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# Dynamic Simulation of Three-Phase Induction Machines Based on Reduced Order Model for Power Systems Analysis

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**ABSTRACT**

Induction machines are a crucial type of electrical equipment utilized as motors in various industries and single-phase forms in household applications. They make up more than 80% of the industrial motors used today. This paper presents a dynamic simulation of three-phase induction machines based on the (d-q) model, providing a clear and easy-to-understand explanation of the behavior of the induction motor in the synchronous reference frame. The simulation is implemented using SIMULINK/MATLAB software, and full-order model analysis is conducted for transient analysis. However, modeling induction machines as part of power system analysis can be done with a less detailed model than the full-order one. In this paper, a reduced-order model is employed to simulate the induction motor using MATLAB/SIMULINK. The results of the reduced-order system and the full-order framework are compared to investigate the model's limits, and the computational benefits of saving time during large power system simulations justify the relative decrease in accuracy. The use of a reduced-order model results in a significant reduction in computation time when simulating large and very large-scale power systems, with a much higher accuracy in transient analysis than the conventional steady-state model.

## 1. Introduction

The Three phase induction machines are asynchronous speed machines; Compared to machines of similar size made of synchronous and DC power machines, they are less expensive. Their size ranges from a fractional hp to 10,000 horsepower or more [1, 2].

Analysis and study of induction motors in power systems are receiving great interest due to their vast range of applications, almost 80% of all electrical loads [3, 4, 5].

Over the past years, the construction of simplified models has received a lot of attention, particularly for the aim of researching and computing electrical machines' dynamic behavior under large excursions in one or more of the machines' variables [2, 3, 6, 7, 8].

Park, R. H. (1929) developed a change of variables, that effectively substituted the variables (currents; voltages; then flux linkages) related to variables associated with fictitious windings rotating with the rotor in the stator windings of synchronous machines [1, 9]. Park effectively converted or mentioned the stator variables toward a rotor-fixed reference frame. Electric circuits about motion besides electric circuits through changing magnetic reluctance both cause time-changing inductances, but Park's transformation; which reformed the electrical machines study, has the special ability to remove all of these inductances as of the

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voltage equations of the synchronous machine [2, 5, 10, 16, 18].

For induction machines simulation inside power systems, reduced order models are vastly used, to simplify the calculations and times consumed to analyze and study the power system. At the voltage equations of total power system components linked to the stator and at the stator voltage machines equations, it is typical toward negligence electric transients (transformers, transmission lines, etc.). The system's 50-60 Hz component's static representation allowed for a significant reduction in the number of calculations needed. [11, 12, 13, 16]. In this study, a dynamic simulation for a three-phase induction motor is these simulations are based on a reduced-order model equation. The results are compared and verified with those from the full-order model [1, 2, 14].

## 2. Induction motor modelling

The induction motor's voltage and torque formulae vary with time. By eliminating any time-changing inductances caused by electric circuits in comparative motion, it is likely to make simpler these equations by changing the variables.

Research design, research methods (in the style of algorithms, pseudocode, or some other), how and when to test, and data collection are all contained in the research methodology. An induction machine analogous circuit is illustrated in Figure 1 [1-3]. The following is flux linkage equations linked to the circuit can be found as follows:

$$\frac{d\Psi_{qs}}{dt} = \omega_b \left[V_{qs} - \frac{\omega_e}{\omega_b}\Psi_{ds} + \frac{R_s}{x_{ls}}\left(\Psi_{mq} - \Psi_{qs}\right)\right] \quad (1)$$

$$\frac{d\Psi_{ds}}{dt} = \omega_b \left[V_{ds} + \frac{\omega_e}{\omega_b}\Psi_{qs} + \frac{R_s}{x_{ls}}\left(\Psi_{md} - \Psi_{ds}\right)\right] \quad (2)$$

$$\frac{d\Psi_{qr}}{dt} = \omega_b \left[V_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}\Psi_{dr} + \frac{R_r}{x_{lr}}\left(\Psi_{mq} - \Psi_{qr}\right)\right] \quad (3)$$

$$\frac{d\Psi_{dr}}{dt} = \omega_b \left[V_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b}\Psi_{qr} + \frac{R_r}{x_{lr}}\left(\Psi_{md} - \Psi_{dr}\right)\right] \quad (4)$$

Where:

$$\Psi_{mq} = X_{ml}\left[\frac{\Psi_{qs}}{X_{ls}} + \frac{\Psi_{qr}}{X_{lr}}\right] \quad (5)$$

$$\Psi_{md} = X_{ml}\left[\frac{\Psi_{ds}}{X_{ls}} + \frac{\Psi_{dr}}{X_{lr}}\right] \quad (6)$$

$$X_{ml} = \frac{1}{\left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right)} \quad (7)$$

Finding the currents by substituting the above flux linkage values:

$$i_{qs} = \frac{1}{x_{ls}}\left(\Psi_{qs} - \Psi_{mq}\right) \quad (8)$$

$$i_{ds} = \frac{1}{x_{ls}}\left(\Psi_{ds} - \Psi_{md}\right) \quad (9)$$

$$i_{qr} = \frac{1}{x_{lr}}\left(\Psi_{qr} - \Psi_{mq}\right) \quad (10)$$

$$i_{dr} = \frac{1}{x_{ls}}\left(\Psi_{qs} - \Psi_{mq}\right) \quad (11)$$

The torque and rotor speed can be reached from the above equations to be:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{1}{\omega_b}\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \quad (12)$$

$$\omega_r = \int \frac{P}{2J}\left(T_e - T_L\right) \quad (13)$$

Where P; poles number; J; moment of inertia ($\mathrm{Kg.m^2}$)

$$v_{qs} = r_s i_{qs} + \frac{\omega_e}{\omega_b}\psi_{ds} \quad (14)$$

$$v_{ds} = r_s i_{ds} - \frac{\omega_e}{\omega_b}\psi_{qs} \quad (15)$$

$$v'_{qr} = r'_r i'_{qr} + \left(\frac{\omega - \omega_r}{\omega_b}\right)\psi'_{dr} + \frac{p}{\omega_b}\psi'_{qr} \quad (16)$$

$$v'_{dr} = r'_r i'_{dr} + \left(\frac{\omega - \omega_r}{\omega_b}\right)\psi'_{qr} + \frac{p}{\omega_b}\psi'_{dr} \quad (17)$$

Where

$$\psi_{qs} = X_{ls} i_{qs} + X_M\left(i_{qs} + i'_{qr}\right) \quad (18)$$

$$\psi_{ds} = X_{ls} i_{ds} + X_M\left(i_{ds} + i'_{dr}\right) \quad (19)$$

$$\psi'_{qr} = X'_{lr} i'_{qr} + X_M\left(i_{qs} + i'_{qr}\right) \quad (20)$$

$$\psi'_{dr} = X_{lr} i_{dr} + X_M\left(i_{ds} + i'_{dr}\right) \quad (21)$$

In the rotor voltage equation, the reference frame speed is visible in the speed voltages, but it is not present in the stator voltage equations. Replacing the flux linkages in 14 - 17 with 18-21. With all derivatives in the and eliminated, while setting equal to in the and equations. According to the previous assumptions the following matrix resulted [12, 13].

$$\begin{pmatrix} v_{qs} \\ v_{ds} \\ v'_{qr} \\ v'_{dr} \end{pmatrix} = \begin{pmatrix} r_s & \frac{\omega_e}{\omega_b} X_{ss} & 0 & \frac{\omega_e}{\omega_b} X_M \\ -\frac{\omega_e}{\omega_b} X_{ss} & r_s & -\frac{\omega_e}{\omega_b} X_M & 0 \\ \frac{p}{\omega_b} X_M & \left(\frac{\omega-\omega_r}{\omega_b}\right) X_M & r'_r + \frac{p}{\omega_b} X'_{rr} & \frac{\omega-\omega_r}{\omega_b} X'_{rr} \\ -\frac{\omega-\omega_r}{\omega_b} X_M & \frac{p}{\omega_b} X_M & -\frac{\omega-\omega_r}{\omega_b} X'_{rr} & r'_r + \frac{p}{\omega_b} X'_{rr} \end{pmatrix} \begin{pmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{pmatrix} \tag{22}$$

$$\begin{pmatrix} v_{qs} \\ v_{ds} \\ v'_{qr} \\ v'_{dr} \end{pmatrix} = \begin{pmatrix} \frac{r_s X'_{rr}}{D} & \frac{\omega_e}{\omega_b} & -\frac{r_s X_M}{D} & 0 \\ -\frac{\omega_e}{\omega_b} & \frac{r_s X'_{rr}}{D} & 0 & -\frac{r_s X_M}{D} \\ -\frac{r'_r X_M}{D} & 0 & \frac{r'_r X_{ss}}{D} + \frac{p}{\omega_b} & \frac{\omega-\omega_r}{\omega_b} \\ 0 & -\frac{r'_r X_M}{D} & -\frac{\omega\omega_r}{\omega_b} & \frac{r'_r X_{ss}}{D} + \frac{p}{\omega_b} \end{pmatrix} \begin{pmatrix} \Psi_{qs} \\ \Psi_{ds} \\ \Psi'_{qr} \\ \Psi'_{dr} \end{pmatrix} \tag{23}$$

Where $D = X_{ss} X'_{rr} - X_M^2$ (24)

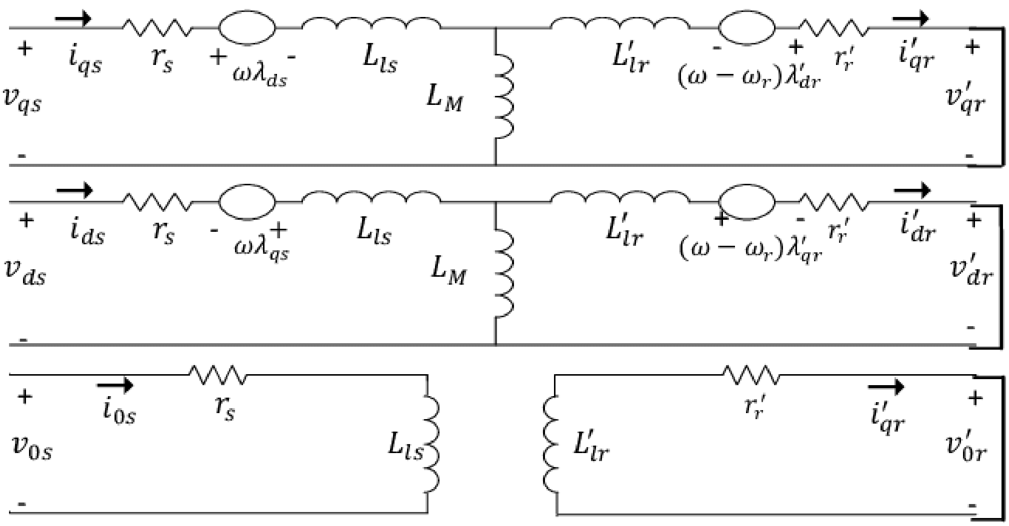


**Figure 1.** dq0 model for a 3-phase squirrel cage induction machine

## 3. Results and discussion

Figures 2a and 2b demonstrate the use of MATLAB/SIMULINK to build a simulation of a three-phase induction motor. Table 1 provides the parameters for a 500-horsepower 3-phase induction motor, as described in reference [1]. The simulation results include both reduced and full-order models for both free acceleration and loaded modes. The full-order MATLAB model has previously been demonstrated in reference [14], and its performance curves have been verified in references [1,2].

**Table 1:** Parameters of 500 hp 3-phase induction machine

| hp | volts | rpm | $T_B(N.m)$ | $I_B amp$ | $r_s$(ohms) | $X_{(ls)}$(ohms) | $X_M$(ohms) | $X'_{(lr)}$(ohms) | $r'_r$(ohms) | $J(kg.m^2)$ | f(Hz) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 500 | 2300 | 1773 | 1980 | 93.6 | 0.262 | 1.206 | 54.02 | 1.206 | 0.187 | 11.06 | 60 |

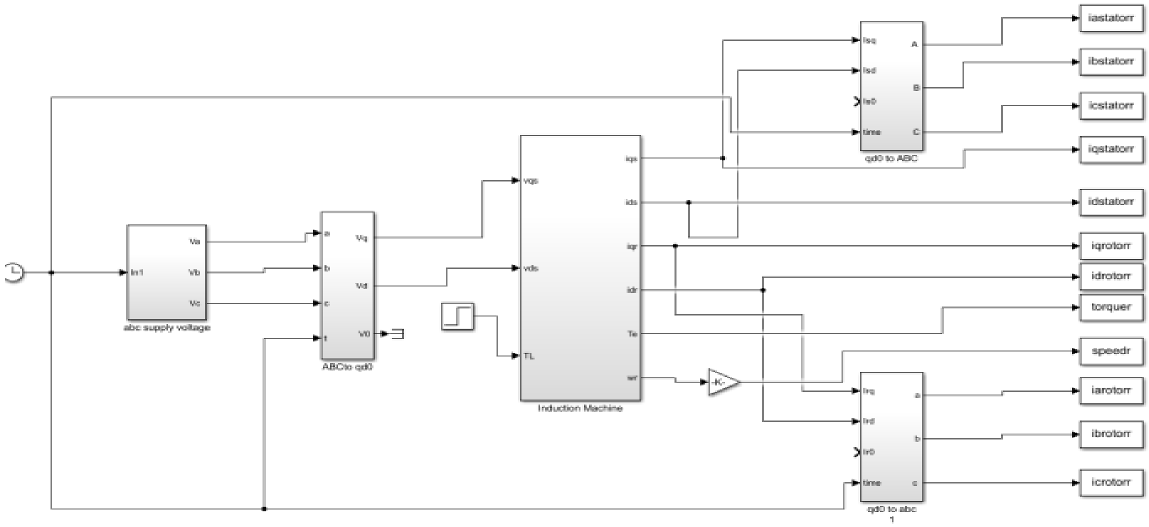


**Figure 2a**. The implementation of three phase induction motor simulation

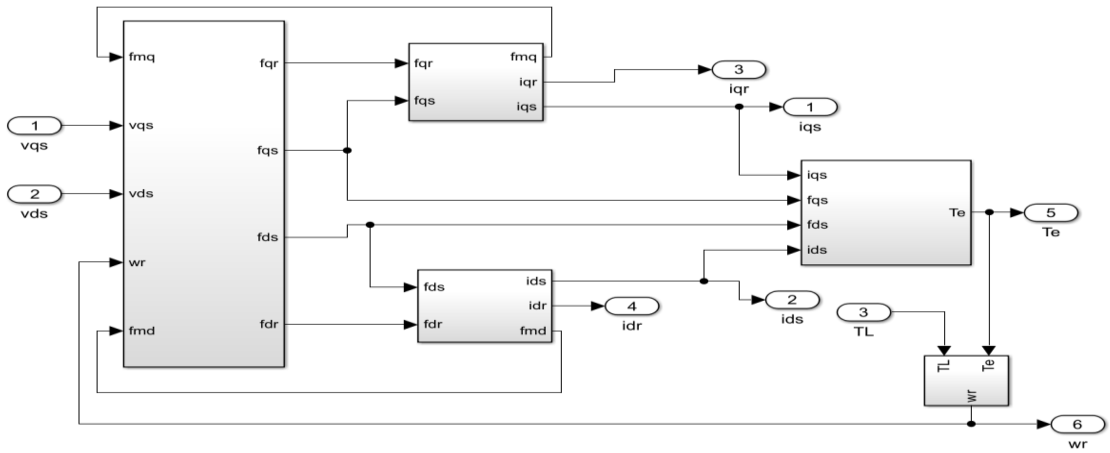


**Figure 2b**. part of the blocks required to implement the simulation in the reduced order model

This study focuses on the three-phase 500-horsepower induction motor and its reduced-order model. The results of the reduced order model are compared with those of the full order model based on the work presented in references [1, 14]. The first set of results compares the machine under free acceleration conditions, while the second set of results considers the machine loaded with 500 N.m. The machine's parameters are shown in Table1.

During free acceleration, Figure 3 displays the currents in the quadrature and direct axis of the machine, including stator and rotor currents. Although the reduced model shows some deviation during the transient period, it remains more accurate than the steady-state model. For an unloaded machine, Figure 4 represents torque and speed versus time, while Figure 5 shows the same for a loaded device. The results from the reduced order model are comparable to those from the full order model, with the difference mainly occurring during the transient period.

Figure 6 shows the torque versus speed in free acceleration mode. It should be noted that the main differences between the reduced and full-order models occur during the concise period of the transient, rather than during steady-state operation.

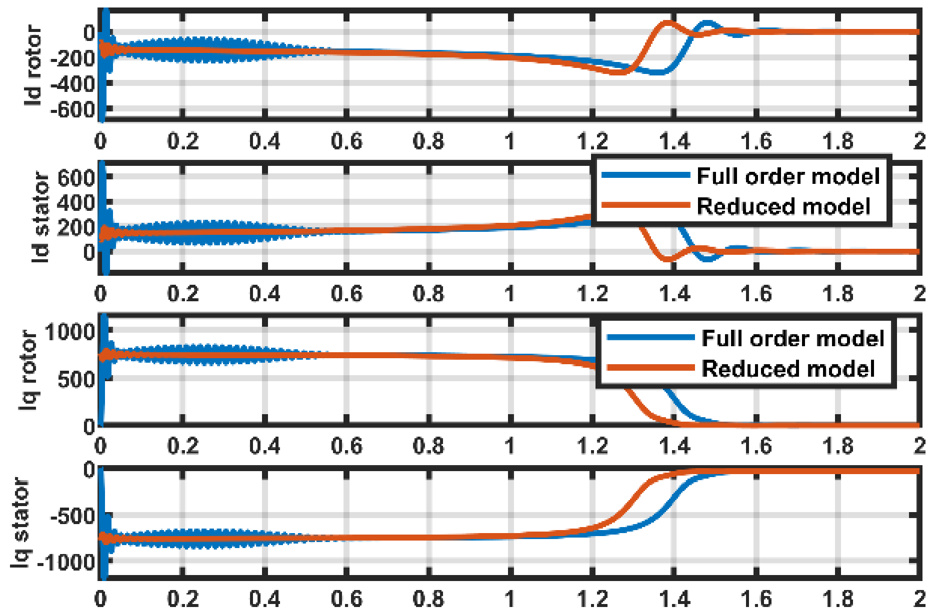


**Figure 3.** Stator and rotor currents at the machine through free acceleration

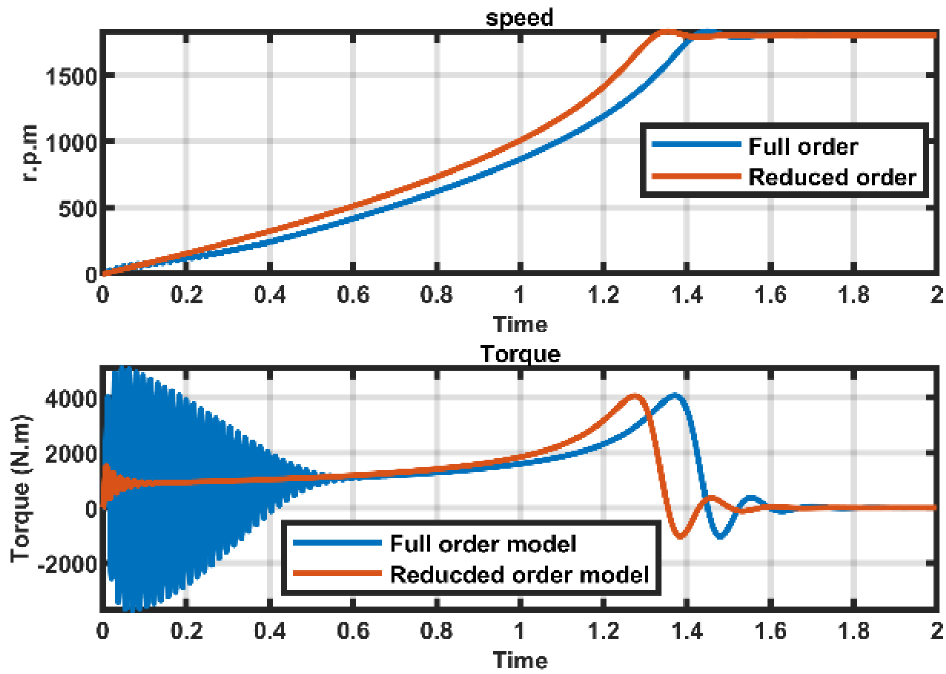


**Figure 4.** Speed vs. Time, Torque vs. Time for the unloaded machine.

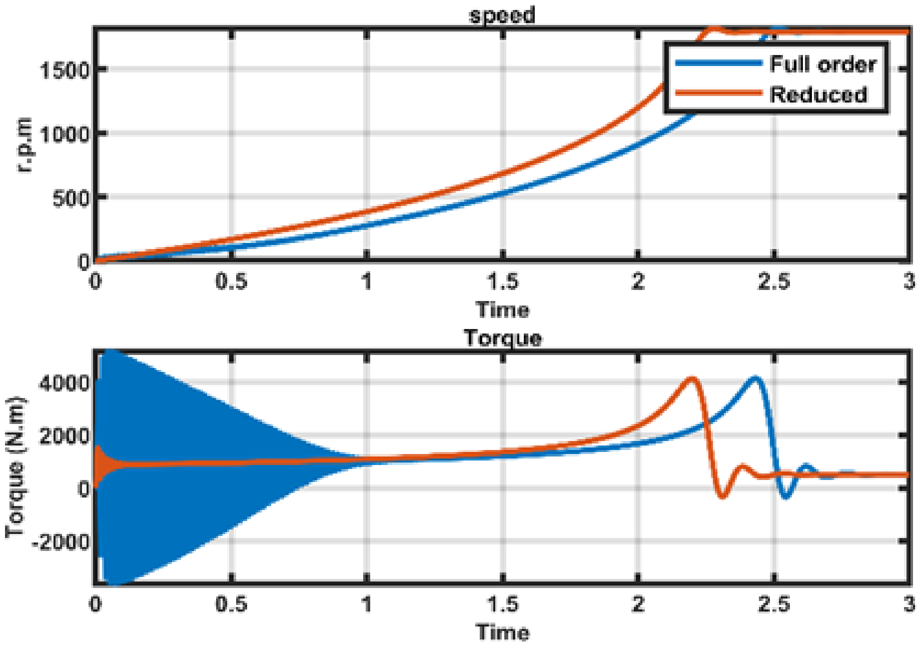


**Figure 5.** Speed vs. Time, Torque vs. Time for the loaded motor

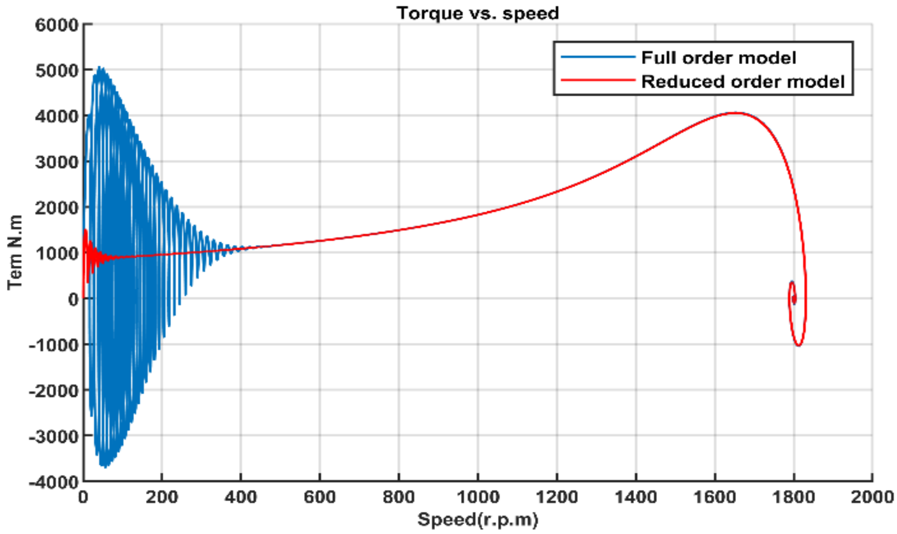


**Figure 6.** Torque vs. speed

## 4. Conclusions

The utilization of the theory of reference frames has proven to be an effective method for analysing the performance of induction electrical machines. This paper presents an implementation and dynamic modelling of a three-phase induction motor using Matlab/Simulink, comparing full order and reduced order models. The results demonstrate that the reduced order model yields satisfactory outcomes, particularly when utilized as a component of larger power system simulation studies. The non-linear form of the reduced order model is more precise and efficient than the linearized steady-state model of the IM. The transient response of the reduced order model is comparable to that of the full order model. It is important to note that the use of the reduced order model leads to significant reduction in computation time, which is highly advantageous in simulating large and very large-scale power systems. Furthermore, this approach provides greater accuracy in transient period analysis compared to conventional steady-state models.

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## List of abbreviation

| | |
|---|---|
| $\Psi_{qs}$ | Flux linkage of the stator in q − axis. |
| $\Psi_{ds}$ | Flux linkage of the stator in d − axis. |
| $\Psi_{qr}$. | Flux linkage of the rotor in q − axis. |
| $\Psi_{dr}$. | Flux linkage of the rotor in d − axis. |
| $\Psi_{mq}$ | Mutual flux linkage in q − axis |
| $X_{ls}$ | Leakage stator reactance. |
| $X_{lr}$ | Leakage rotor reactance |
| $X_{ml}$. | Mutual leakage reactance. |
| $i$ | Current |

| | |
|---|---|
| $\omega_r$ | Rotor speed in rad/sec |
| $\omega_b$ | Speed base value in rad/sec |
| $T_e$ | Electromagnetic torque |
| $T_L$ | Load torque. |
| $v_{qs}$ | Applied voltage in q axis on stator. |
| $v'_{qr}$ | Applied voltage on the rotor in q-axis refferred to stator side. |
| P | Number of poles |
| $p$ | The operator *d/dt* |