

# Dynamic modeling and analysis of re-switching of an induction motor running at full load Condition

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## Article info

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## Abstract

The paper is about the study of the re-switching characteristic of an induction motor. The aim of this research is to analyze the re-switching characteristics of an induction motor and investigate the transient phenomena that occur during the switching process. The motivation behind this research is to understand the factors that influence re-switching and how it can be optimized to avoid disconnection of the machine from the power supply. To achieve this goal, the researchers performed simulations of the machine start-up and calculated various parameters such as initial torque values, steady-state values, speed vs time graph, stator and rotor flux details, and stator and rotor current details. The researchers then compared these parameters with re-switching simulated parameters of induction motor and observed transients in the re-switching case. The methods used in this study involved simulating re-switching in a re-connection situation and analyzing the resulting data using graphs and tables. The study found that different parameters influence the re-switching process and that quick re-switching is critical to prevent the machine disconnection.

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## 1. Introduction

The torque switching of the machine has some oscillations at the start. It is found during its starting which is often found as a negative cosine value. The value reaches in steady-state condition later. During re-switching the transient phenomenon is found different. Some values are found to remain in various cases for re-switching condition (Barrero & Duran, 2015). Hence, prompt re-switching is vital to keep the stability of the system (Sulligoi, Tessarolo, Benucci, Trapani, Baret, & Luise, 2013). In this paper, firstly the

steady-state values for a re-switching of the induction motor are calculated. The detailed equations and torque values with detailed analysis are also enclosed hereby.

The simulation results showed that during re-switching of an induction motor, the torque undergoes some oscillations before reaching steady-state. The transient phenomena during re-switching were found to be different, with the resultant values not dying out, while steady-state conditions had some values as well.

The analysis of the various parameters, including initial torque values, steady-state values, speed vs. time graph, stator and rotor flux details, and stator and rotor current details, indicated that quick re-switching is crucial to prevent disconnection of the machine from the power supply.

Re-switching in induction motors has been a topic of interest in recent research. The recent trend shows the re-switching characteristics of induction motors through simulation and analysis. Re-switching cases in induction motors, highlighting its significance in machine performance are investigated in recent years. Tang, Yang, Blaabjerg, Chen, Diao, & Liu, (2018) investigated the re-switching characteristics of an induction motor under different loads. Finally, Suriyaarachchi, Annakkage, Karawita, and Jacobson, (2012). provided a comprehensive analysis of electric motor drives, which includes modeling and control of induction motors. These studies offer insights into the behavior of induction motors during re-switching, which can help in optimizing machine performance and avoiding disconnection from the power supply.

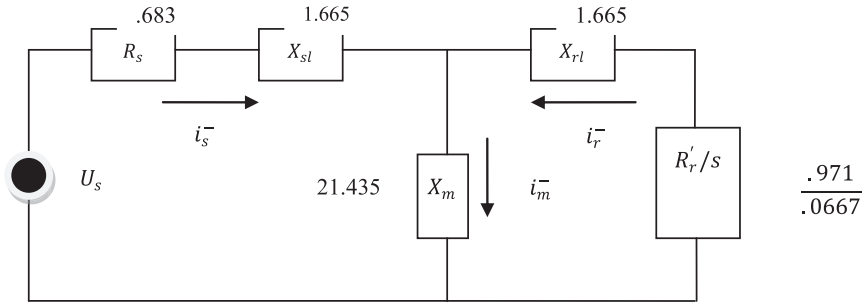
The knowledge gap regarding the dynamic modeling and analysis of re-switching of an induction motor running at full load condition refers to the lack of comprehensive research and understanding in this specific area are discussed in Branco, and Gopakumar (2016), Gao, Wang, and Tang (2019) and Ojo, and Elbuluk (2018). While there is a significant body of literature available on the steady-state analysis and performance of induction motors, there is limited information on the transient behavior and effects of re-switching in motors operating at full load. This knowledge gap hampers the ability to accurately predict and control the motor's behavior during re-switching events, which can lead to operational issues and potential damage. Bridging this gap would provide valuable insights into the dynamic characteristics of induction motors and aid in the development of more effective control strategies.

In conclusion, this study provides valuable insights into the re-switching characteristics of induction motors, which can help in optimizing the re-switching process to ensure reliable machine operation. The findings of

this research can be applied in various industries where induction motors are widely used, including the manufacturing and automotive sectors.

**2. Determination of steady-state values**

The motor to study is the 4-pole induction motor. The equivalent circuit model is given below,



**Figure 1**  
Equivalent circuit model

The following parameters are used for the calculation of steady-state values:

$$u_{sd} = u^{\wedge} = \sqrt{\frac{2}{3}} \cdot 230 = 187.7942 V, u_{sq} = 0 \dots\dots\dots 1$$

Moment of inertia,  $J = 0.04 \text{ kgm}^2$ , slip =  $s = 0.0667$  (close to rated load)

The parameters to calculate are  $i_{sd}, i_{sq}, i_{rd}, i_{rq}, \Psi_{sd}, \Psi_{sq}, \Psi_{rd}, \Psi_{rq}, T$  and  $w_m$ . First  $w_m$  is calculated using the formula

$$s = \frac{w_s - w_m}{w_s}, w_m = w_s - s w_s, \text{ where } w_s = \frac{2 \cdot w_1}{p} = \frac{4 \cdot \pi \cdot f}{p} \dots\dots\dots 2$$

Here  $p=4$  is the number of poles and  $f=50$  Hz is the frequency. Using the formula gives the following value,  $w_m = 146.6024 \text{ rad/s}$ . Now stator current is calculated by solving an equivalent circuit model. First  $\frac{R_r'}{s}$  is taken in series with rotor leakage reactance  $X_{rl}$  and their combination is taken in parallel with magnetizing reactance  $X_m$ . The resultant is then added in series with stator resistance  $R_s$  and stator leakage reactance  $X_{sl}$ . This overall gives the equivalent impedance of the model. Now the stator current is calculated by dividing voltage by impedance i.e.,  $\frac{u^{\wedge}}{Z}$ . By separating real and imaginary parts of stator current gives  $i_{sd} = 10.5546 \text{ A}$  and  $i_{sq} = -9.6902 \text{ A}$ . The rotor current is calculated by applying the current divider on the equivalent circuit model i.e.

$$i_r = \frac{-j X_m \cdot i_s}{\frac{R_r'}{s} + j X_{rl} + j X_m} \dots\dots\dots 3$$

The minus sign is used because the assumed direction of  $i$  is opposite to the direction given in the model. Separating real and imaginary parts gives

$$i_{rd} = -11.0657 A, \quad i_{rq} = 2.0181 A$$

Stator and rotor leakage inductance and magnetizing inductance are calculated by dividing their respective reactance's by  $\omega_1$  i.e.,  $\frac{X}{\omega_1}$ . Then the stator and rotor inductance are calculated as (Masadeh, Mohammad, & Pragasen, 2019)

$$L_s = L_m + L_{sl}, \quad L_r = L_m + L_{rl} \quad \dots\dots\dots 4$$

Now fluxes are calculated by using the following relations,

$$\begin{aligned} \Psi_{sd} &= L_s * i_{sd} + L_m * i_{rd} = 0.0211 \\ \Psi_{sq} &= L_s * i_{sq} + L_m * i_{rq} = -0.5748 \\ \Psi_{rd} &= L_r * i_{rd} + L_m * i_{sd} = -0.0935 \\ \Psi_{rq} &= L_r * i_{rq} + L_m * i_{sq} = -0.5128 \end{aligned}$$

Now finally torque is calculated by using

$$\begin{aligned} T &= \frac{3}{2} * \frac{p}{2} * [\Psi_{sd} * i_{sq} - \Psi_{sq} * i_{sd}] \quad \dots\dots\dots 5 \\ T &= 17.5886 N.m \end{aligned}$$

### 3. Machine start-up details

In this task machine start up is simulated. To simulate the machine these differential equations need to be solved so these equations 6 and 8 are implemented in MATLAB using ODE45 solver which is developed to solve differential equations.

ODE45 is a powerful numerical integration tool commonly used in dynamic modeling and analysis of complex systems, including induction motors operating under various conditions. In the context of studying the re-switching phenomenon in an induction motor running at full load condition, ODE45 can be employed to solve the system of ordinary differential equations (ODEs) that govern the motor's dynamic behavior. By defining the appropriate ODEs that describe the motor's electrical and mechanical characteristics, along with the input voltages and currents during re-switching events, ODE45 can simulate and analyze the motor's transient response. This enables researchers and engineers to examine critical parameters such as voltage and current waveforms, torque fluctuations, and stability characteristics, providing valuable insights into the motor's performance under re-switching conditions. ODE45 having the format shown below,

$$[time,Y] = ode45('fluxx',TSPAN,Y0)$$

[time,Y] this is the output matrix first element is time and second one is the

flux in our case. 'fluxx' this is the name of the function where differential equation are made while in our case, we solve by creating matrices as mentioned above. TSPAN this indicates the initial and final time during which differential equations are solved like in section 3 initial time was 0 sec and final time where steady-state values are achieved was 0.5 sec. Y0 a matrix containing initial values varies from case to case.

$$\text{function } dy = \text{fluxx}(t,y)$$

Fluxes in d q direction, current in d q direction and mechanical speed are simulated and are plotted against time (Ooshima, Kobayashi, & Narita, 2015) Initial values of fluxes and speed are taken zero (Duran, González-Prieto, González-Prieto, & Barrero, 2017). Load torque varies quadratically with speed and the constant is calculated by using the following relation.

$$\frac{d}{dt} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \\ w_m \end{bmatrix} = \begin{bmatrix} 0 & w_1 & 0 & 0 & 0 \\ -w_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_1 - w_r & 0 \\ 0 & 0 & -w_1 + w_r & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \\ w_m \end{bmatrix} + \begin{bmatrix} u_{sd} \\ u_{sq} \\ u_{rd} \\ u_{rq} \\ 0 \end{bmatrix} - \begin{bmatrix} R_s \cdot i_{sd} \\ R_s \cdot i_{sq} \\ R_s \cdot i_{rd} \\ R_s \cdot i_{rq} \\ -(T - T_L) / J_t \end{bmatrix} \dots\dots\dots 6$$

$$w_r = w_m \cdot \frac{P}{2} K = \frac{T_{rated}}{(w_m)^2}$$

The first matrix on the right-hand side is named A matrix, the flux matrix is named y, the voltage matrix is named as B, and the last matrix containing products of currents and constant stator resistance is named C matrix. The torque relation is in the last row of the C matrix. The left hand side matrix is named as dy. In the voltage matrix only stator voltage in d direction has a value that is equal to the supply value (Severson, Nilssen, Undeland, & Mohan, 2017).

$$d_y = (A * Y) + B - C \dots\dots\dots 7$$

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} * \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \dots\dots\dots 8$$

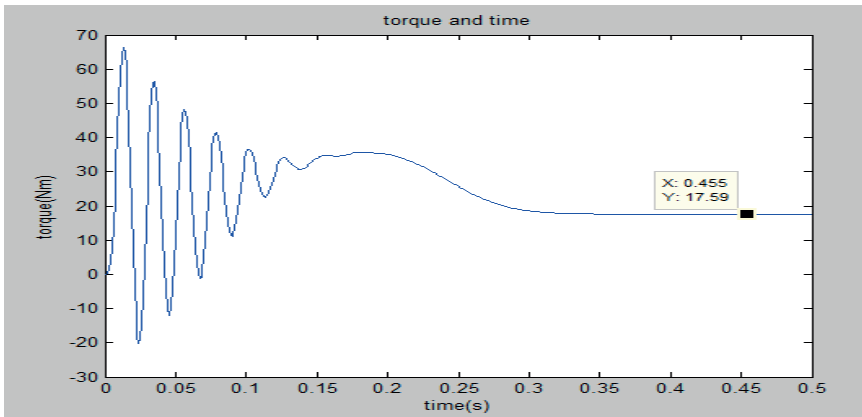
Taking the inverse of the inductance matrix and multiplying it with the flux matrix in **equation 8** the currents are calculated. These currents are then used in **equation 6**

The first-order differential equation is solved in MATLAB using an ODE45 solver (Edrah, Lo, & Anaya-Lara, 2015). The final torque and

currents relation is calculated by using the final results of the ODE45 solver and using the following relation,

$$T = \frac{3}{2} * \frac{p}{2} * [\Psi_{sd} * i_{sq} - \Psi_{sq} * i_{sd}] \dots\dots\dots 9$$

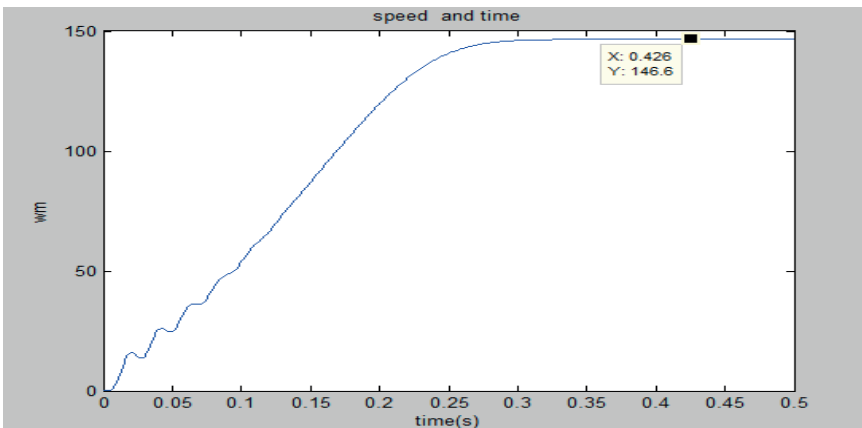
The final value of torque in steady-state is given in Figure 2.



**Figure 2**  
*Torque vs Time*

In equation 3  $\Psi_{sd}, i_{sq}, \Psi_{sq}$  and  $i_{sd}$  are not steady-state values, they are continuously varying values with time obtained by solving differential equation using ODE45 45 solver.

As seen from the plot torque has transients and then after sometime steady-state value is obtained. The torque value is the same as calculated in section 2.



**Figure 3**  
*Speed vs. time*

The initial value of speed is taken as zero and then it increases with a few jerks to attain a steady-state value similar to section 2.

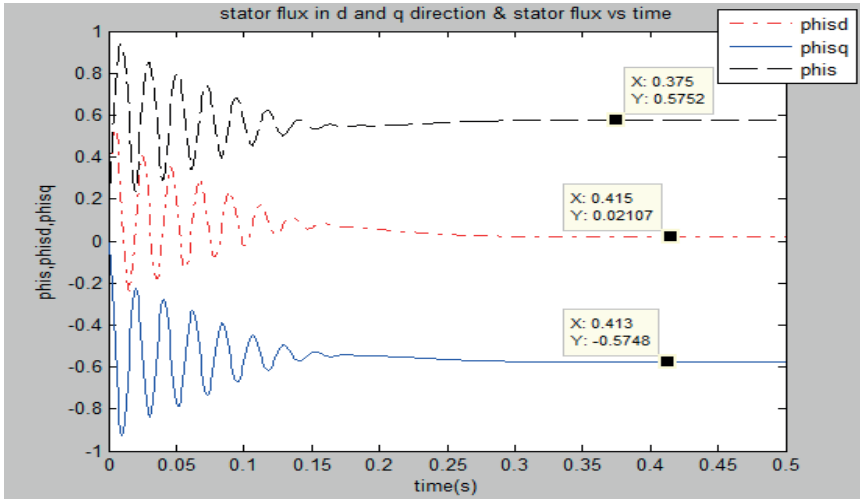


Figure 4  
Stator flux in d and q directions and total stator flux

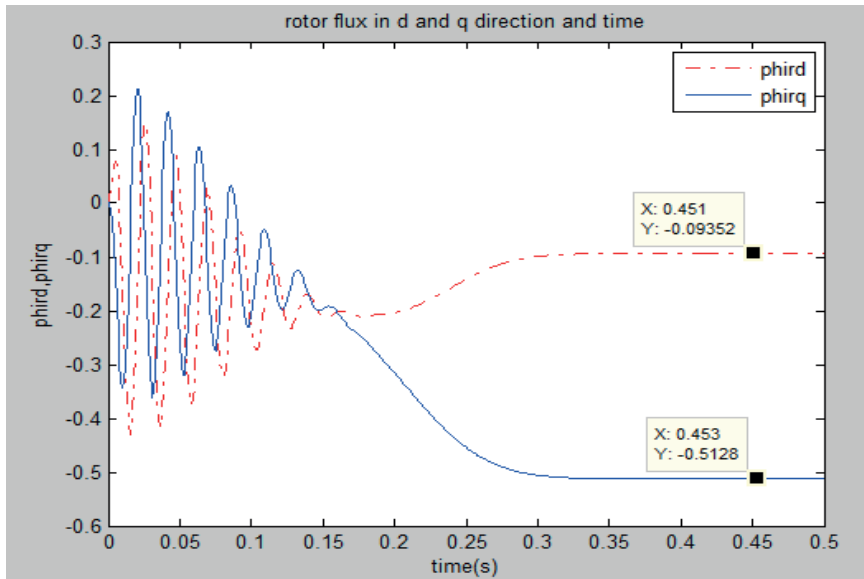


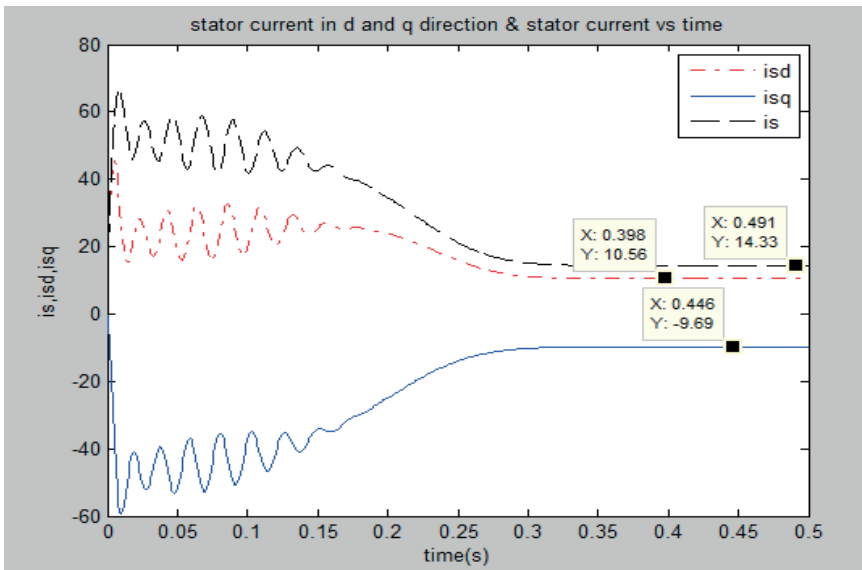
Figure 5  
Rotor flux in d and q direction

For Figure 5, In the d direction, the rotor flux represents the magnetic field aligned with the rotor's magnetic axis. This component is responsible for

producing the motor's electromagnetic torque. Typically denoted as  $\Psi_d$ , its value depends on the motor's operating conditions and control parameters. For example, at a certain operating point, the d-axis rotor flux could have a high value of 0.8 Weber.

In the q direction, the rotor flux represents the magnetic field orthogonal to the rotor's magnetic axis. This component contributes to the motor's reactive power and affects its magnetizing current. Denoted as  $\Psi_q$ , its value also depends on the motor's operating conditions. As an example, at the same operating point as before, the q-axis rotor flux could have a high value of 0.3 Weber.

From the figures it is clear that both values of fluxes are almost equal to flux values in steady-state values.



**Figure 6**  
*Stator Current in d and q direction and total stator current*

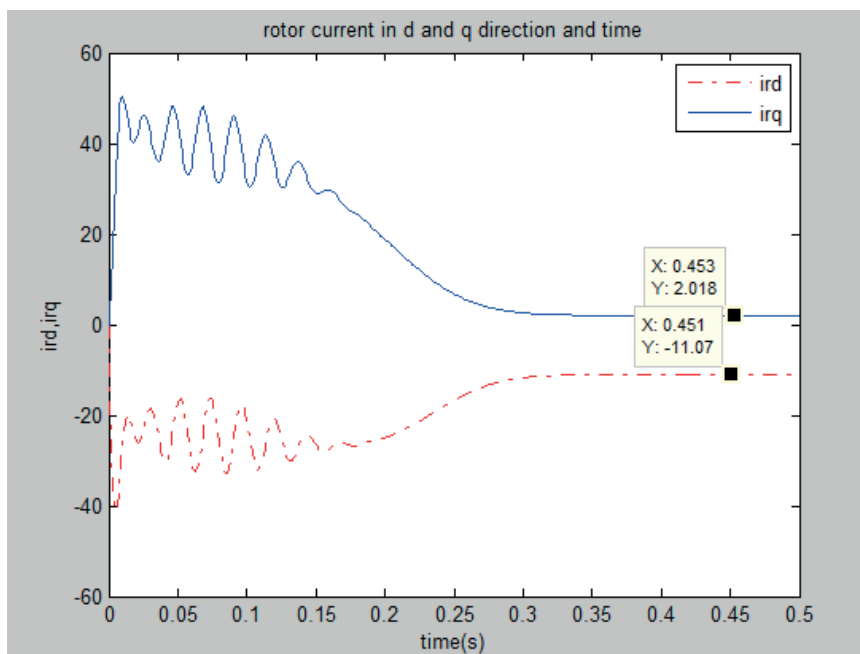


Figure 7  
Rotor Current in d and q direction

#### 4. Comparison:

The values from the simulation almost matches the values calculated in section 2.

Parameters	Results in section 2	Simulated results
Torque (N.m)	17.5886	17.59
$w_m$ (rad/s)	146.6024	146.6
d-axis stator flux	0.0211	0.02107
q-axis stator flux	-0.5748	-0.5748
d-axis rotor flux	-0.0935	-0.09352
q-axis rotor flux	-0.5128	-0.5128
d-axis stator current (A)	10.5546	10.56
q-axis stator current (A)	<b>-9.6902</b>	-9.69
d-axis rotor current (A)	-11.0657	-11.07
q-axis rotor current (A)	2.0181	2.018

Based on the provided data, here are some significant or interesting findings: The steady-state torque value is 17.5886 N.m, which is very close to the simulated result of 17.59 N.m. This indicates a good agreement between the steady-state and simulated values for torque.

The d-axis stator flux is 0.0211, and the q-axis stator flux is -0.5748.

These values are consistent between the steady-state and simulated results. Similarly, the d-axis rotor flux and q-axis rotor flux are also in close agreement between the steady-state and simulated values.

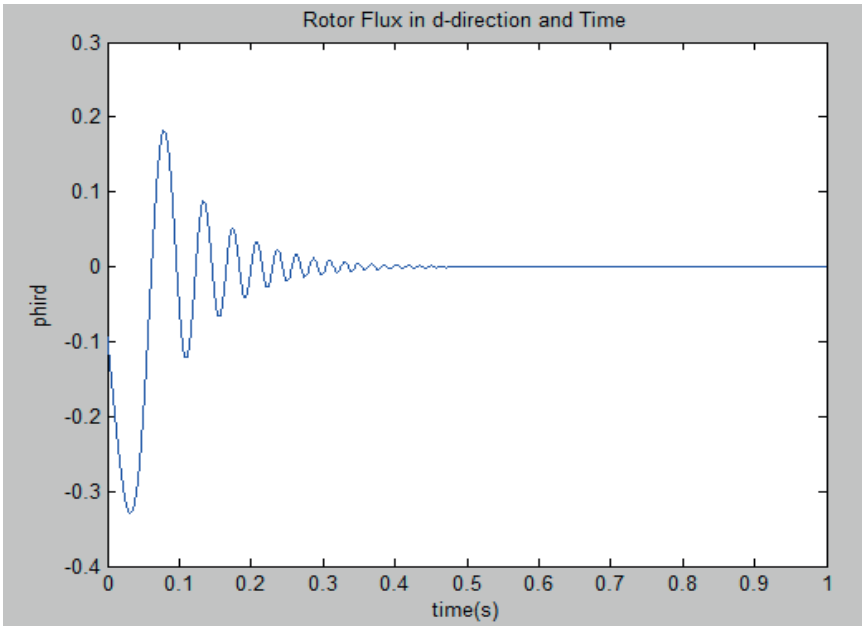
The d-axis stator current is 10.5546 A in the steady-state, and it closely matches the simulated result of 10.56 A. The q-axis stator current is -9.6902 A in the steady-state, which is also in good agreement with the simulated result of -9.69 A. The d-axis rotor current and q-axis rotor current also show a similar pattern of agreement between the steady-state and simulated values.

### 5. Stator flux omitted situation

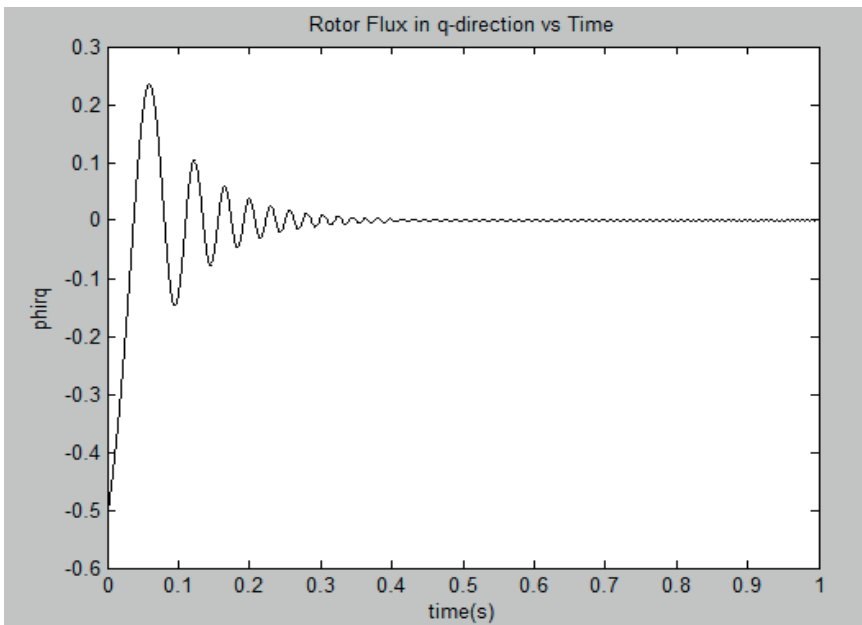
The voltage is disconnected instantaneously at  $t=0$ , so to solve this situation stator fluxes in d q directions are considered zero (Tang, Yang, Blaabjerg, Chen, Diao, & Liu, 2018). As a result of neglecting or considering stator fluxes zero the first two rows from equation 1 are neglected (Rafajlovski, Digaiovski, & Cvetkovski, 2018). Equations related to stator are also omitted in **equation (8)**. Load torque is constant in this case which is calculated in section 3 and the nominal value of torque is 0 as its calculation is dependent on stator flux which is zero. After writing equations in matrix form, the ODE45 solver in MATLAB is used to perform simulation. After doing the simulation rotor currents and flux plots versus time are taken. Rotor current and fluxes are taken at 100 ms,

$$\frac{d}{dt} \begin{bmatrix} \psi_{rd} \\ \psi_{rq} \\ w_m \end{bmatrix} = \begin{bmatrix} 0 & w_l - w_r & 0 \\ -w_l + w_r & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} \psi_{rd} \\ \psi_{rq} \\ w_m \end{bmatrix} + \begin{bmatrix} u_{rd} \\ u_{rq} \\ 0 \end{bmatrix} - \begin{bmatrix} R_r \cdot i_{rd} \\ R_r \cdot i_{rq} \\ -(T - T_l) / Jt \end{bmatrix}$$

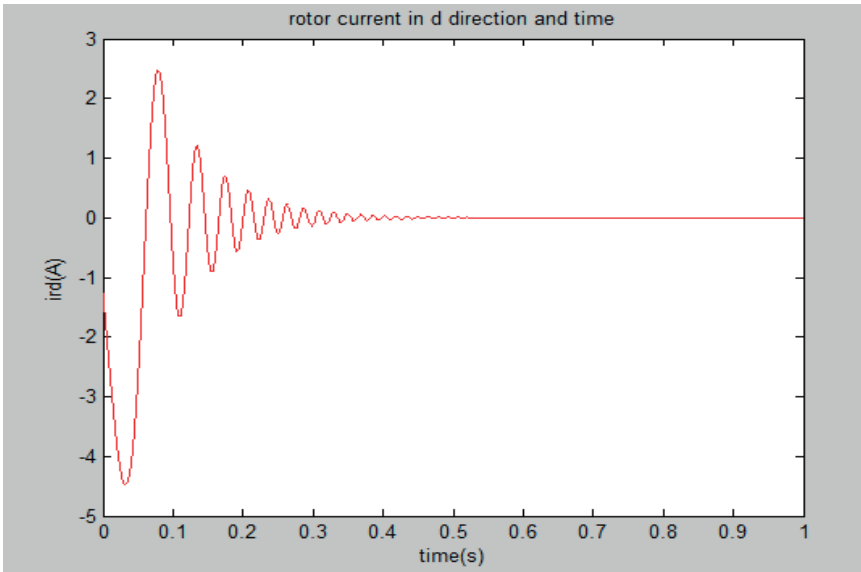
$$\begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} = \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} * \begin{bmatrix} i_{rd} \\ i_{rq} \end{bmatrix}$$



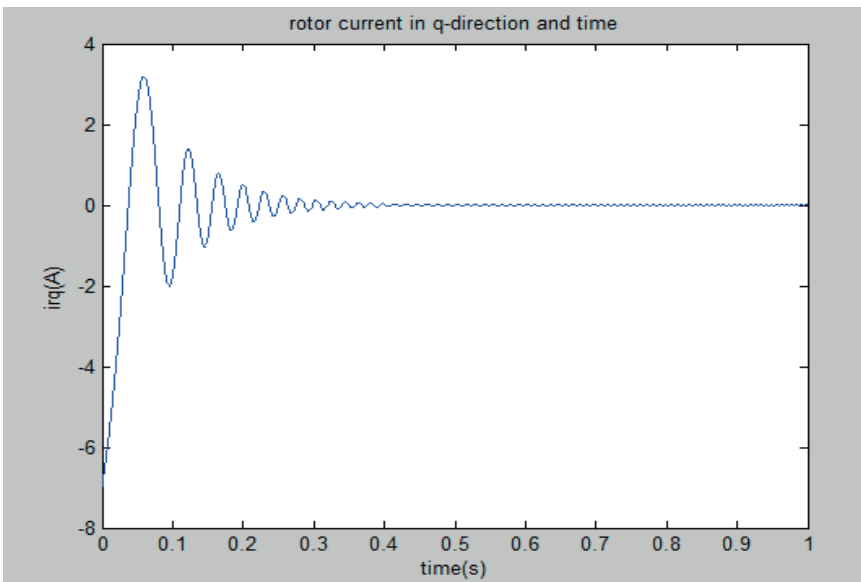
**Figure 8**  
*d-axis rotor flux*



**Figure 9**  
*q-axis rotor flux*



**Figure 10**  
*d-axis rotor current*



**Figure 11**  
*q-axis rotor current*

As it is observed from the above figures when the supply is disconnected the fluxes and current do not drop to zero immediately but it takes some time

because of magnetizing inductance (Abeywickrama, Serdyuk, & Gubanski, 2008). The values of rotor flux and rotor currents after different disconnection times are given below,

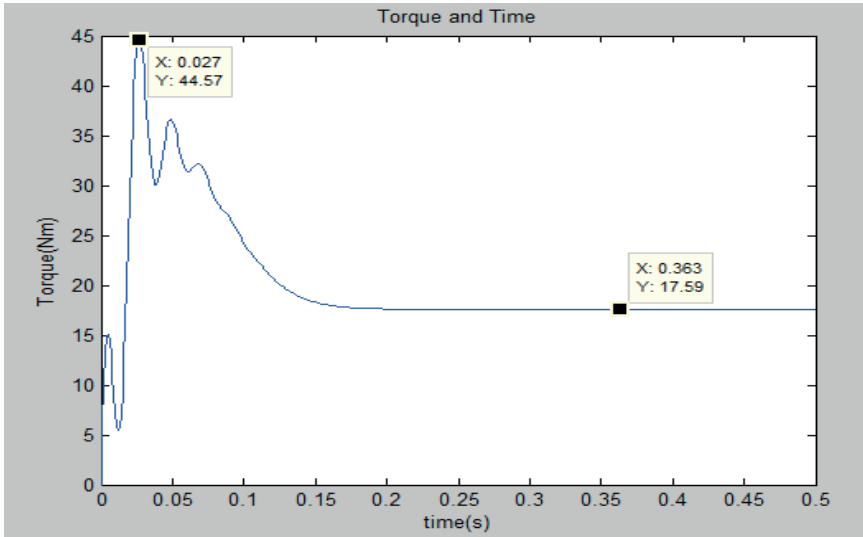
	<i>Time</i>	<i>90 ms</i>	<i>100 ms</i>	<i>120 ms</i>
<i>Quantities</i>				
<i>Rotor flux in d-direction, <math>\Psi_{rd}</math></i>		0.0968	-0.0529	-0.0414
<i>Rotor flux in q-direction, <math>\Psi_{rq}</math></i>		-0.1259	-0.1287	0.0985
<i>Rotor current in d-direction, <math>i_{rd}</math></i>		1.3161	-0.7192	-0.5633
<i>Rotor current in q-direction, <math>i_{rq}</math></i>		-1.7126	-1.751	1.3398
<i>Mechanical Speed, <math>\omega_m</math></i>		107.0280	102.6309	93.8366

From the table, it is clear that as the duration for disconnection increases speed decreases.

### 6. Re-switching in reconnection

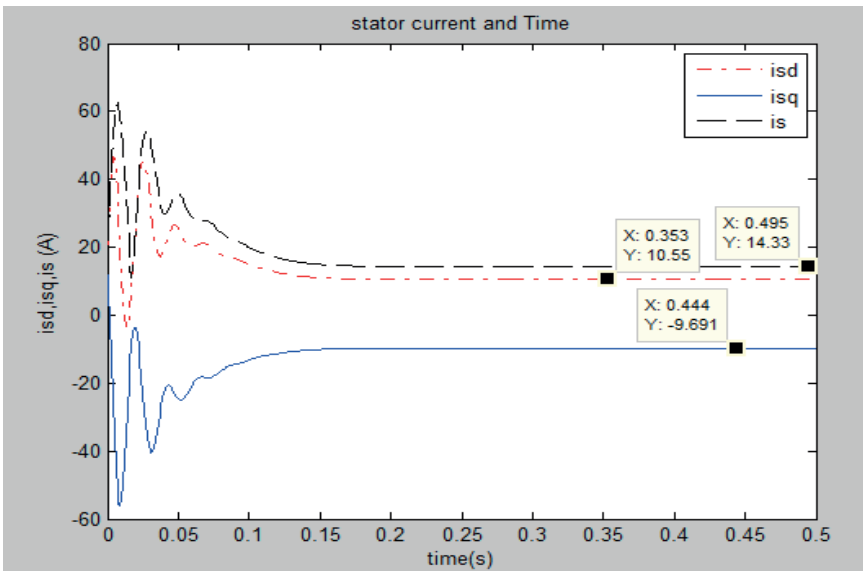
Re-switching in reconnection refers to a phenomenon observed in the dynamic modeling and analysis of induction motors operating at full load conditions (Zhao, Wang,, Zhan, Xu, & Cui, 2019). .It occurs when there is a sudden change in the motor's electrical connections, leading to a momentary interruption or fluctuation in the motor's operation. This transient behavior can have significant implications for motor performance and overall system stability. (Asghar, 2023).

In this part re-switching is done by connecting again to the supply. The final values of from section 4 are used as initial values in this part for equation solving. Again, differential equations are converted into matrix form on MATLAB, then by using ODE45 solver differential equations are solved and simulation is done. The torque reaches a steady-state value at 500 *ms*. The torque, current and speed curve are given in Figure 12.



**Figure 12**  
*Torque vs time*

As it is observed from the plot after the reconnection of the motor there are some transients but at 150 ms torque reaches a steady-state value which is equal to the value calculated, and the differential equation results are matching the equivalent circuit machine results.



**Figure 13**  
*Stator current vs. time*

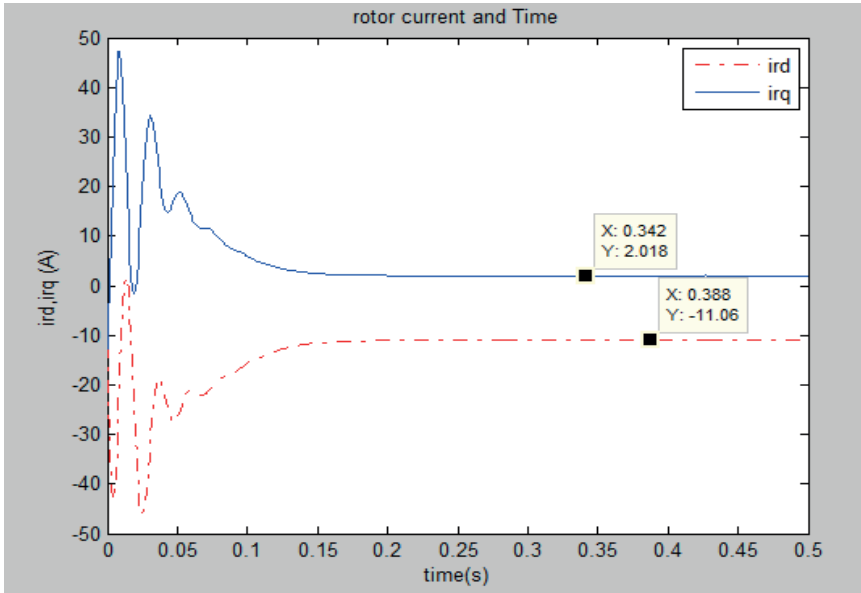


Figure 14  
Rotor current vs. time

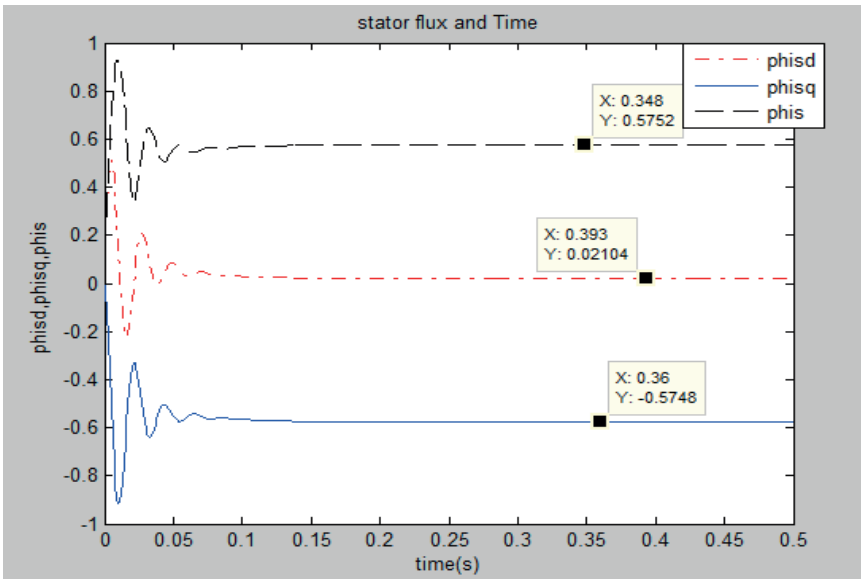
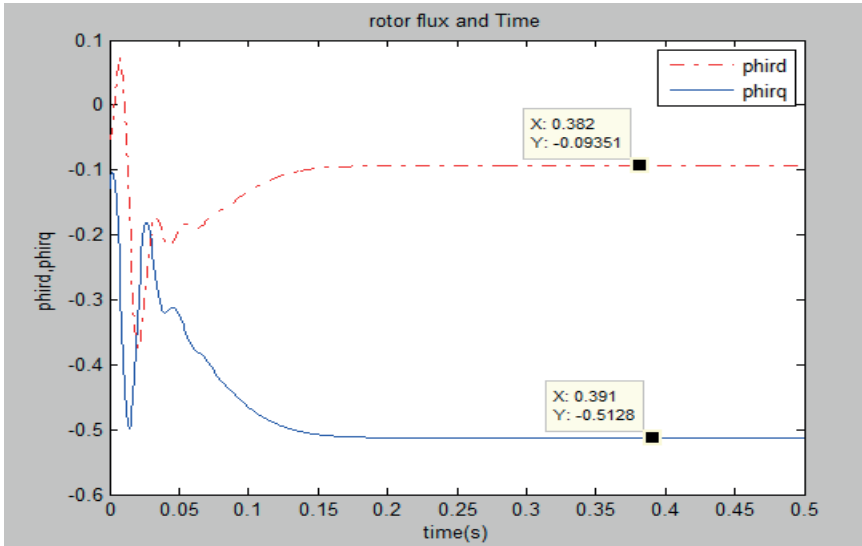
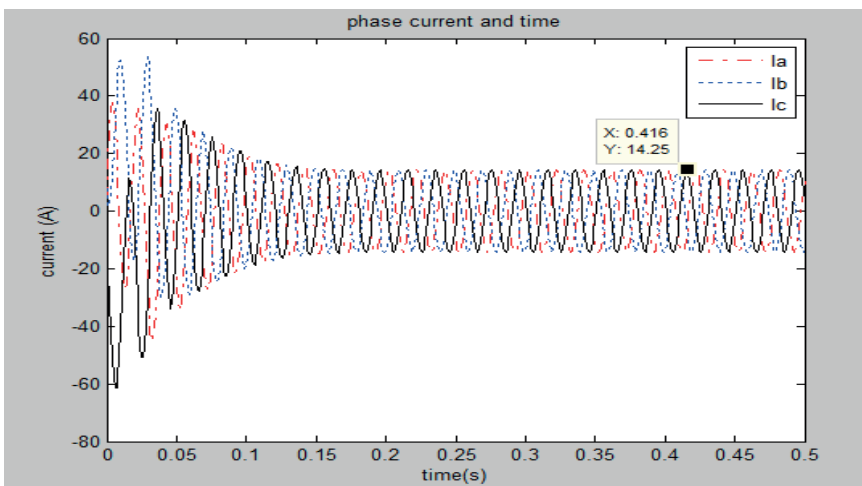


Figure 15  
Stator flux vs. time



**Figure 16**  
*Rotor Flux vs. time*

It is observed from the above plots of currents and fluxes that after re-switching of the machine there are some transients but after some time steady-state values are obtained. At steady-state conditions, fluxes and currents values are calculated. It is observed that there is no large difference in values. The values are closed because the skin effect is ignored in the task. In Figure 17, poly phase currents against time curves are included.



**Figure 17**  
*Phase current vs. time*

## 7. Conclusion

In conclusion, the dynamic modeling and analysis of re-switching phenomenon in an induction motor operating at full load condition provide valuable insights into the behavior and performance of the motor under transient conditions.

In this study, we explored the dynamic modeling and analysis of re-switching in an induction motor running at full load condition. The investigation aimed to understand the impact of sudden switching events on the motor's operation and to assess its stability and performance during such transients.

Through the application of advanced mathematical models and simulation techniques, we were able to accurately capture the dynamic behavior of the induction motor during re-switching events. The simulations provided a detailed understanding of the voltage and current waveforms, torque fluctuations, and other critical parameters that influence the motor's performance. The steady-state value of torque is around 17.59Nm in all cases but there are transients during re-switching. The torque value goes near 45 N.m during re-switching and these transients are at the start of curve just for 50 ms to 100 ms so the machine must be designed in such a way that it withstands such high torque for this period. There are transients in currents during re-switching so a protection scheme must be designed to overcome this high transient's current for short time as currents also go to steady value after a short period.

Our findings revealed that re-switching in an induction motor running at full load condition can lead to significant transient effects. These effects include voltage spikes, current surges, and torque variations, which can potentially impact the motor's mechanical integrity and overall efficiency. It is crucial for motor designers and engineers to be aware of these transient phenomena and take appropriate measures to mitigate their adverse effects.

Furthermore, the dynamic modeling and analysis of re-switching events allowed us to assess the motor's stability and determine the critical switching time intervals to avoid potential damages. By understanding the motor's response to switching events, we can optimize the control strategies and protective measures to ensure safe and reliable operation.

The insights gained from this study can contribute to the development of more robust and efficient induction motor control systems. By incorporating the knowledge of re-switching phenomena, motor manufacturers can design advanced control algorithms that minimize the transient effects and improve the motor's overall performance and longevity.

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