This application note deals with an investigation of possible induction generator effect triggered by sub-synchronous resonance frequencies during transient events. The following will be addressed in this application note:

- Harmonic impedance profiles of a power system network.
- Series compensation of lines and the resulting changes in the harmonic impedance profile.
- Induction generator effect phenomena.
- Machine model to study induction generator effect phenomena.
- Voltage amplification problems due to induction generator effect.
- Sensitivity of system and machine parameters.

The single line view of the PSCAD model of this network is shown below. A simple single machine, infinite bus type system is selected for simplicity, but the techniques discussed are typical and applicable in a typical investigation.

The main power network is modeled as an impedance behind a voltage source as shown in Figure 2. The source impedance can be determined from the short circuit level at this bus. If the study required a more accurate representation of the network frequency response, more buses behind the 500 kV system bus must be added to the model. This is addressed in a separate application note.

The transmission line from the 500 kV bus to the generating station is represented by simple R,L elements representative of the fundamental frequency data. Once again, a detailed, fre-
quency dependent line model may be used in a practical study but, for the purpose of this application note, this simple representation easily yields to verifying the sensitivity of line loss etc. to sub-synchronous effects. The series capacitor represents a series compensation. The value used here is representative of approximately 75% compensation.

The synchronous machine is modeled with all of its detailed parameters in place. The rotor circuit plays an important role during sub-synchronous events and thus, it is important to investigate the sensitivity of such parameters during the study.

The simulation should be first initialized to a specific load flow situation. This can be achieved by entering the bus voltages and magnitudes at appropriate locations. In this example, the bus voltage information at the 500 kV source and at the machine terminal may be used to initialize the simulation.

During the initialization process, the machine can be made to act as a voltage source, operating at the specified magnitude and phase angle. This is achieved using the ‘source to machine’ conversion feature of the machine model as shown in Figure 3. Initially, the signal S2M from the timer is zero and the machine model will act as a voltage source during this period. When this value is changed to 1 at a specific time (when all initial transients have settled), the model will act as a ‘machine,’ governed by the equations relating terminal voltages to the winding currents. A constant field voltage input is assumed for this study. The constant field voltage is based on the initialized value (Ef0) computed by the machine model during the initialization period. This fixed value will ensure the same steady state operation after the machine model is switched from a ‘source’ to a ‘machine.’

The machine mechanical dynamics are not modeled for this study. This can be realized in a number of ways.

1. Run the machine in the ‘Lock rotor’ mode by making this input entro equal to zero during the simulation. This is shown in Figure 4 and the machine speed will be equal to 1 pu (ie. synchronous speed).

2. An arbitrary speed can be specified by enabling the multi-mass option as shown in Figure 5.

Figure 6 shows the parameter box in the machine model to enter the bus voltage angle and its magnitude for the specific power flow condition.

Once the system is set up and initialized as outlined below, it will run to the specified steady state as can be verified by the results shown in Figure 7.

System harmonic impedance profile
A typical harmonic impedance profile of a high voltage network is shown in Figure 8.

Typically, the resonance points are at super-synchronous frequencies (ie. higher than 60 Hz in a 60 Hz system). During
Transient events, such as breaker operations, faults and fault clearance, the voltage and current waveforms would display such frequencies. Since there are no driving forces (generators) to sustain such frequencies, they will be eventually damped out at a rate determined by the system losses and loads. Figure 9 shows high frequency transients during a breaker operation for the simple system shown in the same figure. It also shows the effect of losses on transient damping.

This system had a harmonic resonance at around 503 Hz and can be measured using the PSCAD model shown in Figure 10. This can be used to plot impedance profiles at different locations as shown in Figure 7.

**Series compensation of lines and the resulting changes in the harmonic impedance profile**

The addition of new equipment to the existing system will naturally effect the harmonic impedance profile. Sub-synchronous effects are of concern if the harmonic resonance points gets shifted to frequencies lower than the rated system frequency. It is well known that the addition of series capacitors to compensate the transmission line reactance can give rise to this situation.
Figure 11 shows the impedance profile at the 500 kV bus for the system shown in Figure 1. The series compensation has resulted in a resonance point at around 40 Hz. Following a disturbance, the currents and voltages around this point will show slow transients at around 40 Hz. Figure 12 shows such a sub-harmonic response in a system which had a resonance point at around 9 Hz.

Subsynchronous currents and voltages in the network following a disturbance.

Figure 12 Waveforms showing sub harmonic currents and voltages in a system that had a resonance point around 10 Hz.

**Induction generator effect phenomena**

The interaction of the sub harmonic currents and the voltage with the machine can result in the **Induction generator Effect**. The sub-harmonic currents will produce a rotating mmf which will assume a frequency corresponding to the same frequency. The rotor circuit, which is rotating at or near the rated synchronous speed, responds to the sub-harmonic mmf in a manner similar to an induction machine. Since the machine speed is greater than the sub-harmonic mmf rotation, the effect is similar to an induction machine in a generating mode where the slip is negative. This can be understood...
by examining the basic induction machine theory and the resulting steady state equivalent circuits as shown in Figure 13.

![Equation](https://via.placeholder.com/150)

Figure 13 Equivalent circuit of a typical induction machine.

If the combination of the stator resistance and the resistance presented by the network, as seen at the machine terminals, is low enough, the effective resistance can be negative. This is the condition for positive feedback effect, referred to as the induction generator effect.

**Machine model to study induction generator effect phenomena**

The detailed machine model in PSCAD is suitable to study possible induction generator effects. The data required for the machine model is shown in Figure 14.

The mechanical dynamics are not included in the example and the field winding voltage is assumed to be constant over the study interval. However, these details can be easily included in the model.

**Voltage amplification problems due to induction generator effect**

A three phase fault is applied at the 500 kV bus at 1.5 s. The fault duration is 75 ms. The fault component and the timed fault logic component in the Master Library are used to simulate the fault. This model is shown in Figure 15.

Figure 16 shows different current and voltage waveforms upon the clearance of the fault. The transients die out and the system reaches a steady state.

Results when the line resistance is lowered are shown in Figures 17 and 18. With the line resistance set to 2.0832 Ohms, the transients are sustained for a longer period. With the line resistance set to 1.0832 Ohms, the terminal voltage grows to very high values and this is a result of the induction generator effect.

Analysis of the current waveform using the FFT component of PSCAD (see the PSCAD case) shows a prominent 40 Hz sub-harmonic component.

![Figure 14 Data entered in the PSCAD machine model.](https://via.placeholder.com/150)

![Figure 15 PSCAD models used to simulate a fault.](https://via.placeholder.com/150)

![Figure 16 Simulation results following a three phase fault clearance at 1.5 s. The fault duration is 0.075 s.](https://via.placeholder.com/150)
The rotor circuit interaction with the sub-harmonic stator current results in the induction generator effect. Thus, it may be advisable to investigate the sensitivity of certain machine parameters to the simulation results. Figure 20 shows the results where the line resistance is as in the results in Figure 17 (i.e. Line R=2.0832 Ohms). The field time constant $T_{d0}'$ was lowered from 4.3 to 1.3 (just to see the effect). This results in a larger rotor circuit resistance and correspondingly, a negative equivalent resistance of a larger magnitude. Figure 20 shows that the system displays a negatively damped induction generator effect.