) such as current, induced voltage and linkage flux are represented as two-phase, quadrature, balanced stationary system of variables (alpha-beta axes) and based on Clarke transformation method. The two-phase balanced stationary system of quantities of the current and voltage are then represented or converted to balanced two-phase orthogonal rotating reference system based on Park transformation method as shown in Figure 1 [21]. (α', β') represents the two-phase quadrature rotating system of the rotor. While (α, β) represents the two-phase quadrature system of stator. Where the rotor axes (α', β') rotates by speed (ωr) and by angle (θr) referring to the stator references frame. The synchronous frame (D-Q) axes of both stator and rotor rotates at speed (ωe) with shift angle (θe) referring to the stator reference frame. (θsl) is the angle between the synchronous frame and rotor frame [22].

The rest of this paper is orgnized as follows, Section 2 presents the model of 3-phase induction motor in abc and D-Q formulas. Section 3 provides the results of IM under different operating conditions. In sam section, a comparisions of the dynamic response for the two suggested IM models have been impementd. Finally, the conclusion and the most important differences between the two models is present in section 4.

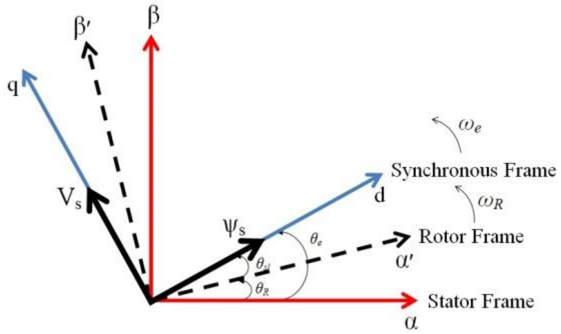


Figure 1. Stator field orientation (SFO) transformation reference frame

2. MODELING OF INDUCTION MOTOR

Based on Clarke transform, the 3-phase supply voltage of the I.Ms. is represented and transformed to (α, β) axis, as shown in Figure 1 and expressed in the (1)-(4) [23]:

$$V_a = V_{max} sin(wt) \tag{1}$$

$$V_b = V_{max} sin\left(wt - \frac{2\Pi}{3}\right) \tag{2}$$

$$V_c = V_{max} sin\left(wt + \frac{2\Pi}{3}\right) \tag{3}$$

$$\begin{bmatrix} andV_\alpha \\ andV_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} and1 & and\frac{1}{2} & and\frac{-1}{2} \\ and & & \\ and0 & and\frac{\sqrt{3}}{2} & and\frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} andV_a \\ andV_b \\ andV_c \end{bmatrix} \tag{4}$$

Where (V_a, V_b, V_c) represent the three phase voltages of the balanced system, (V_α, V_β) are the two-phase quadrating stationary balanced system.

Based on Park transformation method the two-phase stationary system (V_α, V_β) are transformed into two-phase rotating synchronous references frame as illustrate in Figure (2) and given by the (5), (6) [20], [23].

$$\begin{bmatrix} andV_d \\ andV_q \end{bmatrix} = \begin{bmatrix} cos\,\theta & sin\,\theta \\ -sin\,\theta & cos\,\theta \end{bmatrix} \begin{bmatrix} andV\alpha \\ andV\beta \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} andi_\alpha \\ andi_\beta \end{bmatrix} = \begin{bmatrix} cos\,\theta & -sin\,\theta \\ sin\,\theta & cos\,\theta \end{bmatrix} \begin{bmatrix} andi_d \\ andi_q \end{bmatrix} \tag{6}$$

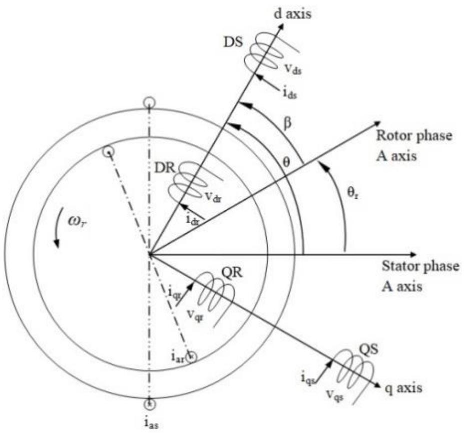


Figure 2. D-Q axes applied on a three phase IM

Figure 3 shows the general three windings model of the three phase cage IM. It is can be represented by set of (7)-(15) which express the electromagnetic coupling between stator and rotor [24]-[26].

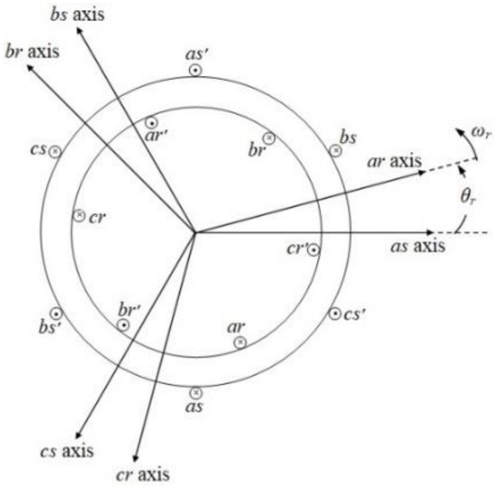


Figure 3. Three-phase component stator and rotor IM

$$v_{abcs} = R_s i_{abcs} + \frac{d\psi_{abcs}}{dt} \tag{7}$$

$$v_{abcr} = R_r i_{abcr} + \frac{d\psi_{abcr}}{dt} \tag{8}$$

Where (v_{abcs}, v_{abcr}, ψ_{abcs}, ψ_{abcr}, i_{abcs}, i_{abcr}, R_s, R_r) are the three phase voltages, linkage flux, current, phase resistance of the stator and rotor respectively.

$$\begin{bmatrix} and\psi_{abcs} \\ and\psi_{abcr} \end{bmatrix} \equiv \begin{bmatrix} andL_s & andL_{sr} \\ and(L_{sr})^T & andL_r \end{bmatrix} \begin{bmatrix} andi_{abcs} \\ andi_{abcr} \end{bmatrix} \tag{9}$$

$$L_s = \begin{bmatrix} L_{ss} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ss} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ss} \end{bmatrix} \tag{10}$$

$$L_r = \begin{bmatrix} L_{rr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & L_{rr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{rr} \end{bmatrix} \tag{11}$$

Where, $L_{ss} = L_{ls} + L_{ms}$, $L_{rr} = L_{lr} + L_{mr}$ are the self-inductance of the stator and rotor, (L_{ls}, L_{ms}, L_{1r}, L_{mr}) are the linkage and magnetizing inductance of stator and rotor winding respectively.

$$L_{sr} = L_{sr} \begin{bmatrix} \cos\phi & \cos(\phi + \frac{2pi}{3}) & \cos(\phi - \frac{2pi}{3}) \\ \cos(\phi - \frac{2pi}{3}) & \cos\phi & \cos(\phi + \frac{2pi}{3}) \\ \cos(\phi + \frac{2pi}{3}) & \cos(\phi - \frac{2pi}{3}) & \cos\phi \end{bmatrix} \tag{12}$$

$$L_{ms} = \frac{N_s}{N_r} L_{sr} \tag{13}$$

Where (L_{sr}, L_{mr}) are the mutual inductances between stator and rotor winding.

$$L'_{sr} = \frac{N_s}{N_r} L_{sr} = L_{ms} \begin{bmatrix} \cos\phi & \cos(\phi + \frac{2pi}{3}) & \cos(\phi - \frac{2pi}{3}) \\ \cos(\phi - \frac{pi}{3}) & \cos\phi & \cos(\phi + \frac{2pi}{3}) \\ \cos(\phi + \frac{pi}{3}) & \cos(\phi - \frac{2pi}{3}) & \cos\phi \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} andv_{abcs} \\ andv'_{abcr} \end{bmatrix} = \begin{bmatrix} R_s + \frac{dL_s}{dt} & \frac{dL'_{sr}}{dt} \\ \frac{d(L'_{sr})^T}{dt} & R'_r + \frac{dL'_r}{dt} \end{bmatrix} \begin{bmatrix} andi_{abcs} \\ andi'_{abcr} \end{bmatrix} \tag{15}$$

Where: (L'_{sr}) is the mutual inductance refer to stator side, (L'_r,R'_r) is the self-inductance and resistance of the rotor winding refer to stator side respectively. The electromagnetic torque in (N.m.) is described as shown in (16) and (17) respectively.

$$T_e = (\frac{p}{2})(i_{abcs})^T \frac{\partial}{\partial\theta_r} [L'_{sr}] i'_{abcr} \tag{16}$$

$$T_e = -(\frac{p}{2}) L_{ms} \{[i_{as}(i_{ar} - \frac{1}{2} i_{br} - \frac{1}{2} i_{cr}) + i_{bs}(i_{br} - \frac{1}{2} i_{ar} - \frac{1}{2} i_{cr}) + i_{cs}(i_{cr} - \frac{1}{2} i_{br} - \frac{1}{2} i_{ar})] \sin\phi + \frac{\sqrt{3}}{2} [i_{as}(i_{br} - i_{cr}) + i_{bs}(i_{cr} - i_{ar}) + i_{cs}(i_{ar} - i_{br})] \cos\phi\} \tag{17}$$

The rotating speed of the rotor (ω_r) and torque are rotated as shown in (18).

$$T_e = J(\frac{2}{p}) p\omega_r + T_L \tag{18}$$

Where (J) is the moment of inertia cofficient of the rotor (kg.m^2), T_L is the applied shaft torque of I.M. D-Q axes with zero sequence component is used to handle the unbalance voltage and current and to reverse park's transformation, by transform the convential ABC rotor parameters into D-Q axes. The linkage flux equations in terms of D-Q axes coils are given below [13]:

$$\frac{d\varphi_{qs}}{dt} = \omega[v_{qs} - \frac{\omega_e}{\omega_b} \varphi_{ds} + \frac{R_s}{X_{1s}} (\varphi_{mq} - \varphi_{qs})] \tag{19}$$

$$\frac{d\varphi_{ds}}{dt} = \omega \quad [v_{ds} + \frac{\omega_e}{\omega_b} \varphi_{qs} + \frac{R_s}{X_{1s}} (\varphi_{md} - \varphi_{ds})] \tag{20}$$

$$\frac{d\varphi_{qr}}{dt} = \omega[v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b} \varphi_{dr} + \frac{R_r}{X_{1r}} (\varphi_{mq} - \varphi_{qr})] \tag{21}$$

$$\frac{d\varphi_{dr}}{dt} = \omega[v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b} \varphi_{qr} + \frac{R_r}{X_{1r}} (\varphi_{md} - \varphi_{dr})] \tag{22}$$

$$\varphi_{mq} = x_{m1}[\frac{\varphi_{qs}}{x_{1s}} + \frac{\varphi_{qr}}{x_{1r}}] \tag{23}$$

$$\varphi_{md} = x_{m1}[\frac{\varphi_{ds}}{x_{1s}} + \frac{\varphi_{dr}}{x_{1r}}] \tag{24}$$

$$x_{m1} = \frac{1}{(\frac{1}{x_m} + \frac{1}{x_{1s}} + \frac{1}{x_{1r}})} \tag{25}$$

The (D-Q) axes values of the current are investigated as given in (26)-(29).

$$i_{qs} = \frac{1}{x_{1s}} (\varphi_{qs} - \varphi_{mq}) \tag{26}$$

$$i_{ds} = \frac{1}{x_{1s}} (\varphi_{ds} - \varphi_{md}) \tag{27}$$

$$i_{qr} = \frac{1}{x_{1r}} (\varphi_{qr} - \varphi_{mq}) \tag{28}$$

$$i_{dr} = \frac{1}{x_{1r}}(\varphi_{dr} - \varphi_{md}) \tag{29}$$

The value of the torque and rotor speed can be determined as follows:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \tag{30}$$

$$\omega_r = \int \frac{p}{2J}(T_e - T_L) \tag{31}$$

Where P represents number of poles;(ω_b) base speed. Since the rotor cage bars of the squirrel cage I.M. is shorted. The rotor voltages (v_{qr}, v_{dr}) are set to zero in the linkage flux equations.

3. SIMULATION RESULTS AND DISCUSSION

Figure 4 depicts the waveform of the electromagnetic torque (Te) generated based on ABC (or actual) transformation model, it is observed that a high oscillation with variation of the value of (Te) at the transient region till (time = 0.5 sec) thereafter, a steady state value can be achieved. The effect of load torque (T_L) on the rotation speed is illustrated in Figures 5 (a) and 5 (b), in another word, as the load torque increase the rotation speed of the I.M decrease to reach a minimum value of 1750r.p.m at maximum load torque of (12 N.m). Alternatively, the electromagnetic torque increases as shown in Figures 6 (a) and 6 (b) and Table 1 respectively.

Table 1. Relationship between speed, TL & Te of IM

Time (sec)	Total Speed	Load torque(N.m)	Developed torque (N.m)	Power (w)
0	1800	0	0.0001022	0
2	1783	4	3.984	744.5
4	1787	8	7.982	1496
6	1750	12	11.98	2198.9
8	1787	8	7.984	1496
10	1783	4	3.984	744.5
12	1800	0	0.0001022	0

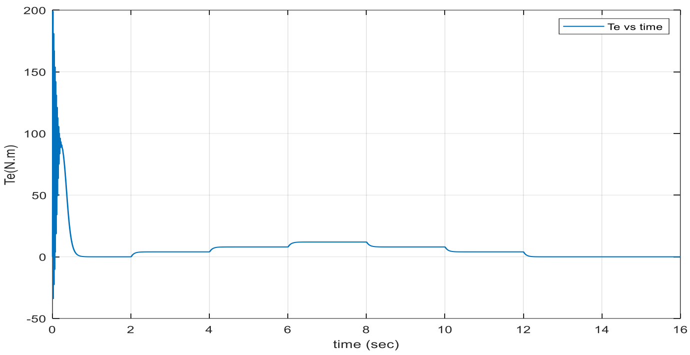
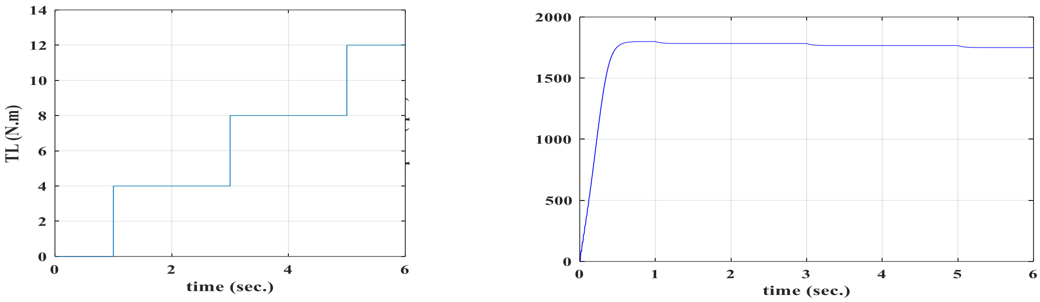
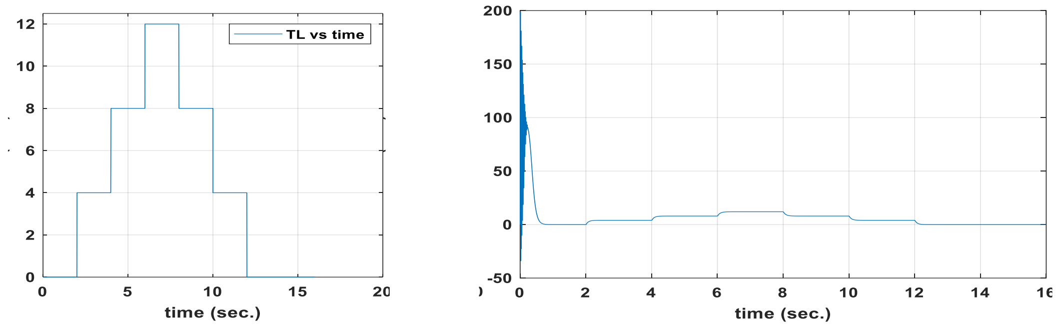


Figure 4. Electromagnetic torque based on actual transformation



(a) (b)

Figure 5. Rotating speed variation at different load condition, (a) applied load torque, (b) speed of motor



(a) (b)

Figure 5. Variation of electromagnetic torque at different load, (a) applied load torque, (b) deveopled torque of motor

Figure 7 compares the waveforms of the generated (or produced) torque based on ABC and D-Q axes transformation of machines models, at different operating condition. Due to the nature of D-Q model which considers the sinusoidal varying of the transformation matrix, the electromagnetic torque (T_e) based D-Q axis transformation has less transient time ending at about (0.25sec) then go to steady state region. Where the transient time of the (T_e) based on actual transformation model is more then (0.5sec). Therefore, the generated torque based on D-Q model.

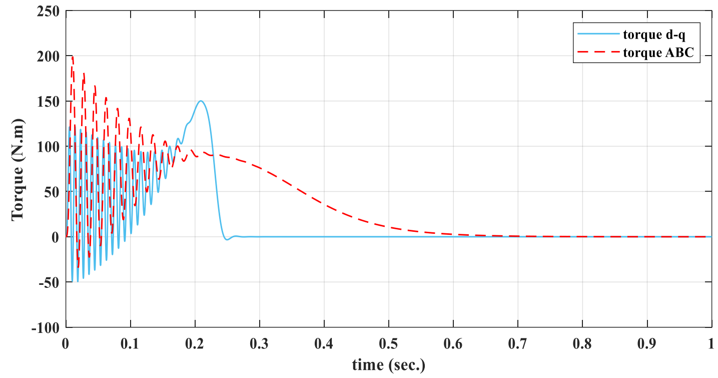


Figure 6. electromagnetic torque waveform (Te)

Figure 8 shows the variation of load torque at different rotation speed. It can be shown that (T_L) predicted based D-Q transformation model has low oscillation till 1000r.p.m. then increased as the rotation speed increase to arrive its maximum value at speed about 1500r.p.m. In contract the oscillation of the (T_L) predicted based on the actual transformation model is very high at the when the machine starts rotate till 1000r.p.m. and then reduced gradually till the rated speed 1800r.p.m. Comparing with ABC (actual) transformation model, a steady state rotation speed with short transient time can be achieved based on D-Q axis model as shown in Figure 9, in which a steady state rated speed of 1800r.p.m is obtained at simulation time of about (0.25 sec). Alternatively, a high transient time with more than (0.5 sec) is predicted at No-Load condition.

Referring to Figures 10 (a) and 10 (b), the waveform of the stator and rotor current as well as id and iq are illustrated. As mentioned above the D-Q axes transformation model plays an important role to get an accurate value of the current with transient time and oscillation. Resulting a high electromagnetic torque and then high output power as shown in Figures 11 (a) and 11 (b). The specifications of the proposed three phase induction motor are detailed in Table 2 and the adopted modeling steps can be stated as shown in Figure 12.

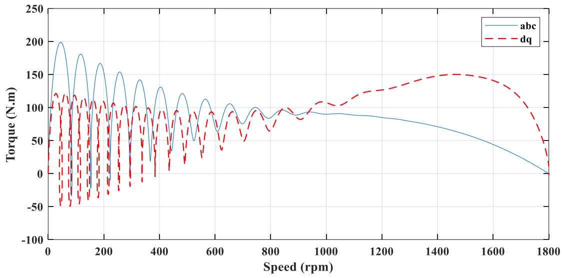


Figure 7. variation of load torque at different rotation speed

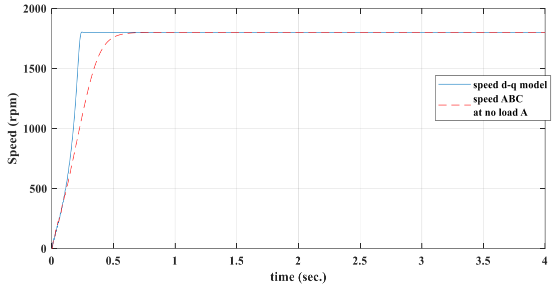
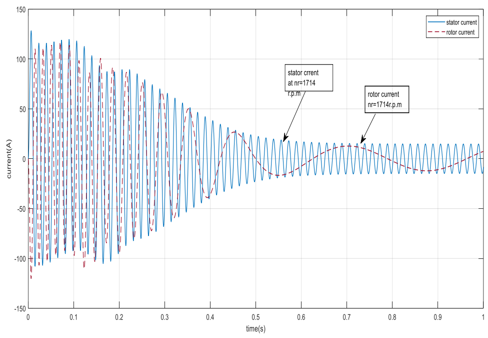
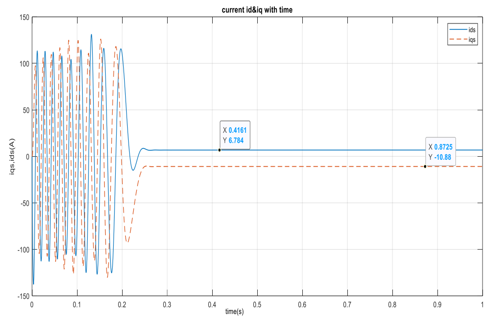


Figure 8. Rotation speed of IM at No-Load

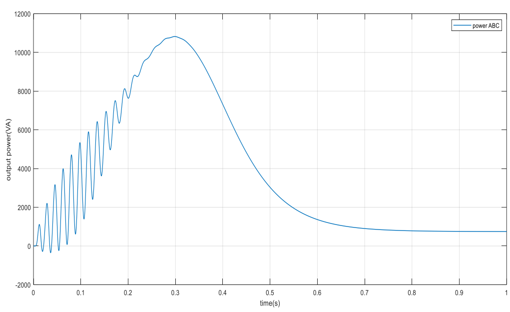


(a)

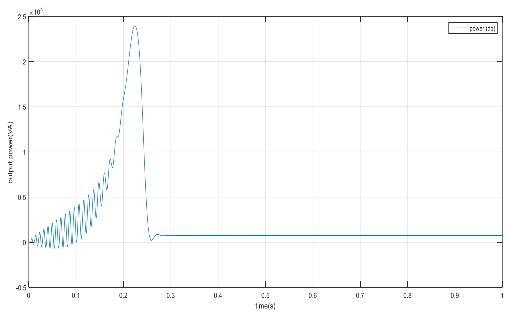


(b)

Figure 9. Stator and rotor current of IM at constant rotation speed, (a) based on conventional model, (b) based on D-Q model



(a)



(b)

Figure 10. Output power of IM, (a) based on conventional model, (b) based on D-Q model

Table 2. Specifications of the three phases IM

Variable	Speed (rpm)
Load voltage (VL)	220 V
Rated speed (r.p.m)	1710 r.p.m
No. Of poles (*P*)	4
Rated frequency (F)	60 Hz
Rated power (Horse power)	3 HP
Stator resistance (R_s)	0.435 Ω
Stator reactance (X_{ls})	0.754 Ω
Rotor resistance (R_r)	0.816 Ω
Rotor reactance (X_{lr})	0.754 Ω
Magnetizing reactance (X_m)	26.13 Ω
Inertia of the rotor (*J*)	0.89 kg.m^2

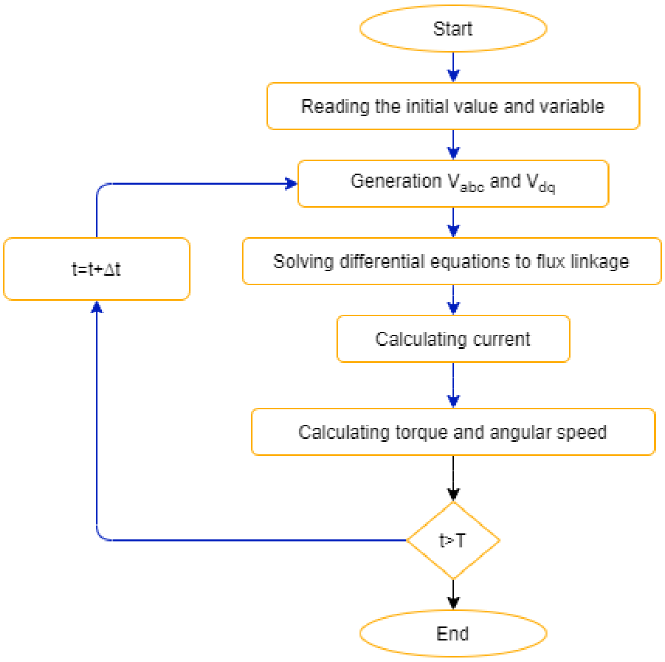


Figure 12. Flow chart for the simulation model of IM

4. CONCLUSION

In current work, an in step by step manner to built a dynamic modeling of three-phase induction motor using MATLAB/Simulink are obtained. The Two models are applied to induction motor in this research a construction of two models of a 3-Φ induction motor based on the two analytical approaches and compare them to clarify the difference in their dynamic performance. Two analytical approaches (D-Q axes and Actual approaches) of a three-phases induction motor are represented and investigated. Comparing to D-Q axes approaches, the Actual model is more convenient to be used in normal and abnormal conditions, such as the unsymmetrical supply voltage. In contrast the D-Q axes model is suitable in normal conditions and is simpler and faster, than actual model to be used as in on Line. The two stimulated machines show adequate response in terms of dyamic parameters characteristics (torque and speed). Both methods provide the altered results. The obtained results prove that MATLAB/Simulink is dependable and a sophisticated approach can be utilized to analyze and predict the behavior of I.Ms. Through this work, a three-phase induction motors modeled using conventional and D-Q methods. Both are simulated to monitor the dynamic behavior. Based on the obtained results, it can be seen that there is a divergence in the performance of the variables of both models. Considering the torque obtained from a D-Q model, it is possible to notice that there is a variation in the value of the torque associated with change of Id and Iq currents. However, a similar variation in the rotor speed compared with the conventional model. Due to nature of D-Q currents, it is difficult to observe and recognize the behavior of the electric machine during the sudden vary of these currents. Where the main aim on which the D-Q theory is built by obtaining constant-value currents, and thus time-dependent inductors and torque.

In addition, there is a difficulty in identifying cases of unbalance condition that occur through the operation of the electrical machine when it subjects to short circuit in the stator and the rotor winding. Among the faults that occur it has been found that 40% of the electrical machines faults is the air gap eccentricity, which is discovered by the harmonics that are injected into the stator current. Thus, due to the fact that one of the conditions for modeling the electric machines using the D-Q method is that the air gap around of the rotor part is uniform, this model cannot be used to detect this type of faults. Due to the continuous development arises in power electronics drives systems that are widely used to control the speed and torque of electrical machines leads to an increased need for introducing model capable of taking into consideration the effect of harmonics associated with the voltage supplied by those types of electric power sources. Due to badly effects of these harmonics, the dynamic parameters of the electric machines vary from its actual values and produce incorrect performance. Since the theory of the D-Q model depends mainly on the consideration of sinusoidal distribution of winding of the stator part., Therefore, it will not be appropriate to check the performance of the motors for non- sinusoidal power supplies. Based on the above mentioned, it can be concluded that the modeling of electrical machines based on D-Q theory is suitable for machines operates in an ideal operation condition. As well as, it cannot be used for the identifying inaccurately the behavior of electrical machines under unbalance and imperfect operating condition conditions such as the state of negligence of the iron core characteristics within the magnetic linear region for the materials of machines parts.

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