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Research paper

Modeling of Three-Phase Induction Motor Performance under Faulty Inverter Condition Using MATLAB GUI and Simulink

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Abstract

Recent advancement in semiconductor technologies have extended the use of induction motors in a wide area of variable speed applications. Traditional fixed speed drives are becoming obsolete and majority of the applications now require inverter-based drives for a more efficient and precise speed control. Nonetheless, the use of power electronic devices came with an increased possibility of the motor drive system failures mainly caused by the switching device itself. Hence, in the development of an induction motor drive system, it is crucial to study not only on the induction motor but also taking into considerations of the inverter system under healthy and faulty conditions. Computer simulation models are often used to get an insight of the system behaviour; however, the implementation of such model is a fairly complicated task and most of the previous literatures does not emphasize on the implementation of the model. This paper is intended to present a computer simulation model using MATLAB Simulink to simulate the power switches open-circuit and short-circuit faults that may occur in an inverter fed induction motor drive. The sub models of the system include an induction motor direct-quadrature (dq) model, a voltage source inverter (VSI) driven by an open-loop sinusoidal pulse width modulation (SPWM) and a simple graphical user interface (GUI) to allow user control on the input parameters during simulation run. The dynamic behaviour of the motor speed, phase current and electromagnetic torque during healthy and faulty condition can be simulated. The simulation shows that the inverter fails in shaping proper outputs under open switch resulting in degraded motor performance while shorted switch lead to abnormal overcurrent forcing the motor to stop.

Keywords: *Induction motor; Inverter faults; MATLAB Simulink*

1. Introduction

Induction motors have a long successful history as the main horse power of the industry, they have been widely used mainly due to their simplicity, ruggedness, and high reliability. Recent advancement in semiconductor technology have further extended their use and majority of the application systems now require inverter-based drives for variable speed applications. Some of the applications include industrial pumps, drilling machines, crane lifters, and traction applications such as in trains and electric vehicles.

Due to their nature of working environment, these motors and its drive are usually subjected to harsh processes requiring rapid speed variation, frequent stop or starting and constant overloading hence they are prone to many kinds of faults. It is known that the power inverter is the weakest component in the drive system, around 38% of the drive faults are due to power devices[1-3]. Therefore, it is of high interest for researchers to have a study focusing on the inverter system faults and their effects to the induction motor performance.

In the design and verification process of the induction motor drive system, elaborate mathematical models with computer simulation implementation are often used. The model would be very useful to predict and simulate operational characteristics and performances under normal and faulty conditions without destructive testing. Yet, building such model is not a straight forward task, an understanding of the machine basic electric, magnetic and mechanical behaviors and some experience in using computer simulation software are required.

There exist several studies on the inverter drive fault that uses computer simulation model in their work. Most of them are focusing on fault detection and isolation method, monitoring either phase currents[1,4,5], phase voltages or switching voltages[6-8], or the combinations of those. Their works however does not emphasize on the implementation method of their model. Thus, this paper is intended to present an overview of the available method to model the induction motor drive and a method to simulate inverter switching fault specifically on short circuit and open circuit condition by using MATLAB Simulink software.

This paper is organized in sections as follows; Section 2 describes the fundamentals on induction motor drives modeling. Then in section 3, a simple method to introduce faulty inverter conditions and the use of MATLAB graphical user interface (GUI) for simulation control are described. Section 4 focuses on the results and discussions of the simulation examples. Finally, the conclusion is made in section 5.

2. Modeling of Three-Phase Induction Motor Drive

The With the rapid development in computer hardware and software technologies, much research efforts have been invested in developing computer simulation models of the induction motor drive. Three sub-model implementations using MATLAB Simulink are discussed in this paper which include the induction motor model, the SPWM generator and the power inverter.

2.1. Induction Motor Model

The induction motor electromechanical operation can be mathematically modeled by applying a few available methods such as the Circuit model, State Space model or Finite Element model as categorized in Figure 1. Among the listed methods, this paper focuses on one of the most widely use induction motor model for computer simulation which is the state space direct-quadrature (dq) model. The model is convenient due to its capability to represent all practical modes of operation and permits to simulate the saturation of the induction motor[9(p184)].

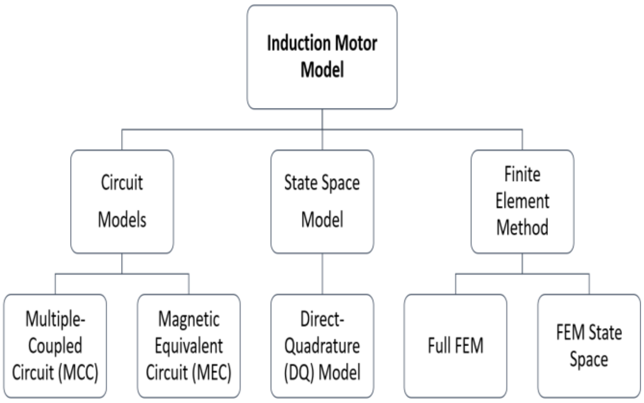


Fig. 1: Induction motor model

The dq-model of the induction motor requires transformation of the three-phase quantities in the abc natural reference frame into the equivalent two-phase quantities in a fictitious direct-quadrature frame. There have been a number of literatures on the reference frame transformation, Krause in his book[9(p109)] summarized the works by earlier researchers and proved that all known real transformations can be represented by one general transformation. This general transformation refers the three-phase machine variables to a two-phase direct-quadrature reference frame that rotates at an arbitrary angular velocity. To simplify the reference frame transformation, it is convenient to first transform the three-phase supply voltages using equation (5) into a two-phase stationary reference frame, then from the stationary reference frame to the arbitrary reference frame using equation (6). Figure 2 shows the transformation of the stator voltages in the natural reference frame (v_{abcn}) to the two-phase arbitrary reference frame (v_{ds}, v_{qs}). To simulate the equations, a Simulink implementation of the transformation is built as shown in Figure 3**.**

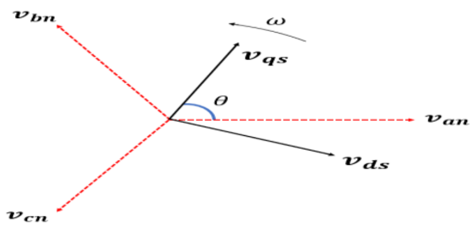


Fig. 2: Reference frame transformation of v_{abcn} to v_{ds}, v_{qs}.

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} \quad (2)$$

Where:

v_{abcn} : stator voltages in natural reference frame
v_{qs}^s, v_{ds}^s: stator voltages in d-q stationary reference frame
v_{qs}, v_{ds}: stator voltages in d-q arbitrary reference frame

The angle θ is calculated by directly integrating the angular speed of the arbitrary reference frame ω,

$$\omega_e = \frac{d\theta}{dt}$$

$$\theta = \int \omega \ dt \quad (3)$$

Once the three-phase voltages been transformed into the equivalent 2-phase voltages, the flux linkage equations can be solved. The equations for simulating the induction motor in arbitrary reference frame may be established by first solving the flux linkage equations for the currents:

$$i_{qs} = \frac{1}{x_{ls}}\left(F_{qs} - F_{mq}\right) \quad (4)$$

$$i_{ds} = \frac{1}{x_{ls}}\left(F_{ds} - F_{md}\right) \quad (5)$$

$$i_{qr} = \frac{1}{x_{lr}}\left(F_{qr} - F_{mq}\right) \quad (6)$$

$$i_{ds} = \frac{1}{x_{lr}}\left(F_{dr} - F_{md}\right) \quad (7)$$

Where:

i_{qs}, i_{ds} : stator current of quadrature & direct axis
x_{ls}, x_{lr} : leakage reactance of stator & rotor
F_{qs}, F_{ds} : stator flux linkage of quadrature & direct axis
F_{qr}, F_{dr} : rotor flux linkage of quadrature & direct axis

The flux linkages equations are defined as follows:

$$\frac{dF_{qs}}{dt} = \omega_b\left[v_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{x_{ls}}\left(F_{mq} + F_{qs}\right)\right] \quad (8)$$

$$\frac{dF_{ds}}{dt} = \omega_b\left[v_{ds} - \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{x_{ls}}\left(F_{md} + F_{ds}\right)\right] \quad (9)$$

$$\frac{dF_{qr}}{dt} = \omega_b\left[v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}F_{dr} + \frac{R_r}{x_{lr}}\left(F_{mq} + F_{qr}\right)\right] \quad (10)$$

$$\frac{dF_{dr}}{dt} = \omega_b\left[v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}F_{qr} + \frac{R_r}{x_{lr}}\left(F_{md} + F_{dr}\right)\right] \quad (11)$$

Where:

ω_b : Motor angular base frequency
ω_e : Electrical supply angular frequency
ω_r : Rotor angular frequency
v_{qs}, v_{ds} : Stator voltages of q and d-axis
v_{qr}, v_{dr} : Rotor voltages of q and d-axis
F_{mq}, F_{md} : Magnetizing flux linkages of q and d-axis

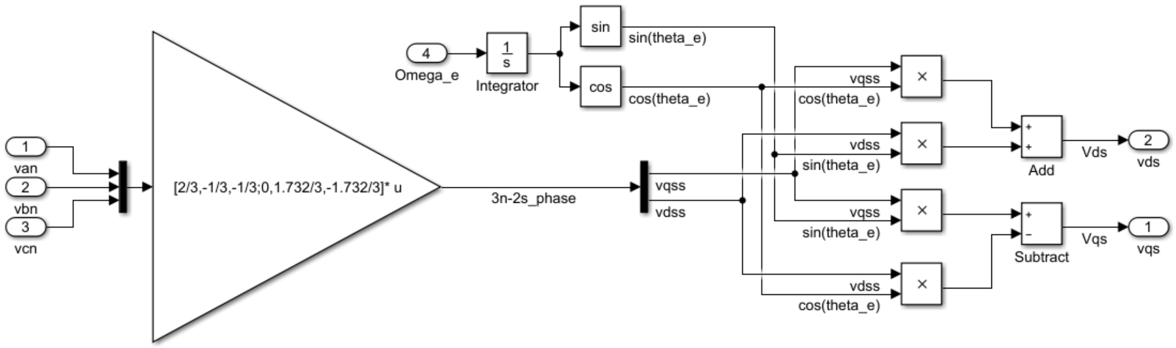


Fig. 3: Simulink implementation of equation (1), (2) and (3)

Magnetizing flux linkages F_{mq} & F_{md} are defined as:

$$F_{mq} = x_{ml}\left[\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}\right] \tag{16}$$

$$F_{md} = x_{ml}\left[\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}\right] \tag{17}$$

Where:

$$x_{ml} = 1\Big/\left[\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right] \tag{18}$$

The electromagnetic torque (T) and rotor speed (ω_r) can then be defined by using the following equations:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}\left(F_{ds}i_{qs} - F_{qs}i_{ds}\right) \tag{19}$$

$$\frac{d\omega_r}{dt} = \frac{p}{2J}\left(T_e - T_l\right) \tag{20}$$

Where p is the number of poles and J is the moment of inertia.

Some literatures such as in[10-12] have shared their respective overview on how the mathematical dq-model can be implemented in a computer simulation software specifically using MATLAB Simulink. However, this paper does not focus on the mathematical implementation of the induction motor model, but instead, the readily available model of the induction machine from Simulink's library which is also based on the state space dq-model is used to simulate the motor performance.

2.2. Spulse Width Modulation (SPWM) and Three-Phase Voltage Source Inverter (VSI)

A typical three-phase voltage source inverter (VSI) consists of six power switches in a topology as shown in Figure 4. There are various techniques ranging from low to high complexity that have been developed for the purpose of shaping the VSI output voltages. Here, the sinusoidal pulse width modulation (SPWM) that was introduced by Schonung in 1964[13] is applied. SPWM is one of the simplest and most common modulation methods for induction motor speed control, it requires a sinusoidal control signal V_a be compared with a high-frequency triangular signal V_t to generate the inverter switching signals**.** This allows the inverter fundamental frequency f to be controlled directly by controlling the frequency of V_a.

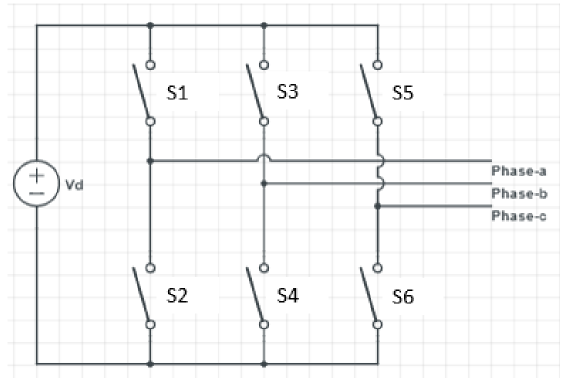


Fig. 4: Typical three-phase inverter topology

To model the three-phase SPWM switching signals, three sinusoidal control signals which are set 120-degree phase apart from each other; V_a V_b V_c are compared with the same triangular signal V_T. This can be demonstrated in Simulink by using a 'Repeating Sequence' block to generate the repeating triangular signal V_T, and three 'Sine Wave' blocks as the control signals V_a V_b V_c. Relational Operator' blocks are used to compare the signals and output the 3-phase PWM switching signal. The implementation is shown in Figure 5.

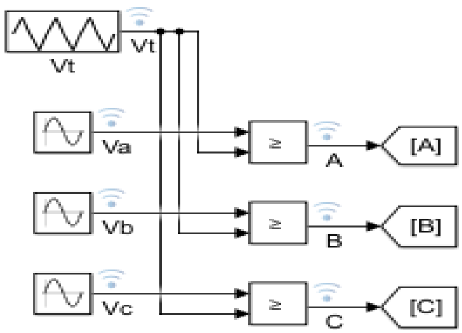


Fig. 5: Simulink implementation of SPWM switching signal generator

Bose in his book[14(p264)] described a simplified three-phase inverter is modeled by using Simulink 'Switch', 'Gain' and 'Sum' blocks based on the relation of phase voltages and pole voltages as in equation (21), (22), (23). Each leg of the inverter is represented by a 'Switch' that has three input terminals and one output terminal. The first input is +0.5* V_d, the third input is -0.5* V_d, and the second input of the Switch works as the control terminal to either passes through the first input or the third input. Note that the second input of the switch is connected to the signal generated by the SPWM signal generator**.** This causes the output of each of the switch blocks (v_{ao}, v_{bo}, v_{co}) to oscillate between +0.5* V_d and -0.5* V_d that simulates the characteristic of a pole in an inverter.

$$v_{an} = \frac{2}{3} v_{ao} - \frac{1}{3} v_{bo} - \frac{1}{3} v_{co} \quad (21)$$

$$v_{bn} = \frac{2}{3} v_{bo} - \frac{1}{3} v_{ao} - \frac{1}{3} v_{co} \quad (22)$$

$$v_{cn} = \frac{2}{3} v_{co} - \frac{1}{3} v_{ao} - \frac{1}{3} v_{bo} \quad (23)$$

Where:

v_{an}, v_{bn}, v_{cn} : Phase voltages
v_{ao}, v_{bo}, v_{co} : Pole voltages
V_d : DC voltage source

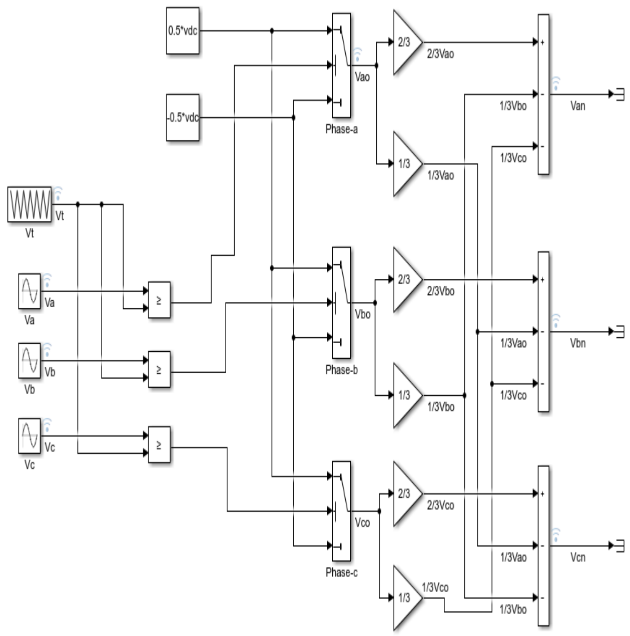


Fig. 6: Three-phase inverter based on the relation of induction motor phase voltages and pole voltages

An alternative way of modeling the three-phase inverter in Simulink is by using the available power switch blocks in the Simulink Power Electronics library. There are a few selections of switches available that include gate turn-off thyristor (GTO), insulated gate bipolar transistor (IGBT) and others. To simulate the basic working principle of a power inverter, the Ideal Switch block proves to be sufficient. Six Ideal Switch blocks are connected in the same way as the physical three-phase inverter circuit topology as shown in Figure 4. Diodes are connected parallel to each Ideal Switch that serves as the anti-parallel diode. The switches are controlled in pairs such that when an upper switch is closed, the corresponding lower switch is open[15], this logical operation can be simulated by adding Logical NOT operator blocks to the implementation shown in Figure 5. Assuming that all the switches used is in ideal condition, the dead time between the change of switching state for the switches working in pairs are ignored. The complete model of the healthy three-phase induction motor drive is shown in Figure 7.

3. Inverter Fault Model

The inverter is the most sensitive subsystem of the induction motor drive in terms of reliability, most of the inverter fault cases are caused by the power switches itself due to aging, overloading, or unpredicted operational conditions[6]. Generally, the faults can be classified into open switch and short switch fault. A short switch can generate abnormal overcurrent causing the motor to stop working whereas an open switch fault does not completely halt operation, but noise can be induced in the system which lead to performance degradation[16].

Using the model in Figure 7, the SPWM signal generator can simply be modified to produce the desired faulty inverter condition. In this case, an open circuit and short circuit faults are simulated by overriding the specific switch signal with constant input values. Figure 8(a) shows the top view of SPWM generator model and (b) shows an example to manually bypass the SPWM signal with constant 0 value for open circuit and constant 1 value for short circuit.

This modification allows open or short circuit of single and multiple switch fault to be simulated with respect to the user input. All the parameters are generally set before simulation run, however, users often want to manually change a few inputs and parameters to see how the model responds without needing to stop and restart the simulation. Rather than altering them directly through the Simulink model, providing a graphical user interface (GUI) to access the Simulink model's internal structure is much more convenient.

There are 3 common approaches to synchronize MATLAB GUI with Simulink; using the 'SET_PARAM' application programming interface (API), using custom MATLAB S-function, or by using the Simulink Event Listener[17]. This work applies the first method as it is simple and works well with the developed Simulink model. The user interface layout comprises of a few components; a single push button used for simulation start and stop control, six groups of radio buttons that provide control over the six switch conditions, and two sliders are used to give access over the load torque input and the sinusoidal control signal frequency. The full layout of the GUI is shown in Figure 9.

4. Simulation Results

Using the developed GUI described in the previous section, all the user input for simulation start and stop, to adjust the control signal frequency and the load torque, and to specify inverter switch condition are done without directly accessing the Simulink model. Simulink Scopes are used to visualize the model's outputs during the simulation run and the output data are logged to the Simulink Data Inspector to be viewed after the simulation ends and saved as MAT file for further analysis.

Figure 10 shows the example of plots on phase currents, rotor speed, and output torque by sequence of healthy, S1-Open Circuit, S2-Open circuit and S1&S2-Simultaneously Open circuit fault conditions. The simulation initially starts with the healthy inverter that shows the induction motor starting transient condition before it goes to a steady state. S1-Open circuit condition is then introduced which causes the loss of current reversibility in phase-a, the current became unidirectional and non-sinusoidal limited to flow only in the negative direction, while currents in phase-b and c undergo a light deformation.

Conversely, S2-Open circuit condition limited the phase-a current to flow only in the positive direction. Both conditions do not result in halting the motor but causing reduced performance by inducing oscillations in the speed and torque. However, when S1 & S2 are simultaneously opened, phase-a became fully non-functional with almost zero current passing through resulting a significant performance degradation as the motor is supplied with only phase-b and phase-c currents. The open circuit simulations show similar phase currents behavior as in the hardware experimental results from other literatures[1,18-20].

Experimental studies on short circuit switch are not common as it is already known to cause abnormally high current in the system which can destroy the hardware setup[21]. For simulation purpose, an example on S1-short-circuit fault is shown in Figure 11. As expected, the abnormal three phase currents cause the motor operation to stop.

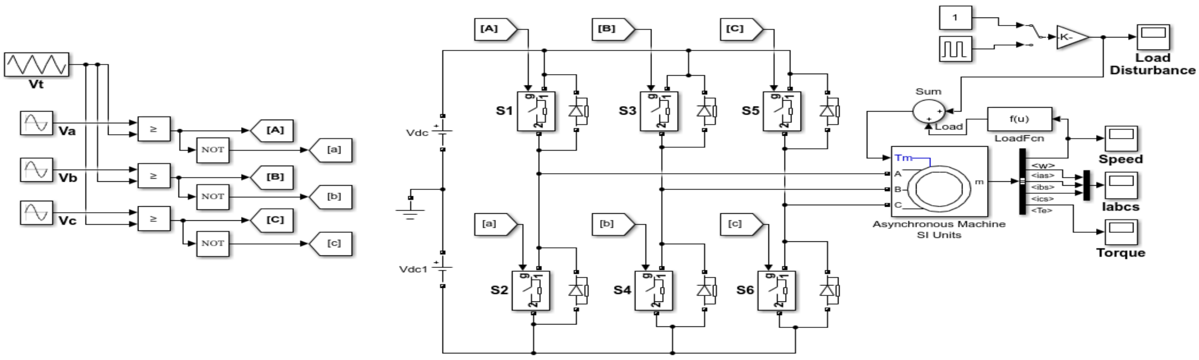
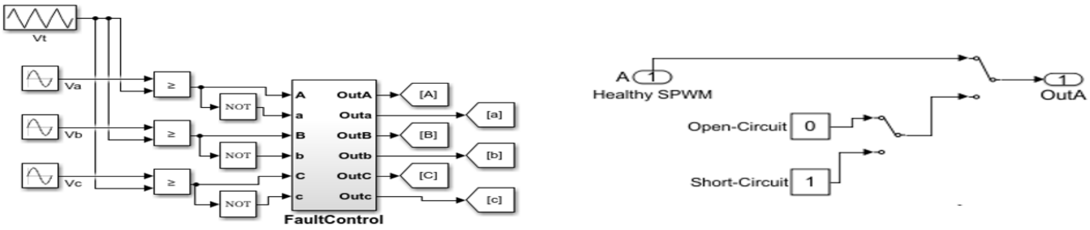


Fig. 7: Complete model of the three-phase induction motor drive in Simulink



(a) (b)

Fig. 8: (a) Modified SPWM generator (b) SPWM signal bypass

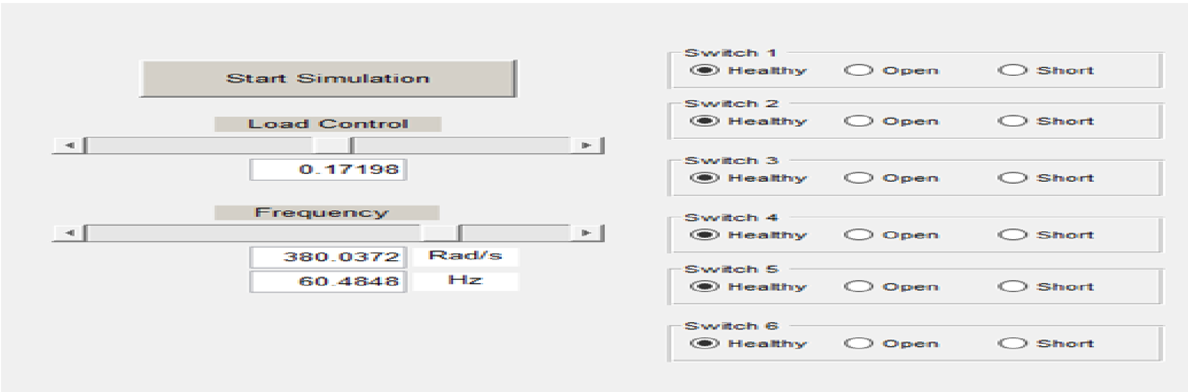


Fig. 9: Custom GUI for Simulink simulation control

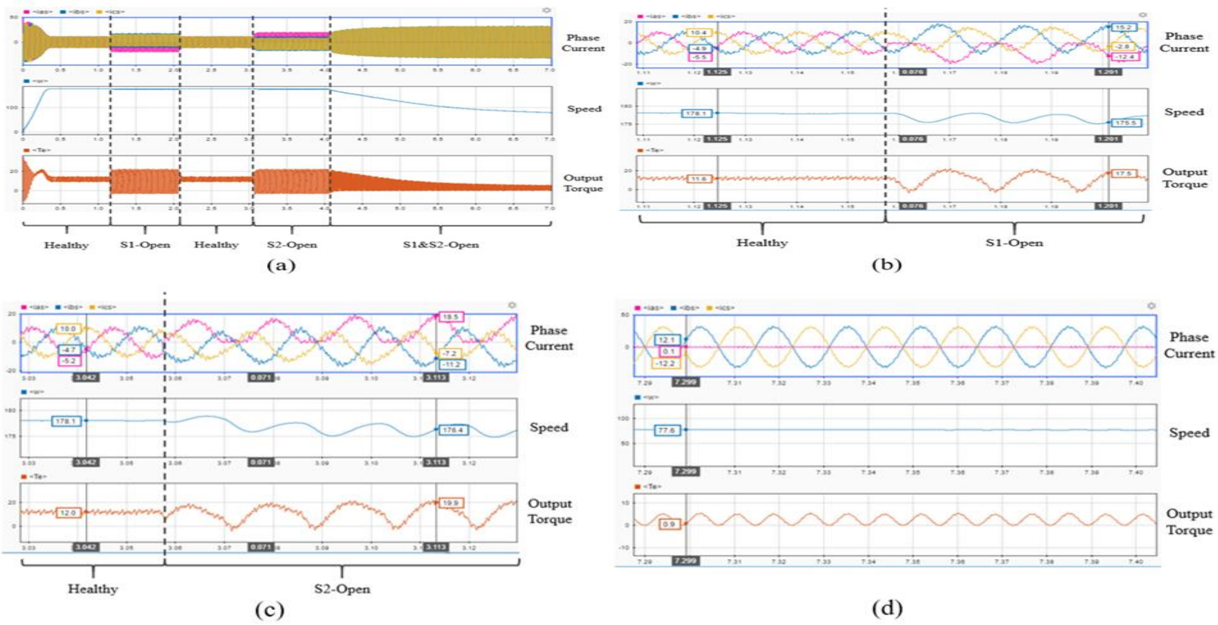


Fig. 10: (a) Example on the simulation output phase currents, speed, and torque (b) Zoomed outputs of switch S1 open circuit fault (c) Zoomed outputs of switch S2 open circuit fault (d) Zoomed outputs of switch S1&S2 simultaneously open circuit fault

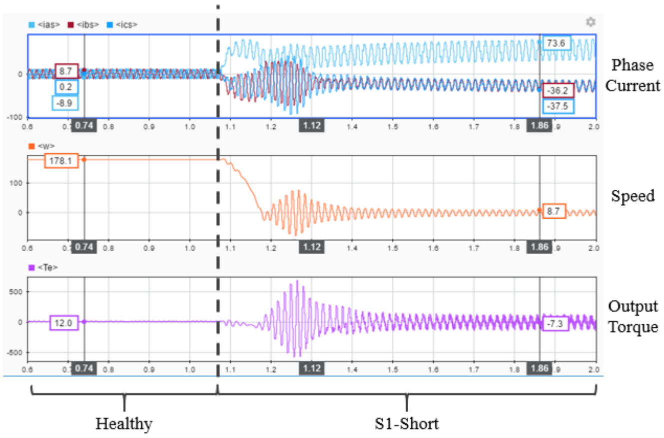


Fig. 11: Simulation outputs of S1-short-circuit fault

5. Conclusion

The use of computer software for electrical machines modeling have become increasingly important due to some advantages against the hardware models. The dynamic model described in this paper can be used to simulate the working principle of the induction motor drive under healthy and faulty inverter switch conditions by utilizing the MATLAB Simulink software. The simulation validates that the open circuit condition causes performance degradation while the short circuit condition forces the motor to halt. The described model can be used for further studies on fault detection and diagnosis which is now gaining importance in the development of efficient, and safe induction motor drive system.

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