PSCAD Cookbook

Synchronous Machine Studies

Manitoba HVDC Research Centre
a division of Manitoba Hydro International Ltd.
211 Commerce Drive
Winnipeg, MB R3P 1A3, Canada
www.hvdc.ca

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10. Synchronous Machine Studies

10.1 Methods of Initializing a Synchronous Machine

Motivation

The objective of this Chapter is to become familiar with the synchronous machine model in PSCAD, and to demonstrate various methods of initializing the synchronous machine to reach a specific load flow steady-state condition.

System Overview

In order to investigate the effect of various phenomena (e.g. faults) in the system, it is crucial that the system is initialized properly and is under proper steady-state load flow conditions.

In PSCAD, the recommended method of initializing the machine is to start it as a fixed voltage source and use this mode of operation to determine the exciter and governor input (or field voltage and mechanical torque) parameters needed to produce the desired steady-state load flow condition.

> **Note**
> The synchronous machine model in PSCAD provides the option of running it as pure source. The model also provides the option of running it at a fixed speed of 1 PU (with the mechanical dynamics disabled).

Case 1 – Machine Model without Controllers (Exciter/Governor)

Figure 1 shows a very simple case to illustrate the load flow initialization of the network when a machine model is used in the simulation. For simplicity, machine controls such as exciters and governors are not included in this model.

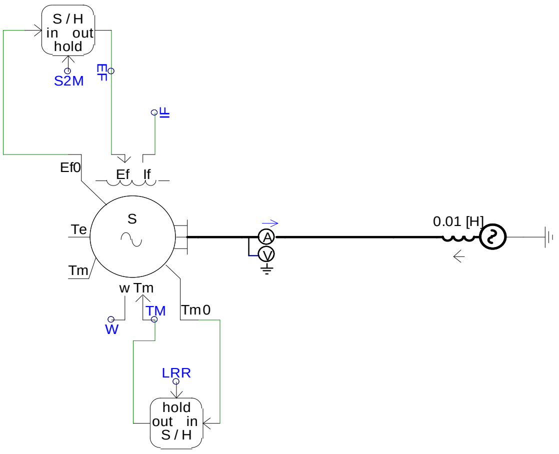
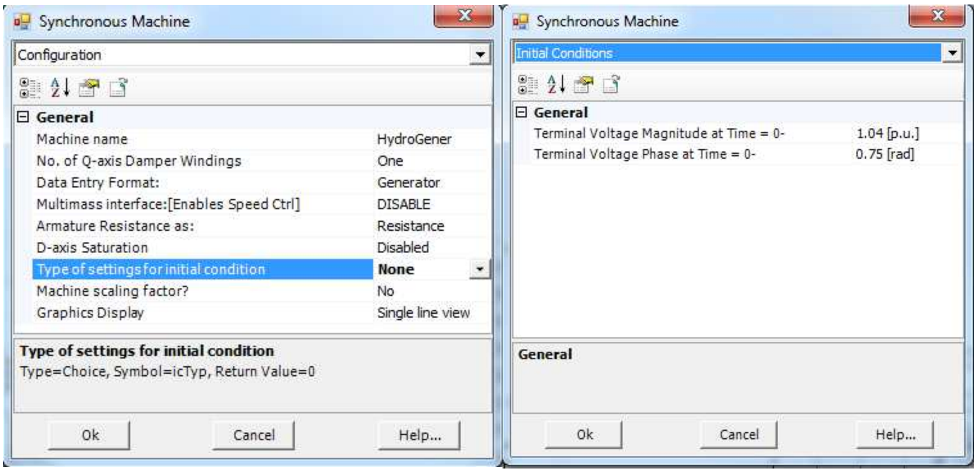


Figure 1: PSCAD Model to Study the Initialization of Synchronous Machine (PSCAD Case SM_study_01_A.pscx)

At time t=0, the machine is run as a pure source with its terminal voltage magnitude and phase as specified by the user. To operate the machine as a pure source, set the initial condition option in the parameter field to 'none', as shown in Figure 2. This enables the user to specify the terminal voltage conditions alone and properly initialize the machine and the network to a specific load flow.



General

Machine name	HydroGener
No. of Q-axis Damper Windings	One
Data Entry Format:	Generator
Multimass interface:[Enables Speed Ctrl]	DISABLE
Armature Resistance as:	Resistance
D-axis Saturation	Disabled
Type of settings for initial condition	None
Machine scaling factor?	No
Graphics Display	Single line view

Type of settings for initial condition
Type=Choice, Symbol=icTyp, Return Value=0

General

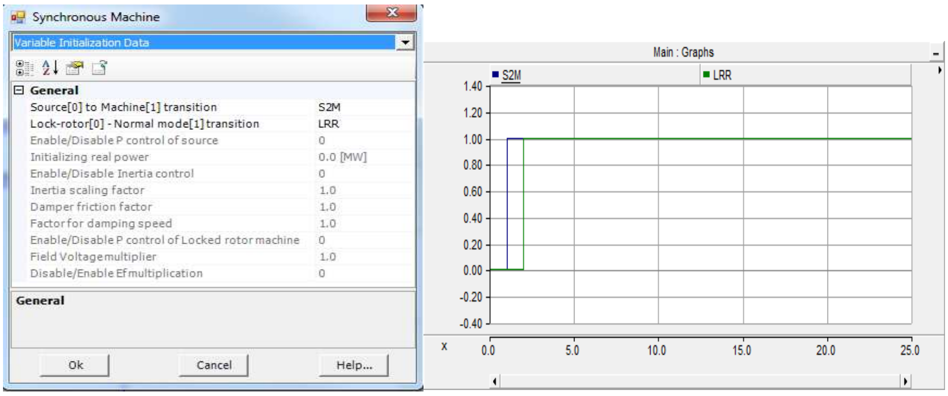
Terminal Voltage Magnitude at Time = 0-	1.04 [p.u.]
Terminal Voltage Phase at Time = 0-	0.75 [rad]

General

Figure 2: Initial Condition Option Available in PSCAD

The variable initialization control (S2M) specifies the time at which the model transitions from source to a normal machine with all of its electrical equations 'active'. To ensure that the machine is operating as a pure source, the 'variable initialization control' (S2M) has to be set to ‘0’ until the required steady-state condition is attained. In this example, the signal ‘S2M’ is set to change its state from 0 to 1 at time t=2 s (Figure 3). At the instant the signal S2M switches from 0 to 1, the model acts as a normal synchronous machine but with the machine speed fixed at 1 PU. The output signal ‘Ef0’ is the ‘initialized’ field voltage of the machine that would be necessary to hold the machine’s steady-state operation. At the instant S2M changes state, the value of Ef0 is sampled and is provided as a constant field voltage input to the machine’s field winding.

If necessary, the user may run the simulation for a further duration at constant speed, allowing small transients that may occur at S2M transition to decay before ‘releasing’ the rotor mechanical dynamics. In this example, the rotor dynamics are ‘unlocked’ at t=2.5 s, the point at which the signal LRR transitions from 0 to 1. The output signal ‘Tm0’ is the ‘initialized’ mechanical torque that would be necessary to hold the machine’s steady-state operation. At the instant the LRR changes state, the value of ‘Tm0’ is sampled, and is provided as a constant input to the machine’s mechanical input field ‘Tm’.



General

Source[0] to Machine[1] transition	S2M
Lock-rotor[0] - Normal mode[1] transition	LRR
Enable/Disable P control of source	0
Initializing real power	0.0 [MW]
Enable/Disable Inertia control	0
Inertia scaling factor	1.0
Damper friction factor	1.0
Factor for damping speed	1.0
Enable/Disable P control of Locked rotor machine	0
Field Voltage multiplier	1.0
Disable/Enable Ef multiplication	0

General

Figure 3: Switching from Source Mode to Machine Mode and Enabling the Rotor Dynamics

Simulation Results

Figure 4 shows the variation of the machine parameters when it is switched from source to machine mode at t=2 s, and also when the rotor is released at t=2.5 s.

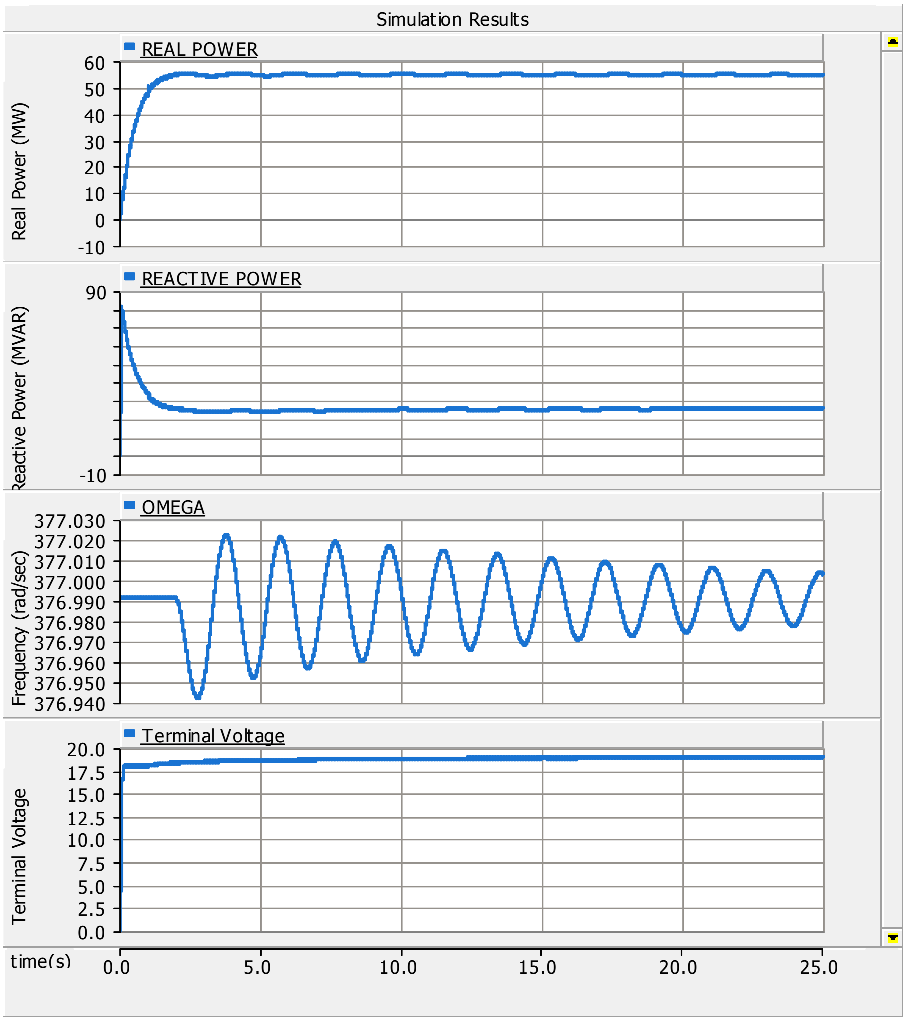


Figure 4: Simulation Results

Case 2 – Machine Model with Exciter, Governor and Turbine Models in the Simulation

For a more realistic simulation, the exciters and governors and turbine models should be included in the simulation. Figure 5 shows the PSCAD model of a synchronous machine with the exciter model in place.

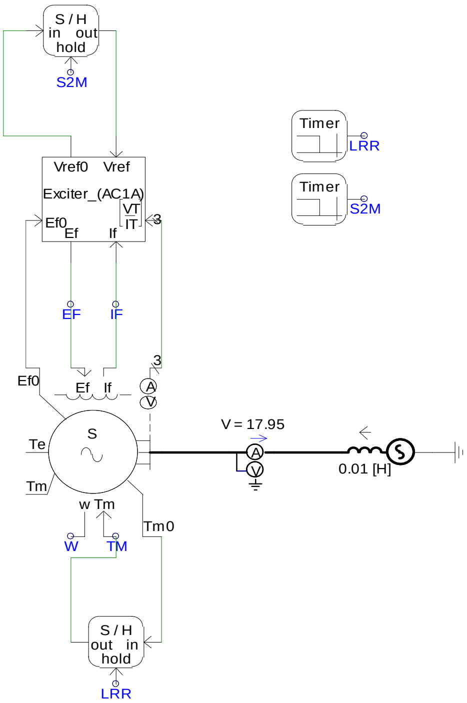
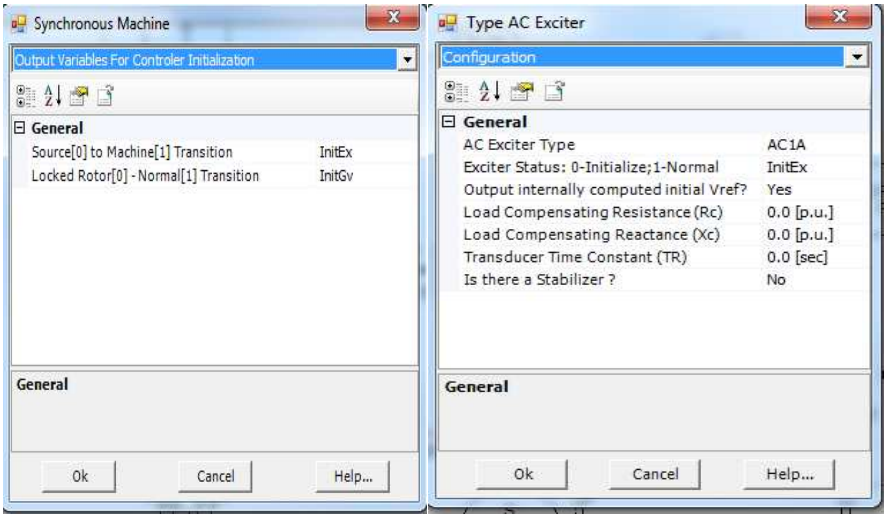


Figure 5: PSCAD Model to Demonstrate Initialization with Exciter (PSCAD Case SM_study_02_A.pscx)

As explained in Case 1, set the initial terminal voltage magnitude and phase of the synchronous machine, and operate it as a pure source. The terminal voltage magnitude and phase, set with respect to a 'reference bus' (i.e equivalent voltage source), ensures the desired active and reactive power flow.

The exciter is initialized at the time instant when S2M changes state. This may be ensured by setting the output controller initialization variable (InitEx) (as defined in the machine model) (see Figure 6). The same signal name is used inside the exciter model to define the instant that it should initialize its internal parameters and output the desired field voltage (Ef) value as given by Ef0.



General

Source[0] to Machine[1] Transition InitEx
Locked Rotor[0] - Normal[1] Transition InitGv

General

General

AC Exciter Type AC1A
Exciter Status: 0-Initialize;1-Normal InitEx
Output internally computed initial Vref? Yes
Load Compensating Resistance (Rc) 0.0 [p.u.]
Load Compensating Reactance (Xc) 0.0 [p.u.]
Transducer Time Constant (TR) 0.0 [sec]
Is there a Stabilizer ? No

General

Figure 6: Controller Initialization Variable

Figure 7 shows the control signals to the synchronous machine and the exciter.

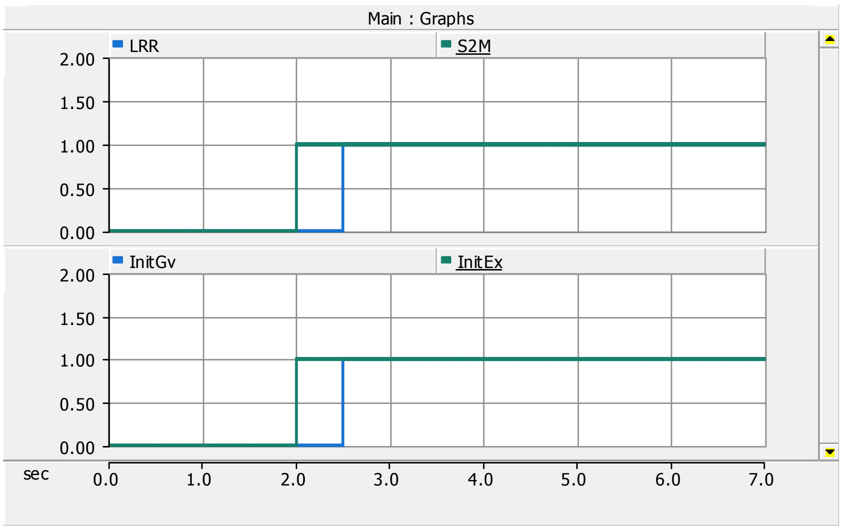


Figure 7: Control signals

Note that, in addition to the desired output field voltage to the machine (Ef0), the field current (If), terminal voltage, and current (VT/IT) are provided as inputs to the exciter model. PSCAD then calculates the initialized value of the reference voltage 'Vref0' required to maintain the steady-state operating condition. Vref0 is the 'initialized' voltage setpoint to maintain the specified steady-state terminal conditions. Once the system enters steady-state, a sample and hold component may be used to hold this steady-state reference voltage and feed the signal back to the exciter through input 'Vref'.

Notes

1. During initialization, the machine is operated as pure source.
2. If the user must change the voltage reference point during the simulation, this may be done through an external (variable) input which is given a zero value initially. See Figure 8.

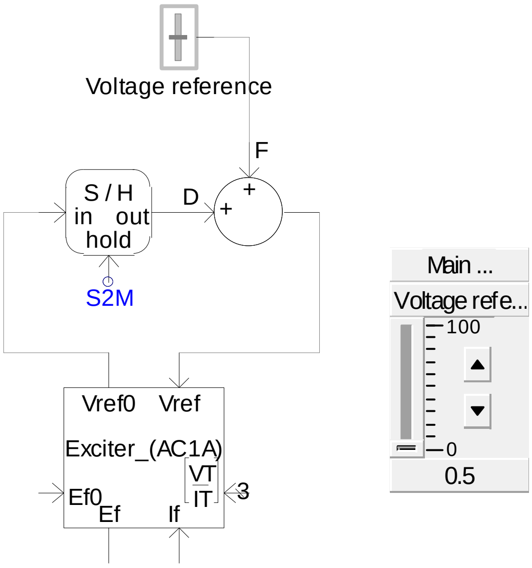


Figure 8: Option for Variable Reference Control

Governor and Turbine Initialization

After the initial transients have settled, the machine mode is activated by switching S2M from 0 to 1. At this instant, the rotor will be spinning at a constant speed as the machine is still in the 'locked rotor' state. The governors and turbines may be initialized at the time instant when the rotor is unlocked, i.e. when the signal LRR is switched to 1. Once this happens, the mechanical dynamics, as defined by Equation [1], is active.

$$T_m - T_e = J\frac{d\omega_m}{dt} + B\omega_m \qquad (1)$$

The simulation model with a governor/turbine model is shown in Figure 9. These models are 'initialized' in a manner similar to that used to initialize the exciter. Signal 'InitGv' (Figure 6) is the control signal that activates the initialization of the governor.

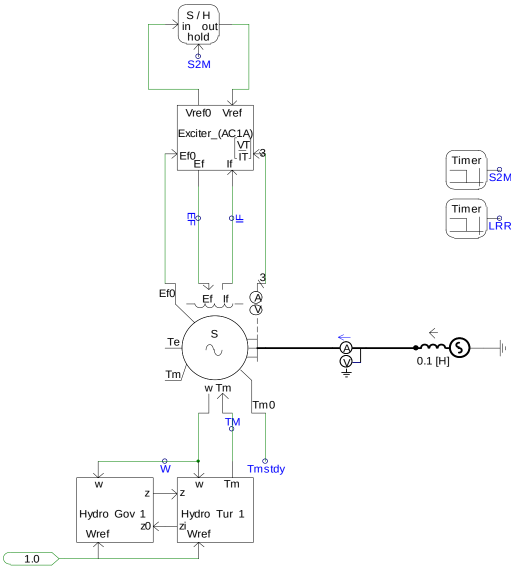


Figure 9: PSCAD Model for Synchronous Machines with Exciter, Governor and Turbines (PSCAD case SM_study_02_B.pscx)

Simulation Results

The variation of the various machine parameters when the machine is switched from source to machine mode at t=2 s and also when the rotor dynamics are activated at t=2.5 s is shown in Figure 10.

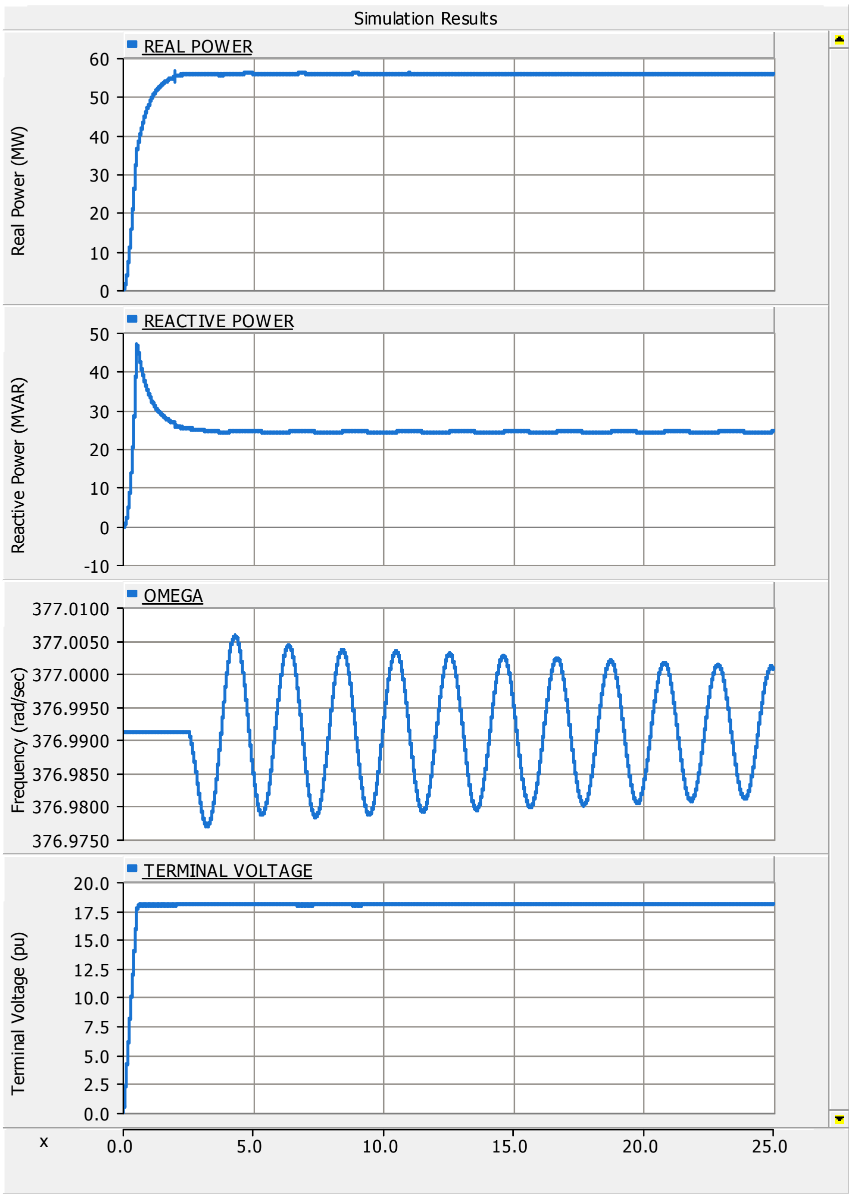


Figure 10: Simulation Results using Governor and Exciter

At the point in time when the machines are running free, and the excitation and governor systems are stable, a 'snapshot' may be taken. Faults and disturbances may be applied to the system with the start-up commencing from the 'snapshot file'.

PSCAD

Refer to PSCAD cases: SM_study_01.pscx , SM_study_02_A.pscx and SM_study_02_B.pscx

10.2 A Short Circuit Test on the Machine Model

Motivation

This study demonstrates the classical short circuit (SC) test of a synchronous machine. The associated discussion of the simulation results serves as a validation of the PSCAD model.

System Overview

The circuit diagram of this example is shown in Figure 11.

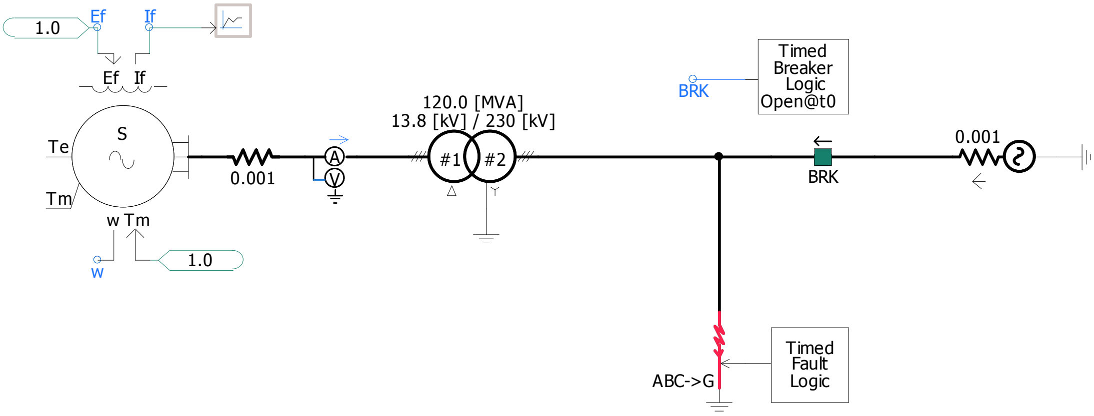


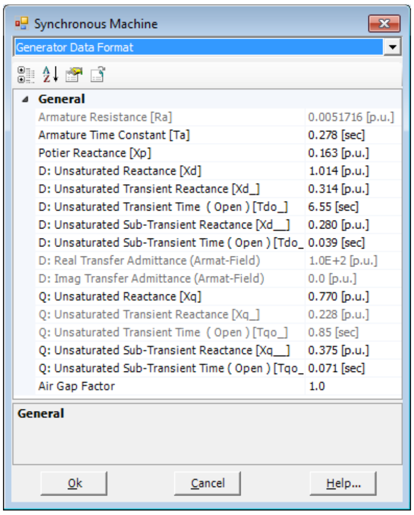
Figure 11: Short Circuit Test Setup

To conduct the SC test, the machine must be running in steady-state in open-circuit conditions. This is achieved by adjusting the phase angle and magnitude of the machine voltage with respect to the source voltage so that the current in the machine is zero (negligible) in steady-state.

Voltage magnitude and phase of the infinite source is 230.0 kV and 0.0°, respectively. The same quantities for the machine are 13.8 kV and -31.08° (includes phase shift by transformer and interface, Δt=50 μs). Field voltage necessary to produce 1.0 PU terminal voltage on the open-circuit machine is 1.0 PU. These initial conditions give open-circuit conditions for the machine.

The machine is run at constant speed by locking the rotor (Enab=0) at synchronous speed. Thus, there are no prime mover dynamics involved. The exciter dynamics are also eliminated by feeding a constant voltage (E_f=1.0 PU) to the exciter. Machine saturation is disabled. The ideal transformer is simply a ratio changer with negligible leakage reactance (0.005 PU) and no saturation. These simplifications allow us to focus primarily on the machine dynamics.

The relevant section of the machine parameters is shown in Figure 12.



General	
Armature Resistance [Ra]	0.0051716 [p.u.]
Armature Time Constant [Ta]	0.278 [sec]
Potier Reactance [Xp]	0.163 [p.u.]
D: Unsaturated Reactance [Xd]	1.014 [p.u.]
D: Unsaturated Transient Reactance [Xd_]	0.314 [p.u.]
D: Unsaturated Transient Time (Open) [Tdo_]	6.55 [sec]
D: Unsaturated Sub-Transient Reactance [Xd__]	0.280 [p.u.]
D: Unsaturated Sub-Transient Time (Open) [Tdo_	0.039 [sec]
D: Real Transfer Admittance (Armat-Field)	1.0E+2 [p.u.]
D: Imag Transfer Admittance (Armat-Field)	0.0 [p.u.]
Q: Unsaturated Reactance [Xq]	0.770 [p.u.]
Q: Unsaturated Transient Reactance [Xq_]	0.228 [p.u.]
Q: Unsaturated Transient Time (Open) [Tqo_]	0.85 [sec]
Q: Unsaturated Sub-Transient Reactance [Xq__]	0.375 [p.u.]
Q: Unsaturated Sub-Transient Time (Open) [Tqo_	0.071 [sec]
Air Gap Factor	1.0

General

Figure 12: The 13.8 kV 120 MVA Generator Parameters

A short circuit is applied at 0.5056 s (time 0.5056 s is chosen just for convenience so that the Phase A current does not have a dc component during the SC test).

Analysis and Simulation Results

Validate the model by comparing the theoretical time constants for the given machine parameters with the time constants, as demonstrated by the simulation graphs. For details refer to [1].

Subtransient Time Constant

The subtransient component of short circuit current should decay with the subtransient (or damper) time constant (Td”), as given by the following equation:

$$Td^{''} = \left(\frac{Xd\,\_\_}{Xd\,\_}\right)\cdot Tdo\,\_\_ = \left(\frac{0.280}{0.314}\right)\cdot 0.039 = 34.7\,ms \qquad (1)$$

Thus, the subtransient effects will be seen for only about two cycles.

Transient Time Constant

The transient component should decay with the transient time constant (Td’):

$$Td^{'} = \left(\frac{Xd\,\_}{Xd}\right)\cdot Tdo\,\_ = \left(\frac{0.314}{1.014}\right)\cdot 6.55 = 2.03\,s \qquad (2)$$

The subtransient and transient time constants may be seen from the expanded view of the Phase A fault current in Figure 14.

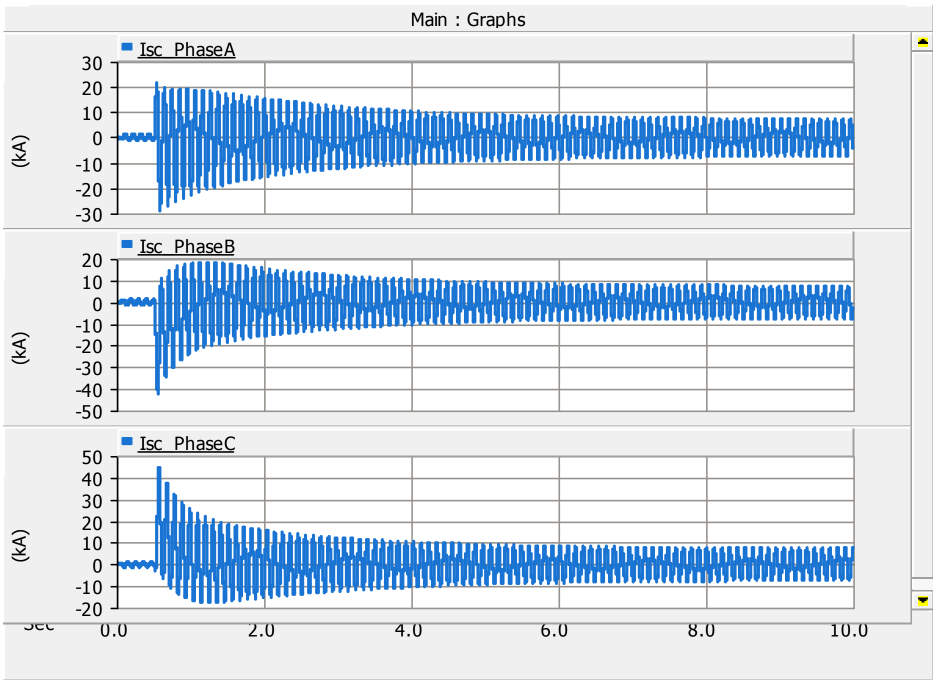


Figure 13: Fault Current (Isc)

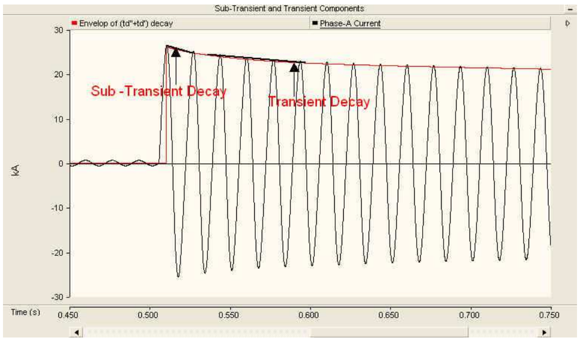


Figure 14: Decay of Subtransient and Transient Components of the Phase A Fault Current

Field Current Decay Time Constant

The time constant of the field current to decay to its pre-fault value is also Td” (given a constant field voltage, as applied in this case). This may be verified from the field current plot in Figure 15.

After the subtransient effects have disappeared, but the transient component is still present, the magnitude of the field current is given by:

$$I'_{fo} = \left(\frac{Xd}{Xd\_}\right)\cdot I_{fo} = \left(\frac{1.014}{0.314}\right)\cdot 1 = 3.23\,PU \qquad (3)$$

The initial dc component of field current is approximately the midpoint of the first cycle, which is about 3.2 PU. This agrees with Equation [1], and is shown in Figure 15. With a fixed field voltage, the field current will return to its pre-fault value in steady-state. The decay of the field current during the transient period is given by:

$$I'_f = I_{fo} + \left(I'_{fo} - I_{fo}\right)\cdot e^{-t/T_d'} = 1 + (3.23-1)\cdot e^{-t/T_d'} \qquad (4)$$

Thus, after a time period equal to Td', the field current will decay to around 37% of its initial value.

$$I'_{f-Td'} = 1 + (3.23-1)\cdot 0.37 = 1.825\,PU$$

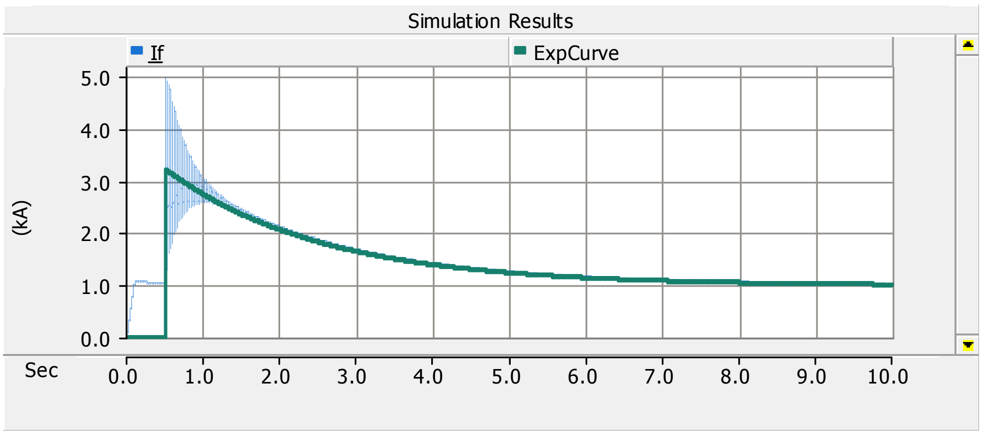


Figure 15: Field Current Response

From Figure 15, it may be seen that I_f reached approximately 1.825 PU after about 2.0 s from the fault inception. This agrees with the theoretical calculation of Td'. An exponential curve (ExpCurve) with a time constant of 2.03 s is superimposed on I_f to show that I_f indeed decays with this time constant. If SC is not ideal, but has a resistance (the fault resistance in our case is considered negligible), this time constant could further be reduced.

Moreover, the transient and subtransient components of current are only different by about 12% as shown below:

$$\frac{I_a^{''}}{I_a^{'}} = \left(\frac{Xd\,\_}{Xd\,\_\_}\right) = \left(\frac{0.314}{0.280}\right) = 1.12$$

With the fast decay rate of I_a'', this difference is difficult to observe. Hence, from Figure 14 it may be noted that the subtransient and transient currents are almost of the same magnitude (I_a''=25.35 kA and I_a'=22.6 kA).

Another calculation that may be verified is the ratio of the subtransient component I_a'' to the steady-state fault current I_a. Note that with constant field excitation, we have:

$$\frac{I_a^{''}}{I_a} = \left(\frac{Xd}{Xd\,\_\_}\right) = \left(\frac{1.014}{0.280}\right) = 3.6$$

From the top plot of Figure 13 (phase A fault current), we obtain a ratio value of 3.57 (=25.0/7.0), which is close to the value calculated using the above equation.

The steady-state I_a of 7.0 kA also exactly matches the calculated value as seen in Figure 16.

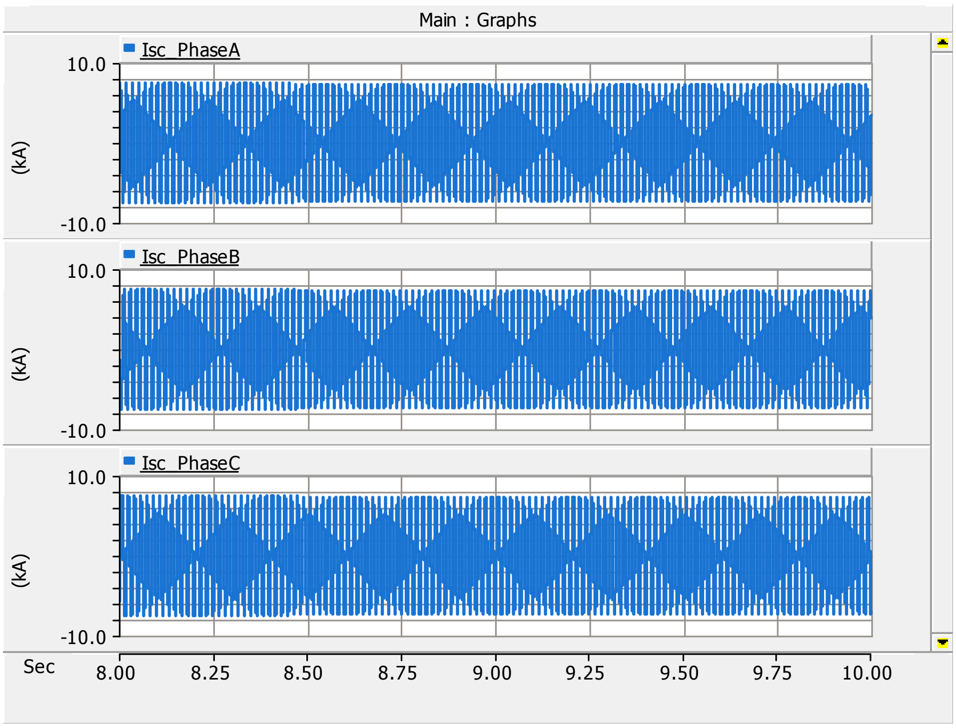


Figure 16: Steady-State Fault Current

The armature time constant, Ta (0.278 s), is the decay time constant of the fundamental frequency component of I_f (on the stator side, this is the time constant at which the dc component and the second harmonic component of stator current decay). This time constant is estimated in Figure 17. The initial peak-to-peak magnitude of the 60 Hz component after subtransient influence disappeared is about 3.0 PU. The 60 Hz component reached 37% of this value (1.1 PU) in about 0.270 s. This value closely agrees with the given value for parameter Ta.

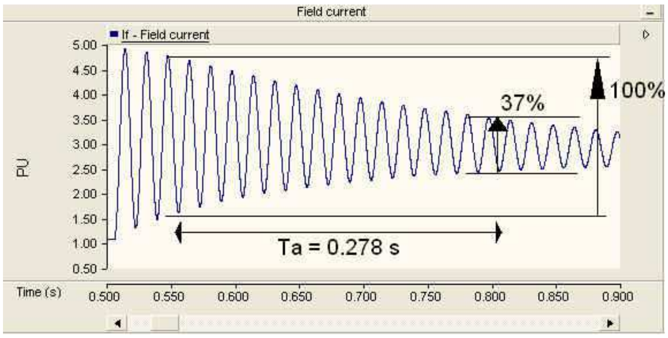


Figure 17: Decay of the Fundamental Frequency Component in the Field Current

Discussion

The theoretical results and the simulation results are very close. Therefore, the model of the synchronous machine is accurately represented in PSCAD.

PSCAD

Refer to PSCAD case: *SM_study_03.pscx*

References

[1] Jones, C.V. "The Unified Theory of Electrical Machines", Plenum Press, N.Y., 1967, Chapter 20.

DOCUMENT TRACKING

Rev.	Description	Date
0	Initial	01/Jun/2013