

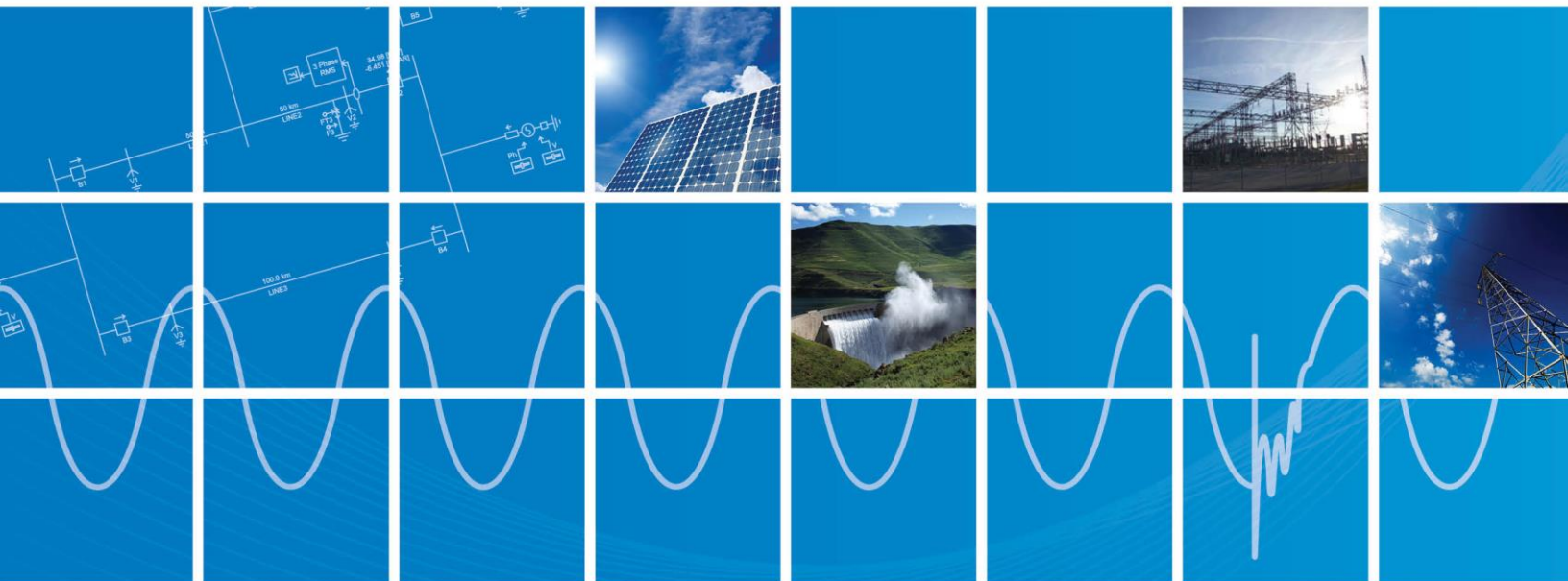


## PSCAD Cookbook

### Induction Machines Study

Written for v4.5

Revision 2: November 9, 2020





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## 5. Induction Machines Study

### 5.1 Induction Machine Basics

#### Motivation

The induction machine is by far the most common type of motor used in industrial, commercial and residential settings. The two main reasons for the wide use of the induction motor are that they are cheap and highly robust. Induction machines can be operated in either generation mode or as a motor (i.e. load). The purpose of this section is to familiarize the user with the speed and torque input mode of the induction machine model in PSCAD.

#### PSCAD Model

The PSCAD master library has two fully developed induction machine models, the squirrel cage and wound rotor induction machines.

The wound rotor model (Figure 1), with the rotor terminal shorted, is mathematically identical to a squirrel cage machine. It is recommended to use the wound rotor model for all induction machine simulations.

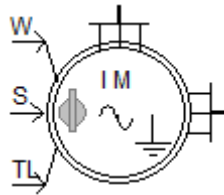


Figure 1: Wound Rotor Induction Machine in PSCAD

The model can be controlled by specifying either the mechanical torque (input TL) on the machine shaft or the machine speed (input W) as the input to the induction machine. The input 'S' is simply a switch to select between the two input modes (i.e. when S=0 input and 'TL' is selected, and if S=1 input and 'W' selected).

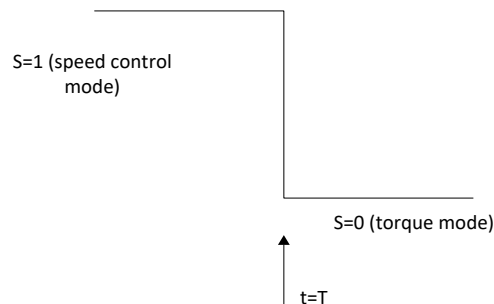


Figure 2: Machine 'Operated' in the Torque Input Mode and changed over to 'Speed' Input Mode at  $t=T$

**Torque input mode:** In the ‘torque input’ mode, the speed of the machine is calculated based on the equations of mechanical motion.

$$T_m - T_e = J \frac{d\omega_m}{dt} + B\omega_m$$

The electrical torque ( $T_e$ ) is calculated by the model based on its terminal conditions (voltage/current).  $T_m$  is the mechanical torque, which is an input to the machine.  $J$  is the inertia due to all the moving parts of the machine shaft.  $\omega_m$  is the frequency of the rotor, and  $B$  accounts for mechanical damping.

**Speed input mode:** In the ‘speed’ mode, the machine will operate at the speed specified input ‘ $W$ ’. This can be a variable or a constant. In some simulations, it may be advantageous to start the machine in the ‘speed input’ mode, and then switch to the ‘torque input’ mode once steady-state has been achieved. This can be done by switching input ‘ $S$ ’ from 1 to 0 (**Error! Reference source not found.**). For a more complex representation of the mechanical system such as a ‘multi mass torsional shaft model’, the input ‘ $W$ ’ must be selected.

**General:** Some general points on the induction machine are listed below as a quick refresher for the model users:

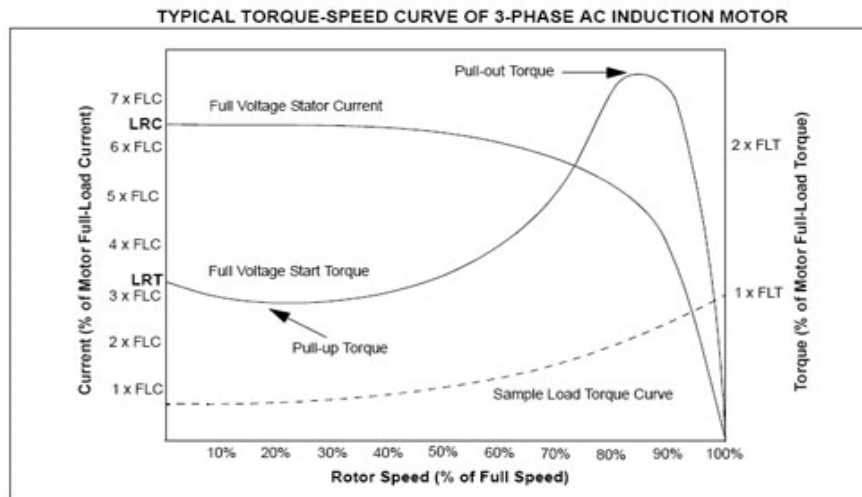


Figure 3: Torque-Speed Curve

- In steady-state operation, an induction motor will operate at the speed at which the mechanical load equals (approximately) the electrical torque developed by the motor. Figure 3 shows the torque-speed characteristic of an induction machine.
- Normal operation is to the right of the maximum torque. In this region, an increase in the load torque will cause the motor to slow down; as a result the motor torque ( $T_e$ ) increases until equilibrium is reached. However, no such equilibrium point can be reached to the left of the pull out torque. Note that the dotted line represents the torque-speed characteristic of the load connected to the motor.
- Unlike a synchronous machine, an induction machine does not allow for voltage (reactive power) control.
- In the motoring mode, the steady-state speed of the machine will be slightly lower than the 'synchronous speed' and higher in the generating mode.

## 5.2 Induction Machine Motor Starting

### Motivation

This section illustrates the important steps when investigating motor-starting in PSCAD.

### System Overview

Figure 4 shows the PSCAD model of an induction machine connected to a power system. The power system is represented by an equivalent Thevenin voltage source for simplicity. The machine is set to be in the ‘torque input’ mode with  $S=0$  and the initial speed set to zero. The breaker (BRK) is initially open and closes at time  $t=0.5$  s. This initiates the motor starting.

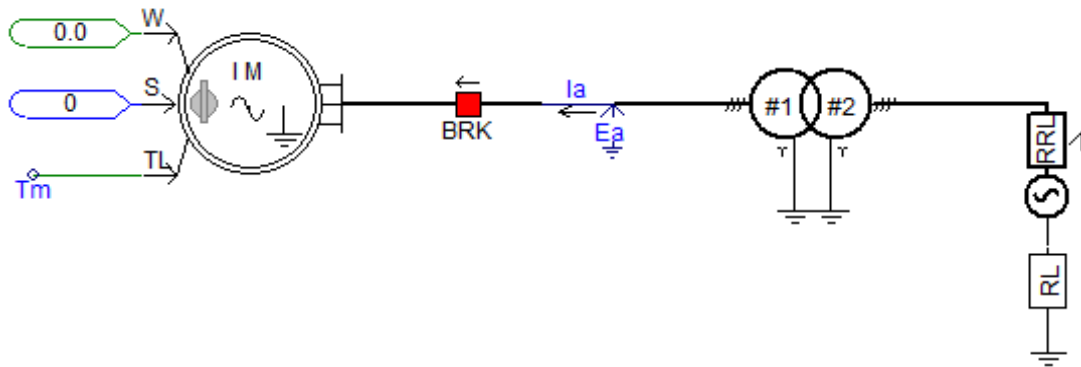


Figure 4: Torque Mode

The mechanical load characteristics greatly influence the starting response of the motor; hence, it must be adequately represented in the model. In this example, the relationship shown in equation (5-1) is used to represent the load torque characteristics.

$$T_m \propto \omega^2 \quad (5-1)$$

Based on the above relation, the mechanical load is modeled in PSCAD as shown in Figure 5. This is effectively an 80 % load with respect to the machine MVA rating.

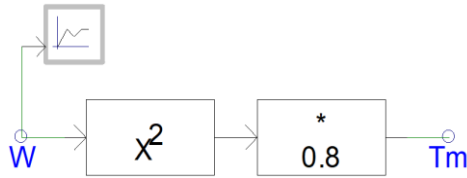


Figure 5: Implementation of the Load Torque Characteristics

### Simulation Results

At the instant the breaker closes, a large starting current is drawn by the induction machine as shown in Figure 6. The speed builds up and finally settles at a speed slightly lower than the synchronous speed. Note the surge in reactive power drawn from the system during the starting process. This will lead to huge voltage drop problems in weak systems.

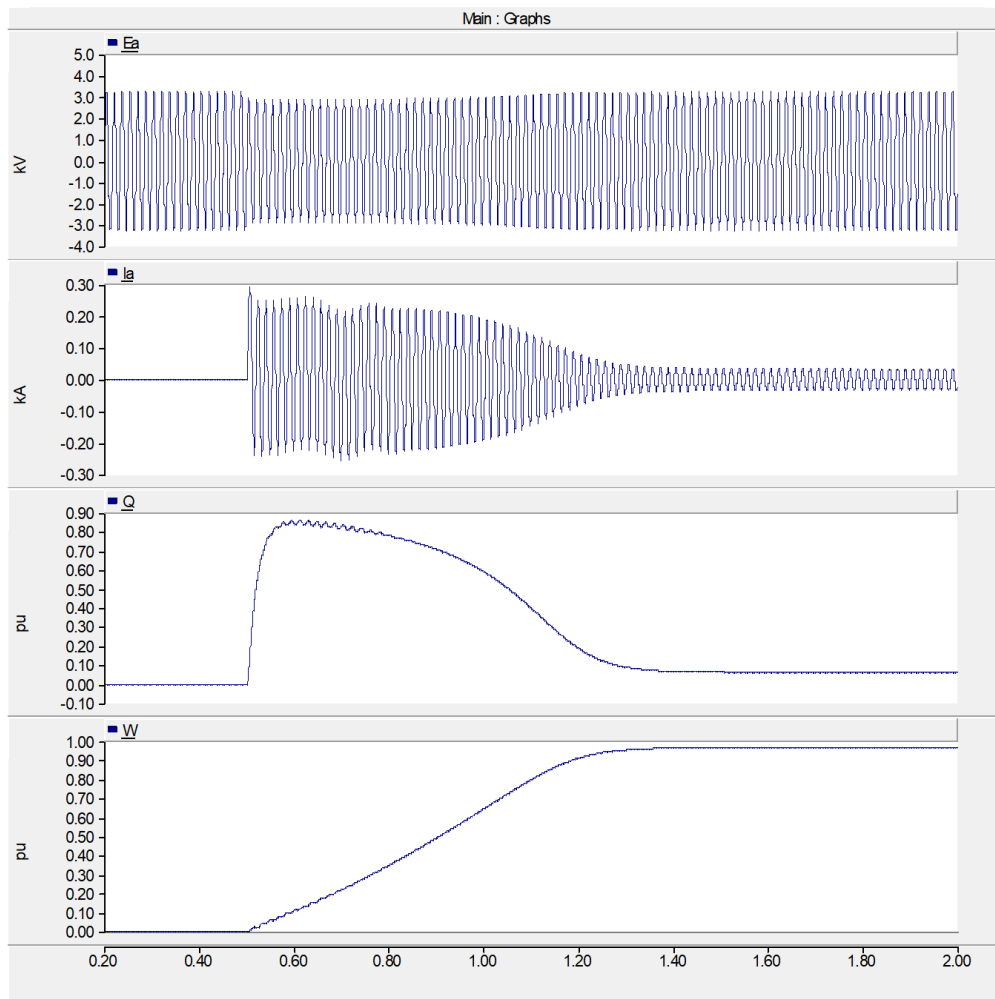


Figure 6: Motor Starting Transients

Figure 7 shows the variation of electric torque and mechanical torque during start-up. Note that the motor can take up to a few seconds to settle into steady-state operation.

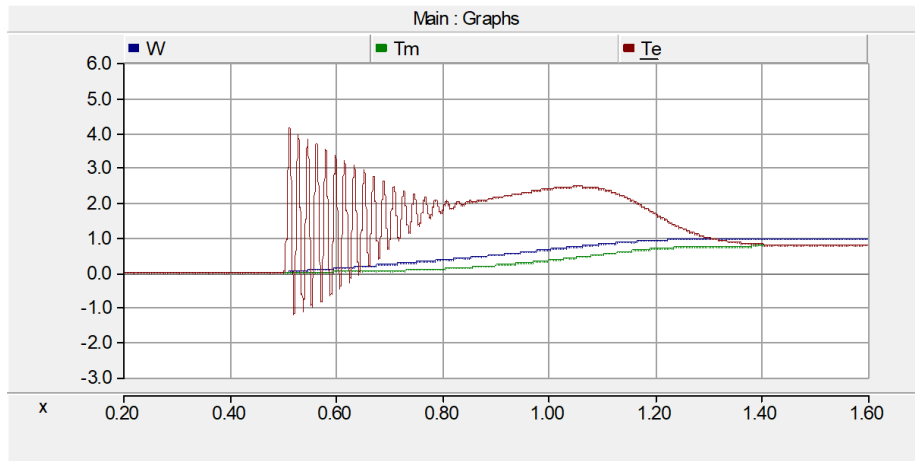


Figure 7: Comparison of Electrical and Mechanical Torque during the Motor Starting Process

## PSCAD

Refer to PSCAD case: *IM\_study\_02.pscx*



### 5.3 Induction Motor Initialization – Starting the Machine in Steady-State

#### Motivation

The motor starting study described in [Section 5.2](#) considered the scenario in which the motor starts from rest. However, for most other studies, it is required that the motor be operating in steady-state before contingencies such as faults are applied. Therefore, this section illustrates the techniques required to start an induction machine from steady-state.

#### System Overview

The network model and the details are as listed in [Section 5.2](#). Note that the machine speed ( $W$ ) has been set to the steady-state value, which is slightly lower than synchronous speed. The network is shown in Figure 8.

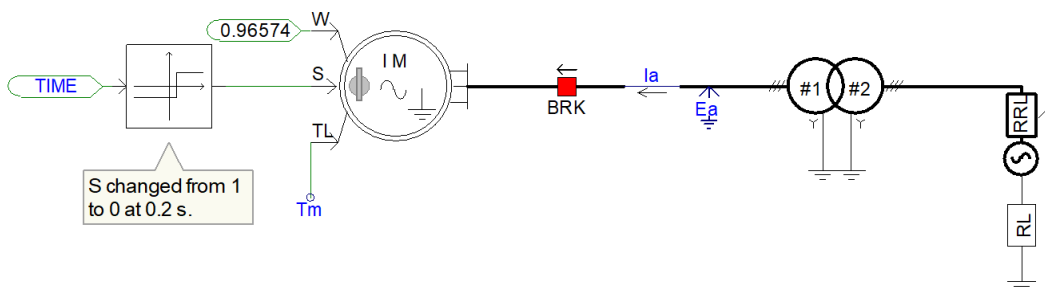


Figure 8: Speed Control to Torque Control Mode

To accomplish steady-state operation more quickly, the motor may be started in the ‘speed input’ mode with the steady-state speed assigned to input ‘ $W$ ’ (the steady-state speed can be computed based on machine data if required, or a value close to unity may be assigned as an approximation).

Initially, selector  $S=1$ , and the machine is operated at the specified speed which in this case is 0.96574. ‘ $S$ ’ is then changed to 0 at  $t=0.2$  s (torque input mode). In torque mode, the machine speed is calculated based on the mechanical torque, developed electrical torque of the machine, machine inertia and damping.

#### Simulation Results

The above procedure helps the simulation to attain steady-state much faster than if the machine was started from zero speed (note that the mechanical time constants are in the order of few seconds). In the simulation results shown in Figure 9, steady-state is achieved almost immediately following the transition ( $S - 1$  to 0). At 0.5 s, a fault on the system side (single phase fault lasting 6 cycles) is applied to study the machine response during such a fault (Figure 10).

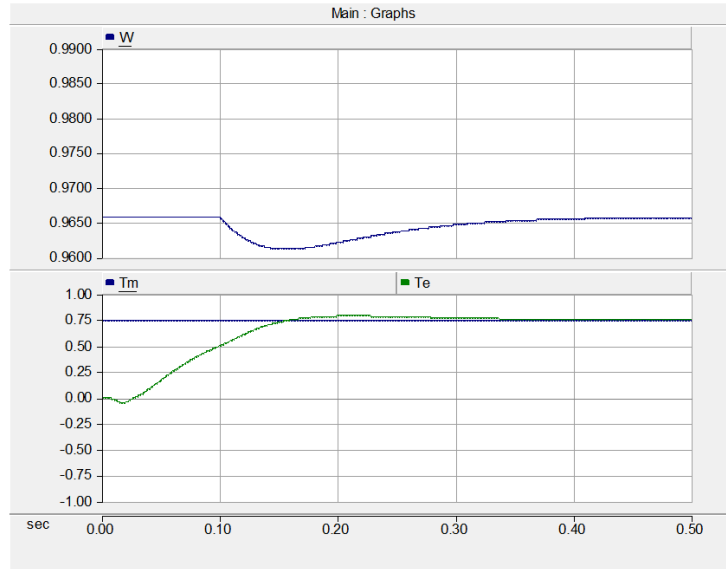


Figure 9: Comparison of  $W$ , Electrical ( $T_e$ ) and Mechanical ( $T_m$ ) in Switching Mode

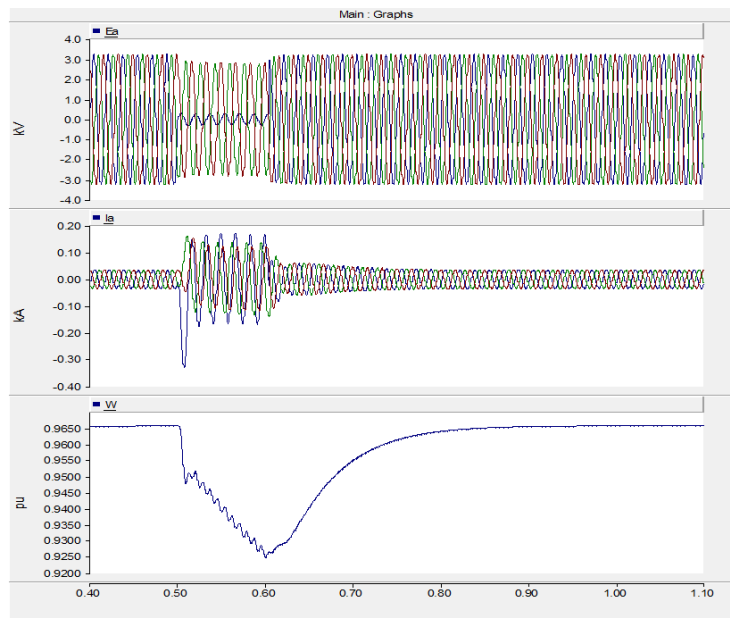


Figure 10: Response during a System Fault

**PSCAD**

Refer to PSCAD case: *IM\_study\_03.pscx*

### 5.4 Characteristic Curve of an Induction Motor

#### Motivation

The purpose of this section is to compare the accuracy of the characteristic curve of the induction machine generated by PSCAD with theoretical data.

#### Background

The induction machine can be represented by the equivalent circuit model show in Figure 11.

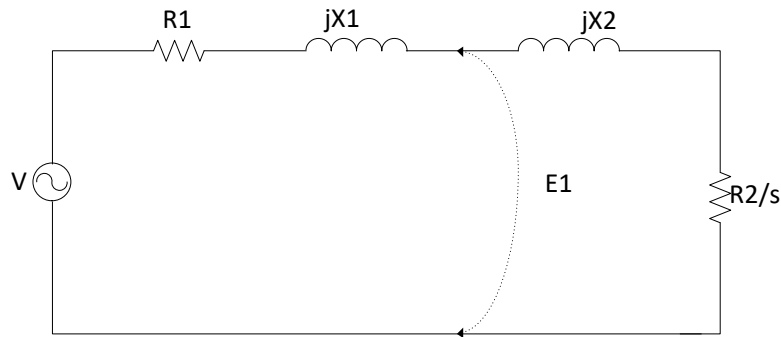


Figure 11: Equivalent Circuit of Induction Machine

The torque-speed curve of the induction machine is obtained based on equation (5-2).

$$T(s) = \frac{3V^2 R_2}{s\omega_0 \left[ \left( R_1 + \frac{R_2}{s} \right)^2 + (X_{eq})^2 \right]} \quad 5-2$$

$R_1$  and  $R_2$  are the equivalent resistances of the stator and rotor respectively,  $X_{eq}$  (i.e.  $X_1 + X_2$ ) is the equivalent reactance, and  $\omega_0$  is the synchronous angular speed. PSCAD modeling of the induction machine in steady-state is shown in Figure 12. The model is used to generate the characteristic curve of the induction machine operated in steady-state. The  $T_e - \omega_m$  curve of the induction machine is shown in Figure 12. All torque and rotation speed data in PSCAD are in per unit.

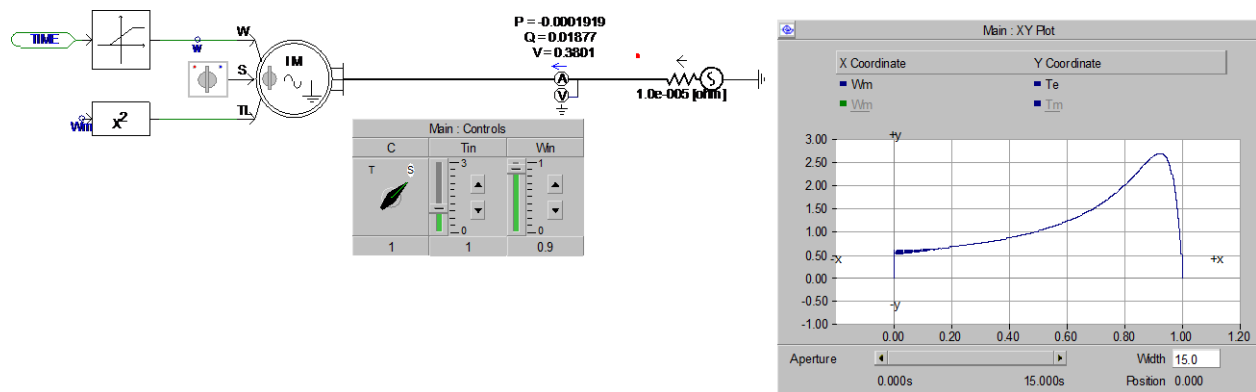


Figure 12: PSCAD Model

**Data Acquisition**

The torque-slip equation was set up in MathCAD and the 15 points were selected to plot the characteristic curve. This result was compared with the characteristic curve obtained from PSCAD. The theoretical calculation is shown in Figure 13.

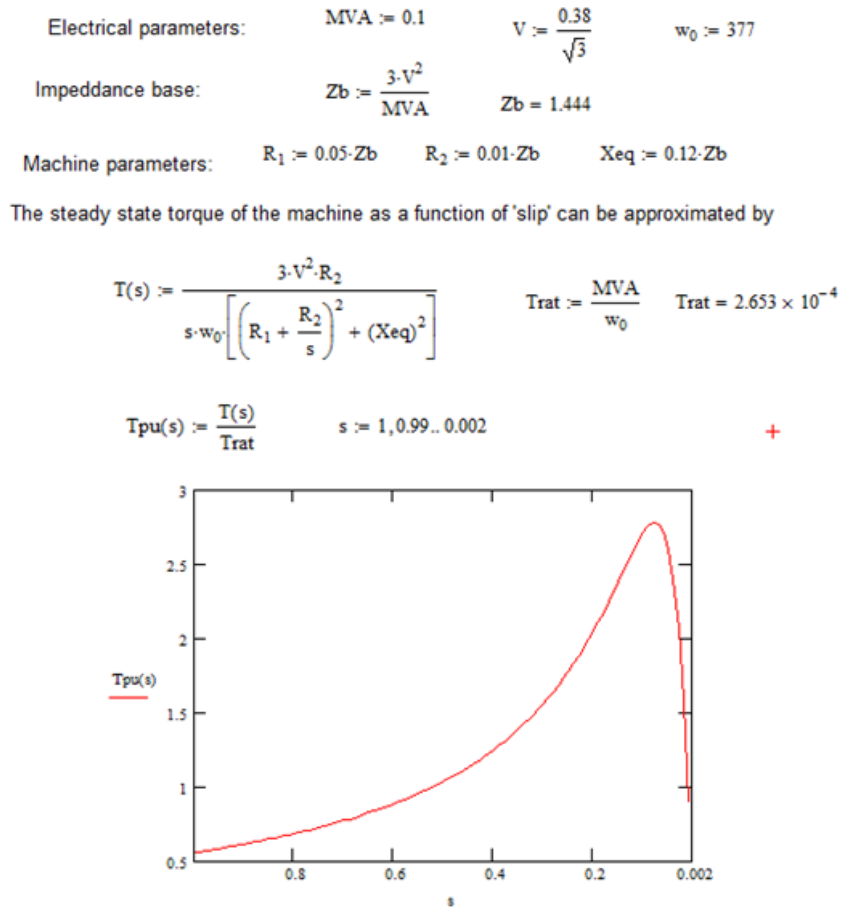


Figure 13: Theoretical Results from MathCAD

In PSCAD, the machine is run in speed control mode and the corresponding torque at different speed is recorded. Figure 14 shows the data acquisition in PSCAD.

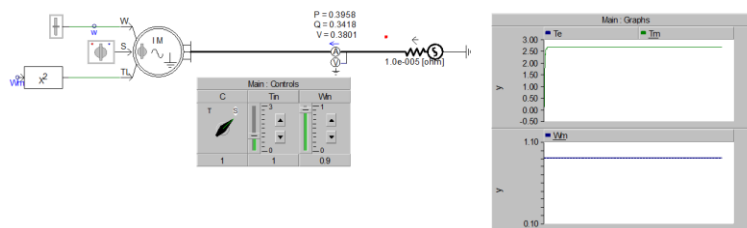


Figure 14: Data Acquisition using PSCAD

## Simulation Results

### Comparison of Data between Two Models

Table 1 shows all acquired data from MathCAD and PSCAD.

Slip	Speed Wm	Te in MathCAD	Te in PSCAD
0.002	0.998	0.196	0.191
0.01	0.99	0.895	0.876
0.02	0.98	1.578	1.55
0.03	0.97	2.066	2.03
0.04	0.96	2.395	2.35
0.06	0.94	2.717	2.68
0.09	0.91	2.753	2.72
0.1	0.9	2.71	2.68
0.2	0.8	2.049	2.02
0.4	0.6	1.248	1.23
0.6	0.4	0.884	0.87
0.8	0.2	0.683	0.674
0.9	0.1	0.613	0.6

*Table 1: Comparison of Theoretical and PSCAD Data*

Figure 15 compares the two plots and it clearly shows that the PSCAD results compare accurately with the theoretical data.

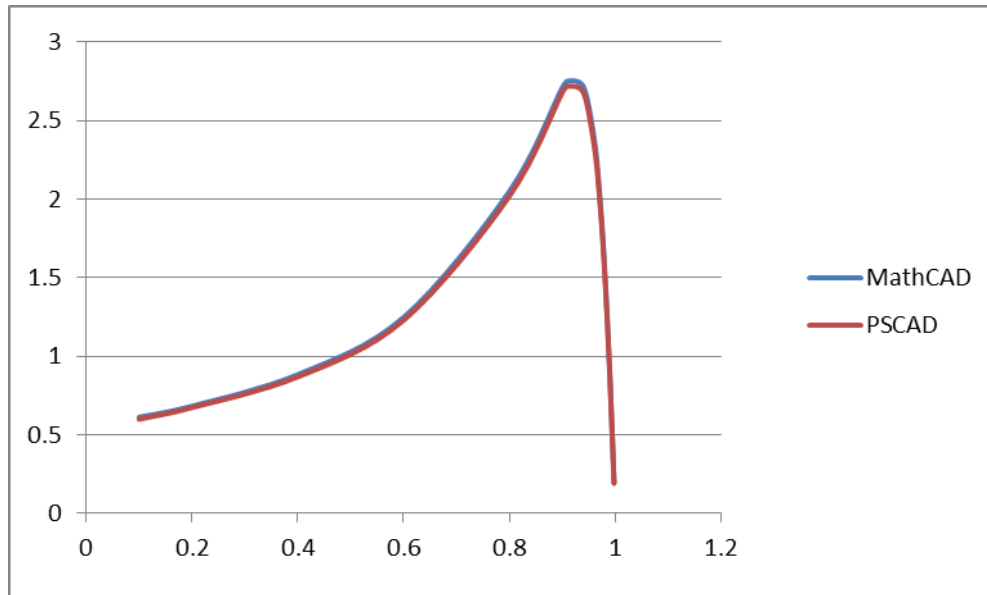


Figure 15: Comparison of the Characteristic Curve from Both Methods

Dynamic Performance of IM under a Non-Linear Load

In Figure 16, the induction machine is operated in torque input mode with a non-linear load on its shaft. The power source breaker BRK is closed at 0.5 s to empower the IM. The simulation result of  $T_e - \omega_m$  is shown in Figure 17. Figure 18 displays the corresponding induction machine terminal current I, mechanical load on the shaft, and rotation speed.

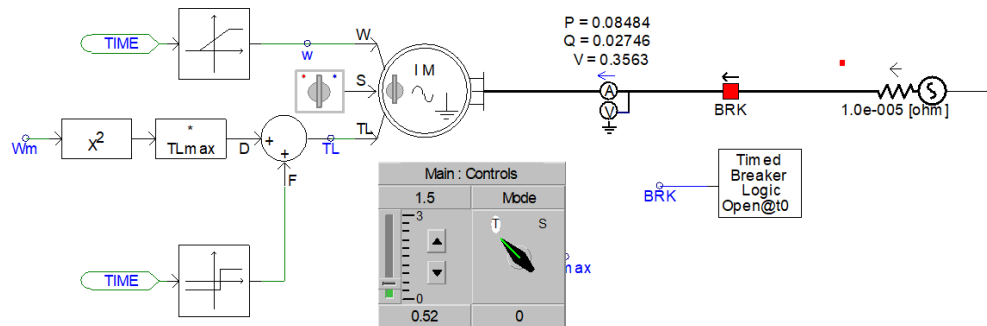


Figure 16: Induction Machine in Torque Input Mode

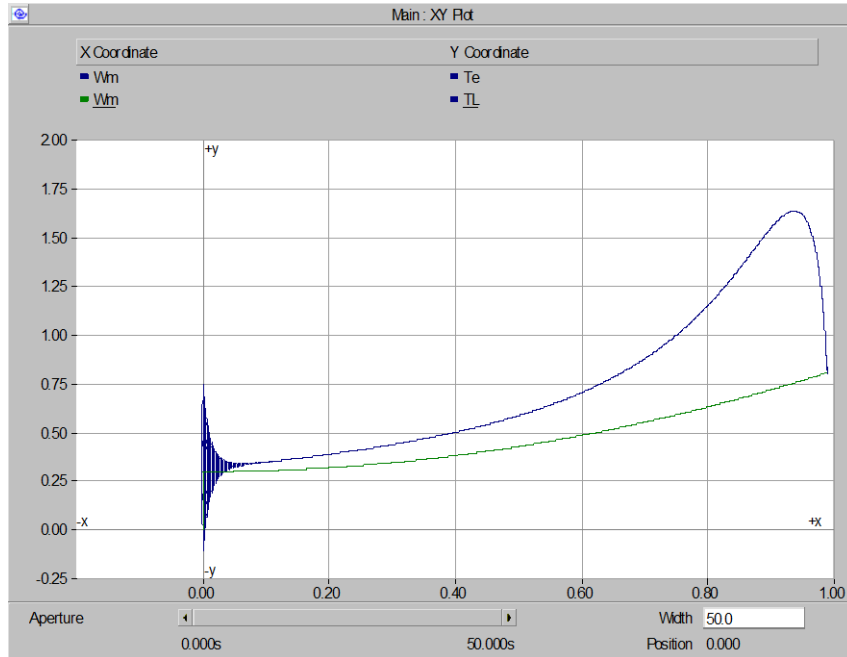


Figure 17: Torque-Speed Curve

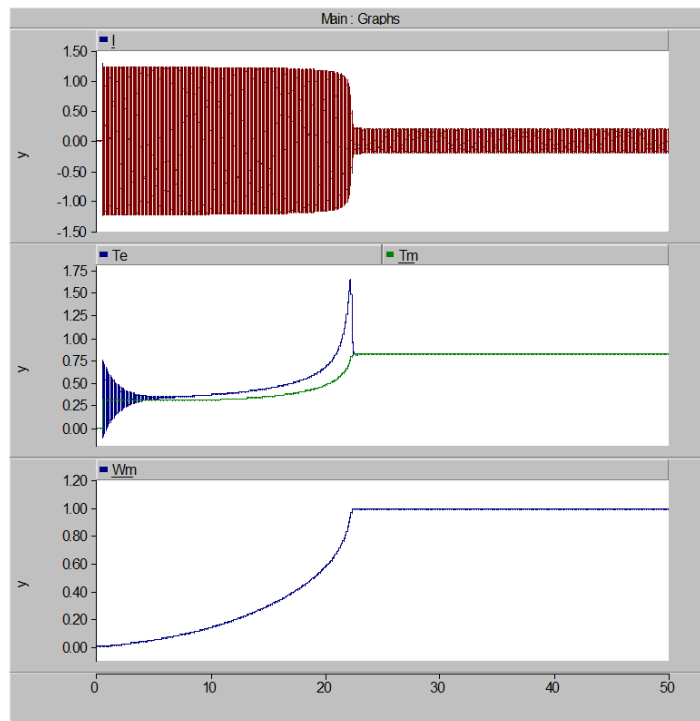


Figure 18: Variation of Induction Machine Parameters

## 5.5 Induction Generator Self Excitation Affects with External Capacitors for Reactive Power Compensation

### Motivation

This section presents the harmful behaviors of self-excitation in an induction generator at fixed torque input mode. External capacitors for reactive power compensation are connected at the three-phase terminal.

### System Overview

The case circuit is shown in Figure 19.

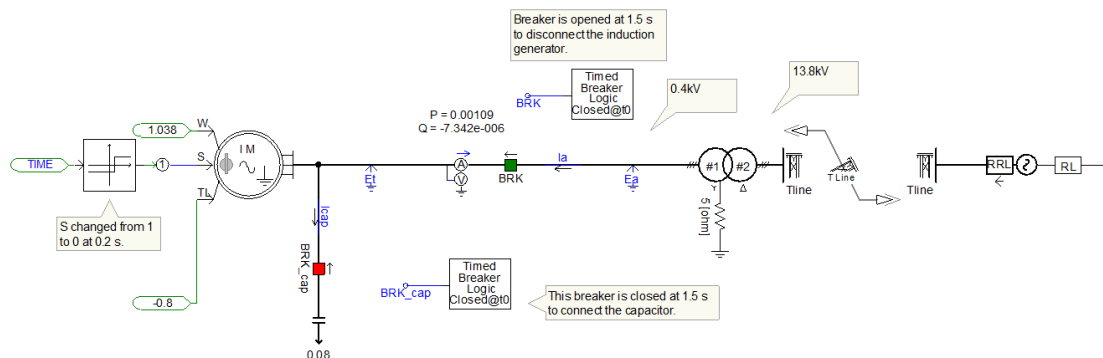


Figure 19: Case Circuit

### Induction Generator

An induction motor does not require a separate field circuit and does not have to work at a fixed speed. It works as a generator as long as the rotor speed is faster than the synchronous speed of the connected power system. If a greater torque is applied to the rotor shaft, the stator outputs greater power. The generator does not require a fancy regulation. Because of its advantage of simplicity, it is applied in windmills, heat recovery systems, and similar supplementary power sources attached to an existing power system [1].

An induction generator produces no reactive power since has no separate field excitation circuits. It needs an external source of reactive power to maintain its stator magnetic field because it consumes reactive power. Because the induction generator is unable to control its own output voltage without field current, the external reactive power source is used to control its output voltage. Therefore, the induction generator is connected to the external power system to maintain the terminal voltage. In this situation, capacitors provide power-factor correction, and the external power system controls the generator's terminal voltage [1].

With no connection to any power system, an induction motor can function as an independent generator, as long as available capacitors or any attached loads supply required reactive power [1].

The relation between the magnetizing current required by the induction machine and terminal voltage can be found by measuring its armature current  $I_m$  as a function of terminal voltage  $V_t$ .



Figure 20(a) shows this magnetization curve at different rotation speeds. In order for an induction generator to achieve a given voltage level, external capacitors must supply the magnetization current corresponding to that level [1].

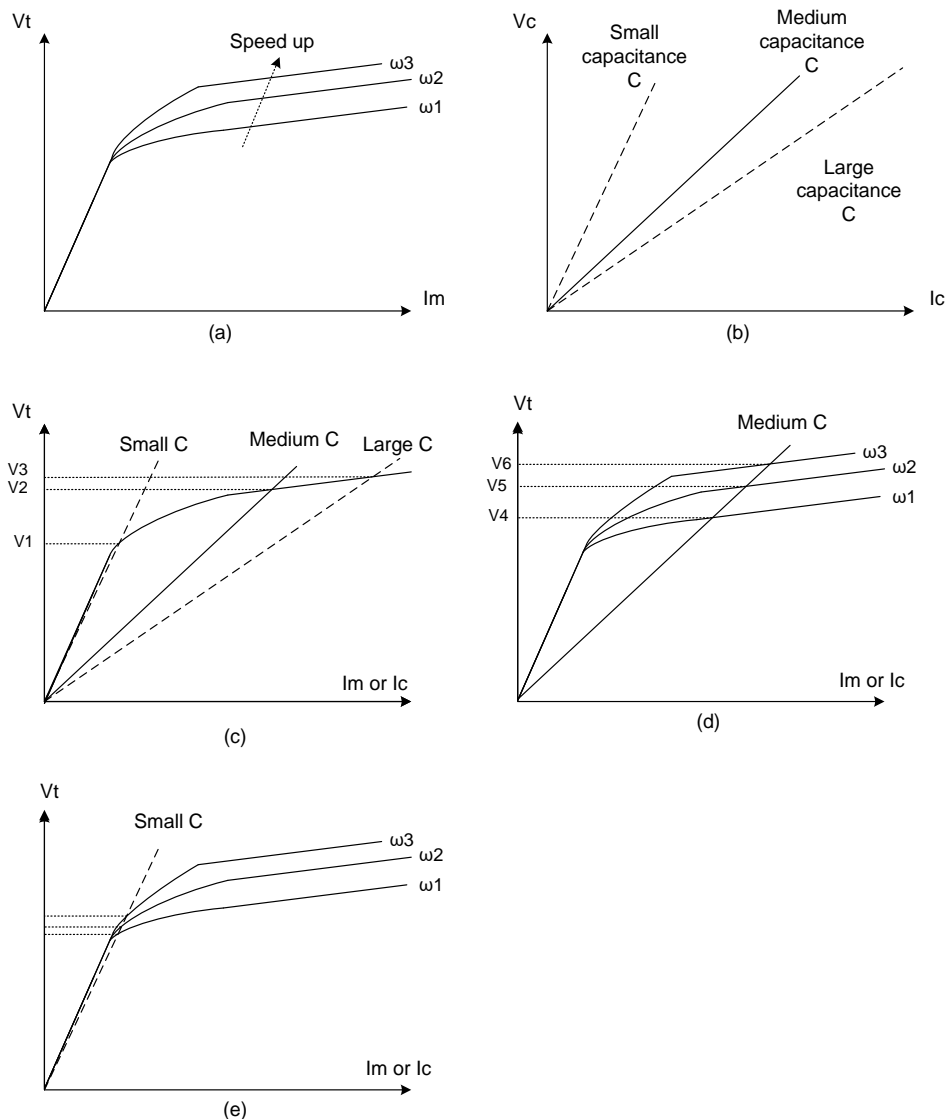


Figure 20: Magnetizing Current

A capacitor produces a reactive current which is directly proportional to the voltage applied to it. The relation of the voltage and current through a capacitor is a straight line for a given frequency; this is shown in Figure 20(b). Figure 20(c) shows the terminal voltage of an induction generator for three different sets of capacitance [1]. When the capacitor is fixed, the terminal voltage also varies if the rotor speed changes, as shown in Figure 20(d). But if the terminal shunt capacitor is very small, the magnitude of the generator terminal voltage does not escalate based on the theory illustrated in Figure 20(e) even though the generator speed increases.

The induction generator has two serious problems. First, its terminal voltage varies wildly with changes in load, especially reactive load. Secondly, the induction generator's frequency varies with

changing loads because of the nature of the induction machine's torque-speed characteristic. But the total frequency variation is usually limited to less than 5% because the torque-speed characteristic is very steep in the normal operating range [1].

### Simulation Results

The induction generator connected to a compensation capacitor and power system in Figure 19 has been simplified in Figure 21. An external power source may or may not provide reactive power to the generator, depending on the load in the external power system. Therefore, capacitors are connected at the terminal of the generator to provide the major reactive power  $Q_1$  as required by the generator, in order to ensure rated generator terminal voltage. Based on the theory shown in Figure 20(c), proper capacitor banks must be chosen, to provide the generator enough magnetic current at rated terminal voltage and rated rotation speed.

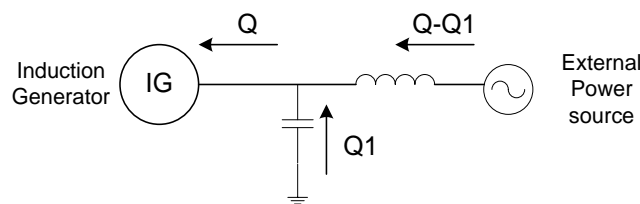


Figure 21: Simplified Case Circuit

When the induction generator and the capacitor are disconnected at 0.5 s from the external power source, terminal voltage of the induction generator will change because the reactive power input and active power load at the external power source are cut off. At this time, the generator speed will keep increasing because the constant driving torque coming from the prime mover is still working, but there is no active power load at the generator terminal any more. Based on Figure 20(d), at the condition of fixed terminal shunt capacitor and increasing generator speed, the terminal voltage also increases. The capacitor acts as a reactive power source to the generator and tries to sustain the voltage. In practical machines, the iron saturation (of the machine core) will have a limiting effect on the over-voltage. The simulation result is shown in Figure 22, when the capacitive load is 0.2MVAR. At this moment, the capacitive load provides not only enough reactive power to the generator but also to an external power source. But if the capacitive load is 0.02MVAR, the terminal voltage does not increase as shown in Figure 23. And the generator needs reactive power not only from the reactive load but also from the external power source.

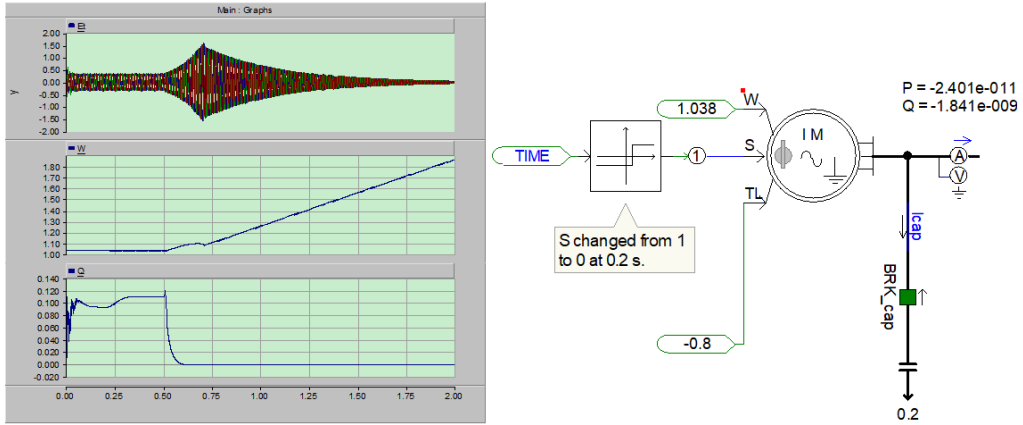


Figure 22: Simulation Results (Capacitive Load is 0.2 MVAR)

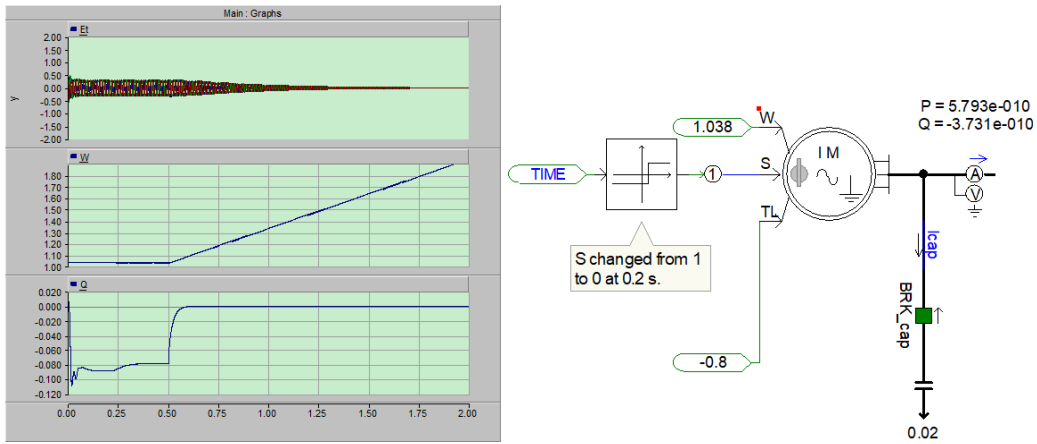


Figure 23: Simulation Results (Capacitive Load is 0.02 MVAR)

In addition to the terminal voltage changes, the frequency of the terminal voltage may change. The reason is explained in Figure 24. When the breaker cuts the external power source off, the RLC circuit is formed, and the frequency of the transient response is  $1/2\pi\sqrt{LC}$ . This phenomenon is called self-excitation. Therefore, one of the solutions to protect the generator is to cut off the capacitor banks after the external power source has been disconnected.

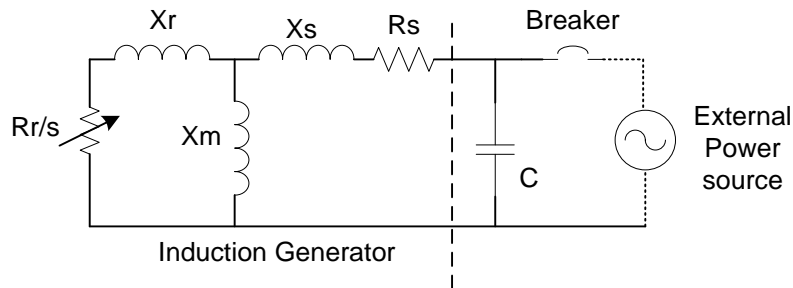


Figure 24: Solution for Protecting the Generator

## PSCAD

Refer to PSCAD case: *IM\_study\_05.pscx*

## References

- [1] Chapman, Stephen J., "Electric Machinery Fundamentals", 4th ed. New York, NY: The McGraw-Hill Companies, 2005.

## 5.6 Wound Rotor and Squirrel Cage Induction Machine Models

### Motivation

The PSCAD master library has two induction motor models:

- A squirrel (SQ) cage induction machine model representing a double cage design
- A wound rotor (WR) induction machine (IM) model

Mathematically, the SQ cage machine can be represented by the WR machine. The WR model could also be used to represent a double cage SQ machine.

PSCAD users are encouraged to use the WR IM model for all the induction machine applications. The two examples below describe relevant data entry considerations and also compare results for validation purposes.

### System Overview

A 0.6 kV, 60 Hz source is connected to a 0.6 kV SQ cage and a WR induction machine. Both machines have identical ratings (see Figure 25).

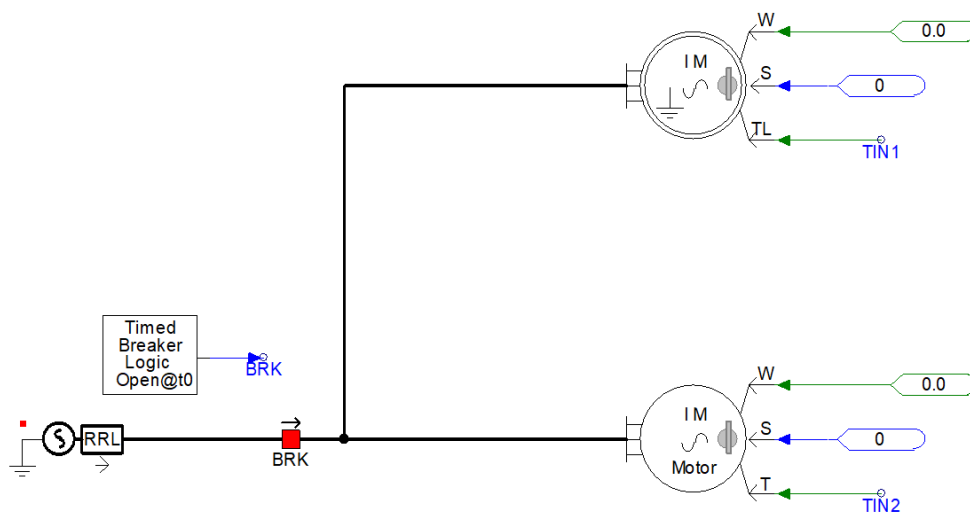


Figure 25: Circuit Diagram (WR – Top, SQ Cage – Bottom)

### Example 1 - Modeling a Single Cage Induction Machine

The SQ cage machine model or the WR machine model may be used to represent a single cage (SQ) machine. Refer to PSCAD case *IM\_study\_06\_A.pscx*.

The equivalent circuit of a double cage design, squirrel-cage machine is shown in Figure 26.

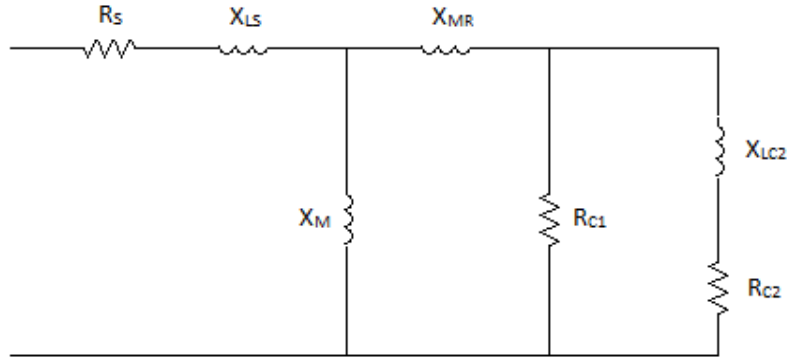


Figure 26: Squirrel Cage (Double Cage) Equivalent Circuit

The equivalent circuit of a wound rotor machine model (single rotor winding) is shown in Figure 27.

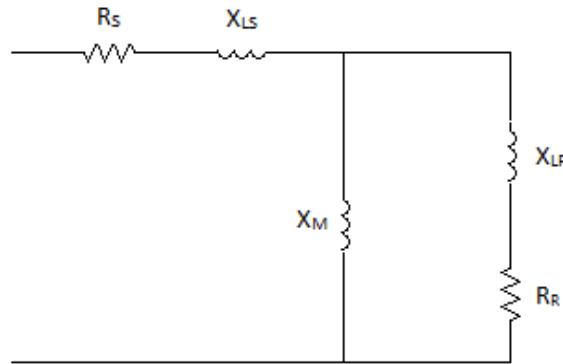


Figure 27: WR IM (Single Winding) Equivalent Circuit

To use the SQ cage machine model to represent a single cage machine:

- Make the 'second cage resistance' ( $R_{C2}$ ) and the 'second cage unsaturated reactance' ( $X_{LC2}$ ) relatively large (compared to the other leakage inductances/resistances). In this case, they are changed to  $R_{C2} = 5$  PU and  $X_{LC2} = 5$  PU, which is much larger than  $R_{C1} = 0.0507$  PU and  $X_{MR} = 0.091$  PU.
- Give the SQ cage 'rotor unsaturated mutual reactance' ( $X_{MR}$ ) the value of the WR 'rotor leakage reactance' ( $X_{LR}$ ).

Figure 28 shows the data entry for the SQ cage (left) and WR models (right). By using equivalent values, both models show comparable behaviour and represent a single cage machine design.

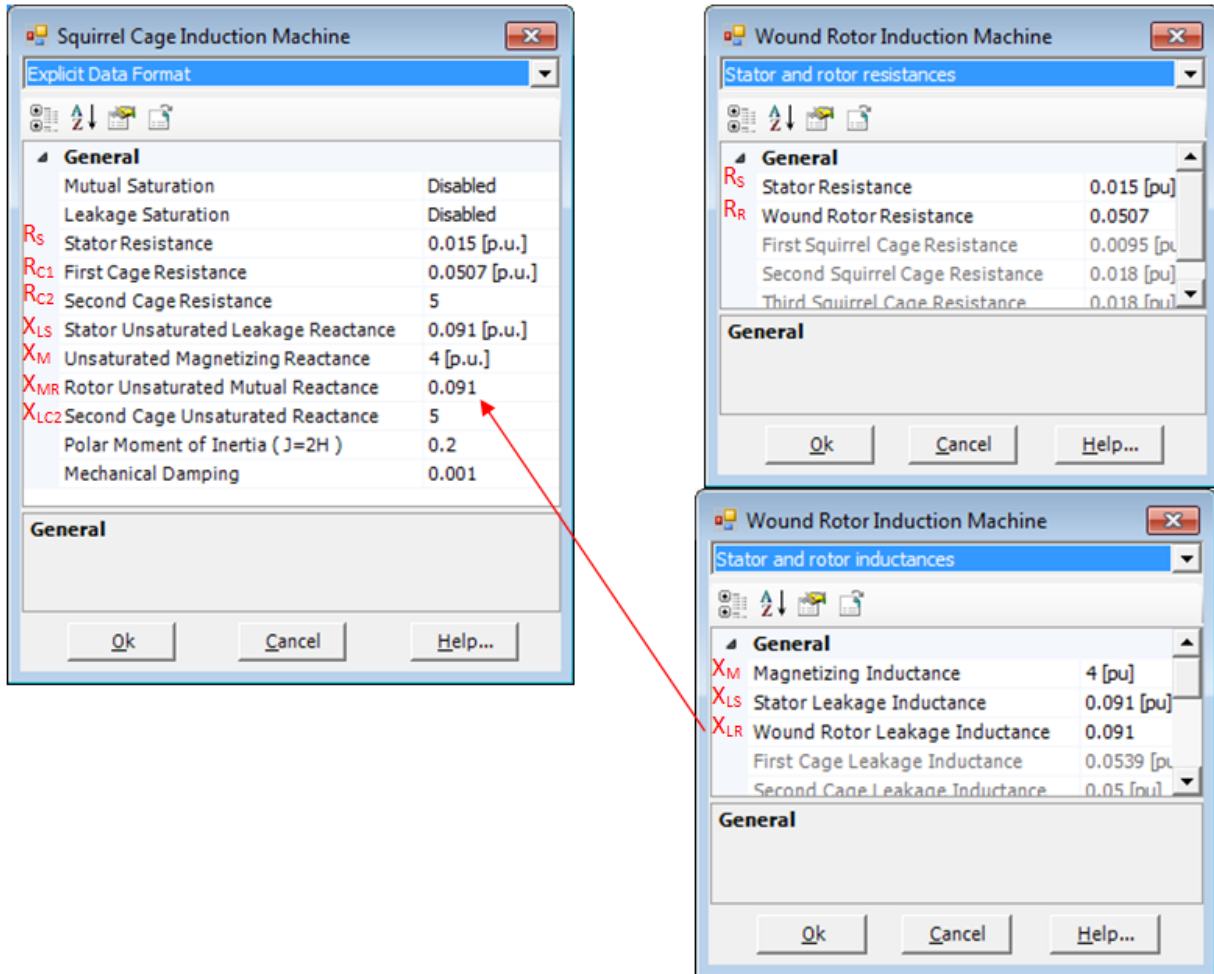


Figure 28: WR IM (Single Winding) Equivalent Circuit

The simulation results shown in Figure 29 show that the speed (W – WR, W2 – SQ cage) and torque (T – WR, T2 – SQ cage) of both machines are the same. Thus, any one of the induction machine models may be used to represent a single cage induction machine.

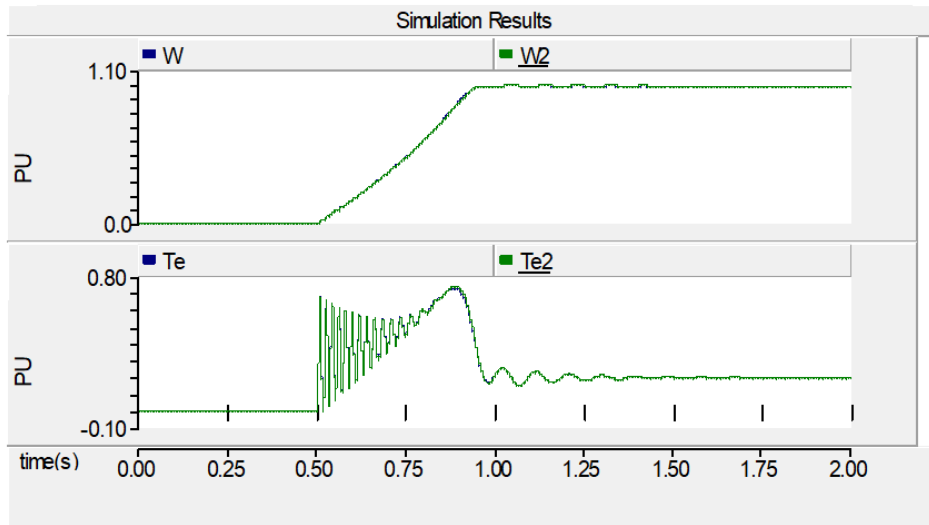


Figure 29: Simulation Results (IM\_study\_06\_A.pscx)

### Example 2 - Modeling a Double Cage Induction Machine

The WR machine model can be set up to represent a double cage SQ cage machine (see PSCAD case *IM\_study\_06\_B.pscx*).

In the WR model, select the “Number of Rotor Squirrel Cages” to “1”, as shown in Figure 30.

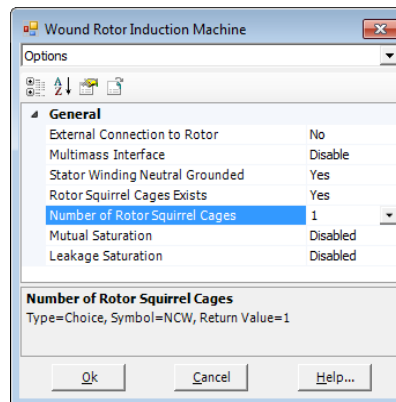


Figure 30: WR Configuration



Once this has been set, the equivalent circuit representation is as shown in Figure 31.

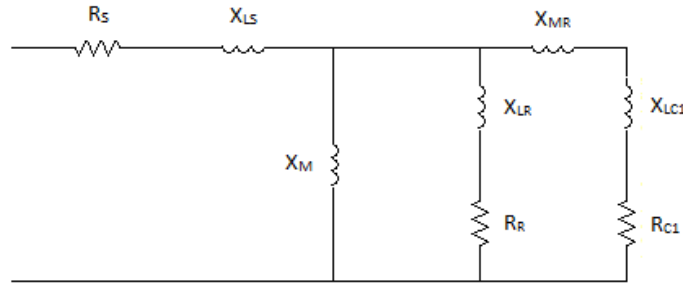


Figure 31: WR IM (Two Winding) Equivalent Circuit

Figure 32 shows the data entry for the WR model. With the appropriate data, the SQ cage and WR machine models will give similar results.

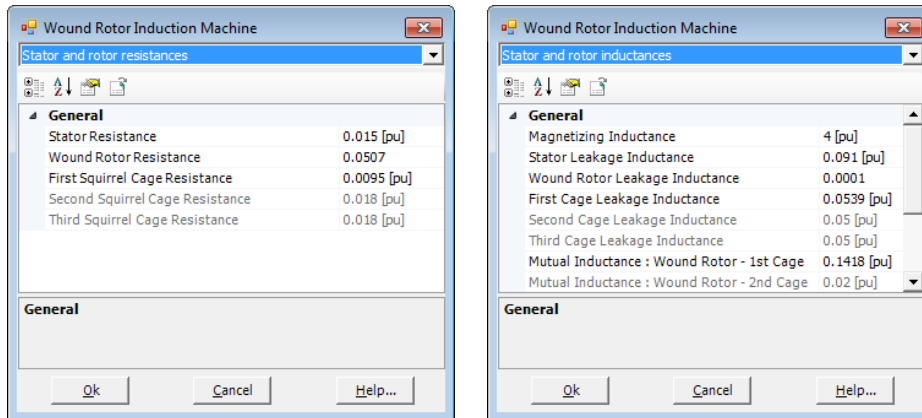


Figure 32: WR Setup Configuration

The simulation results shown in Figure 33 show that the speed ( $W - WR$ ,  $W2 - SQ$  cage) and torque ( $T - WR$ ,  $T2 - SQ$  cage) of both machines are identical. Therefore, a double cage SQ machine can be accurately modeled using the WR induction machine model in PSCAD.

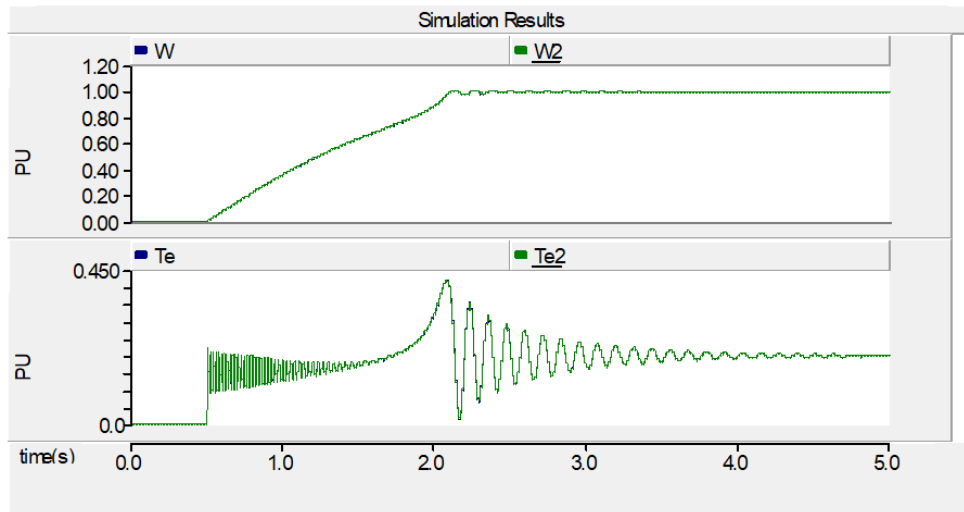


Figure 33: Simulation Results (*IM\_study\_06\_B.pscx*)

### Discussion

As can be seen from the results, a SQ cage and WR machine model deliver equivalent results when configured properly. Hence, a SQ cage machine model can be accurately represented using a WR machine model. PSCAD users are encouraged to use the WR IM model for all the induction machine applications.

### PSCAD

Refer to PSCAD cases: *IM\_study\_06\_A.pscx* and *IM\_study\_06\_B.pscx*



## DOCUMENT TRACKING

Rev.	Description	Date
0	Initial	01/Jun/2013
1	Update to New Brand Guidelines	09/May/2018
2	Correction to broken figures	09/Nov/2020

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