Digital twin development for an inverter circuit for motor drive systems

7

7.1 Introduction

This chapter guides the reader through developing a digital twin model for a three-phase motor drive system using two three-leg inverters connected in series with the three-phase motor. The developed model can be used to perform off-board diagnostics of the real system's fault tolerant capability for open-circuit, short-circuit, and DC link failure modes. The model is developed using MATLAB®, Simulink, and Simscape™ Electrical and Simscape Power Systems tools. Simscape™ components like IGBT switches, diodes, voltmeter, ammeter, resistor, and inductors are used to develop two three-leg inverters. A PWM generator is created to generate the gate signals for each IGBT switches using Simulink blocks. Failure conditions are induced, and simulated behavior of the inverter configuration and results are discussed. Fig. 7.1 shows the Off-BD steps that are going to be covered in this chapter.

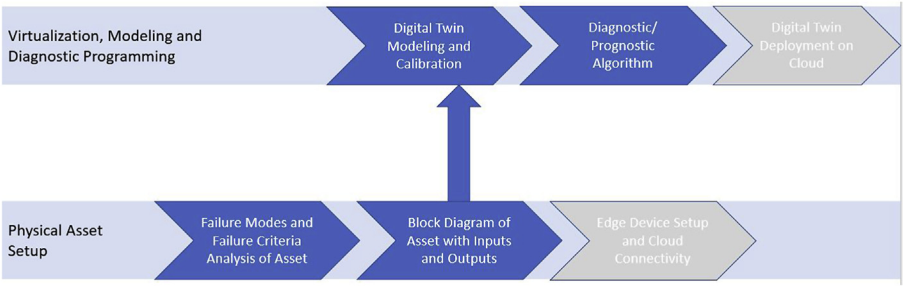

Figure 7.1 Off-BD steps covered in this chapter.

All the codes used in the chapter can be downloaded for free from MATLAB *File Exchange*. Follow the below link and search for the ISBN or title of the book:

https://www.mathworks.com/matlabcentral/fileexchange/

Alternatively, the reader can also download the material and other resources from the dedicated website or contact the authors for further help:

https://www.practicalmpc.com/

Digital Twin Development and Deployment on the Cloud. https://doi.org/10.1016/B978-0-12-821631-6.00007-4

One of the advantages of a three-phase motor drive system employing two three-leg inverters connected in series with the three-phase machine is its fault tolerance compatibility. This chapter analyzes and discusses the simulation of such three-phase motor drive system. Simulation results are obtained for different type of faults like open-circuit failure, short-circuit failure, and DC link failure. Simulation has been done on MATLAB environment with a model-based implementation of fault diagnostics and mitigation for three-phase, two three-leg inverters connected in series using MATLAB, Simulink, and Simscape. One scenario that is considered for analyzing fault tolerance capability in which the fault compensation has been achieved by reconfiguring the power converter topology with Y connection of the motor without adding any additional devices is discussed in this chapter. We will develop the Simscape model for the two three-leg inverters connected in series with the three-phase machine as shown in Fig. 7.2.

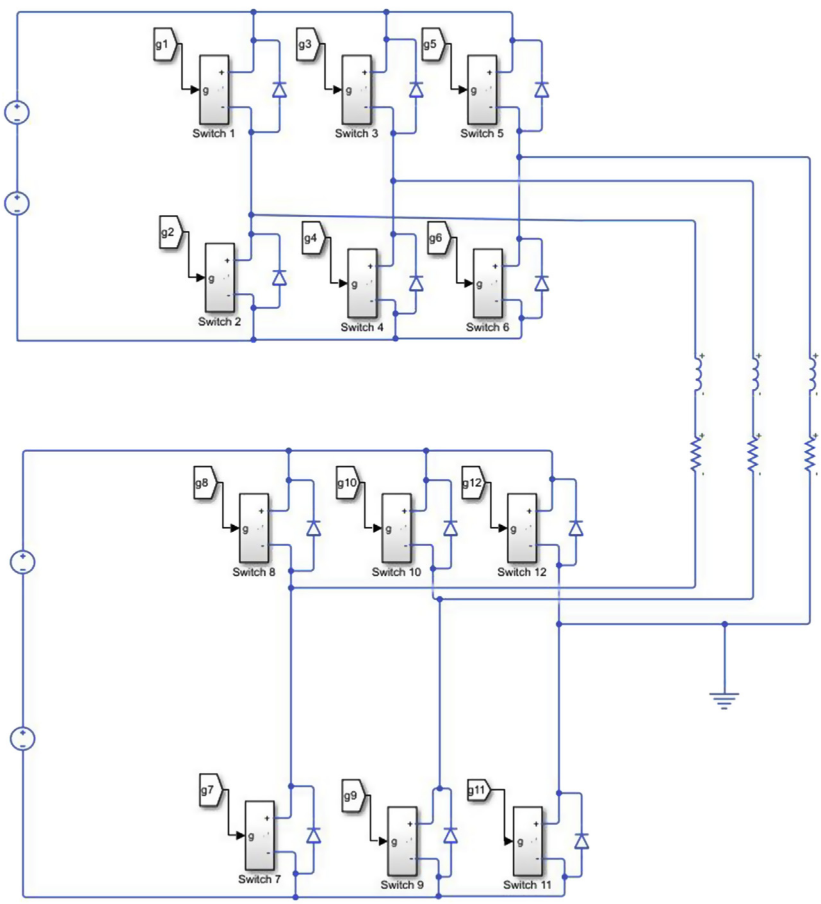

Figure 7.2 Motor drive system [1].

7.2 Block diagram of the motor drive inverter system

Fig. 7.3 shows the block diagram of the motor drive inverter system. The inputs to the system are the input DC voltage and the gate pulse signals to turn on the IGBT switches of the inverter. And the outputs to the system are the load voltages, currents for all three phases, and also the currents and voltages through IGBT switches.

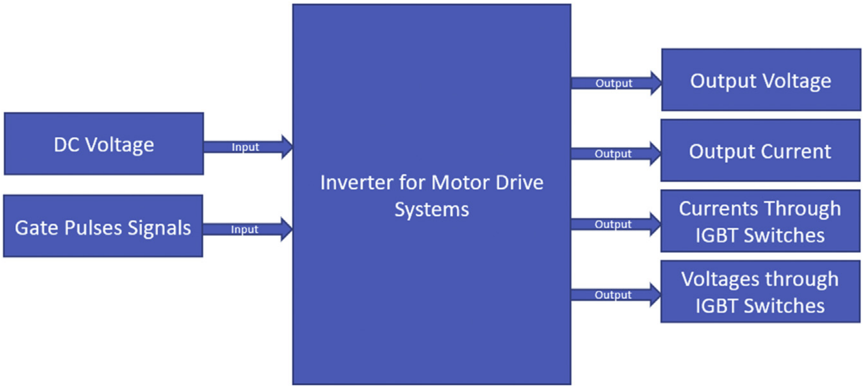

Figure 7.3 Block diagram of the motor drive inverter system.

7.3 Failure modes and diagnostics concept of the motor drive inverter system

Fig. 7.4 shows a concept block diagram for the off-board diagnostics process for the motor drive system. The same DC input voltage and the gate pulse signals that are fed to the actual inverter system can be fed to the digital twin as well. The digital twin will not be made aware about the faults introduced in the actual system such as open-circuit or short-circuit failures. So if there is a failure in the actual system with the same inputs given to both actual system and digital twin, the output voltages and currents and the currents and voltages through the IGBTs will also be different. The diagnostics algorithm will compare the difference between the signals from actual and digital twin and take a diagnostics decision about the actual system based on the comparison results.

7.4 Simscape model of the motor drive inverter system

Below are the detailed steps to building the Simscape model:

1. Create a new **Simulink model**.
2. Click on the **Simulink Library Browser** as shown in Fig. 7.5.

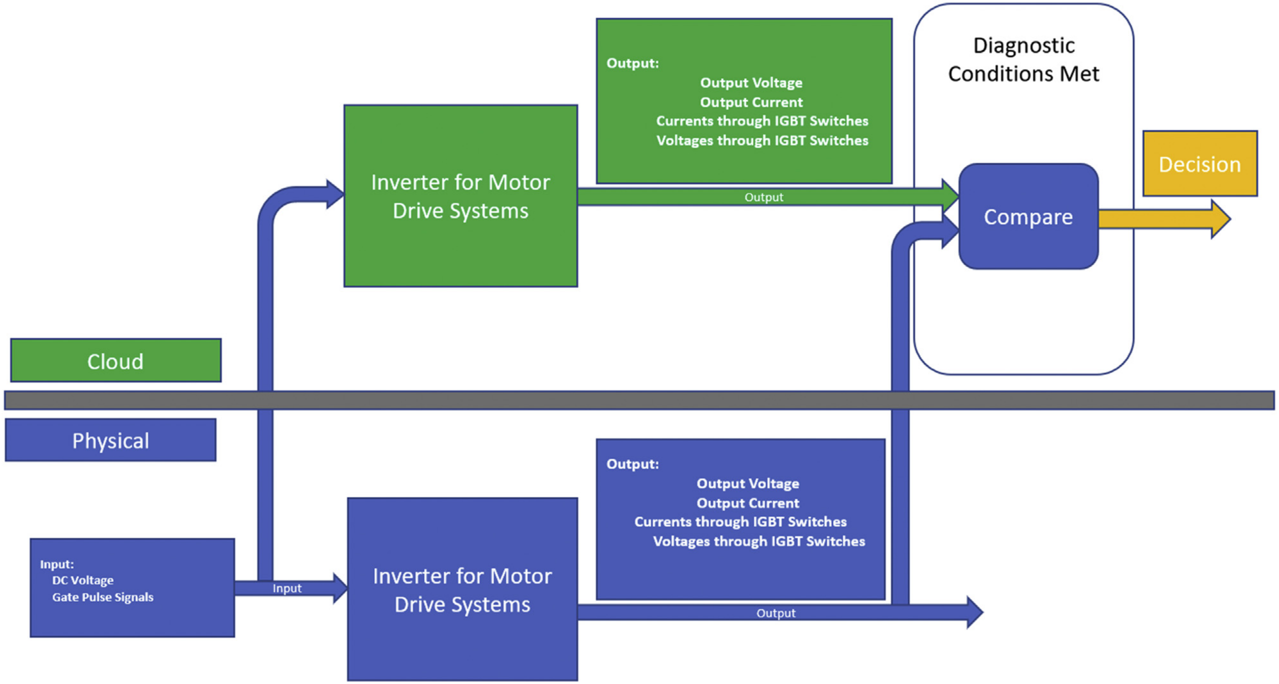

Figure 7.4 Off-BD diagnostics process for motor drive inverter system.

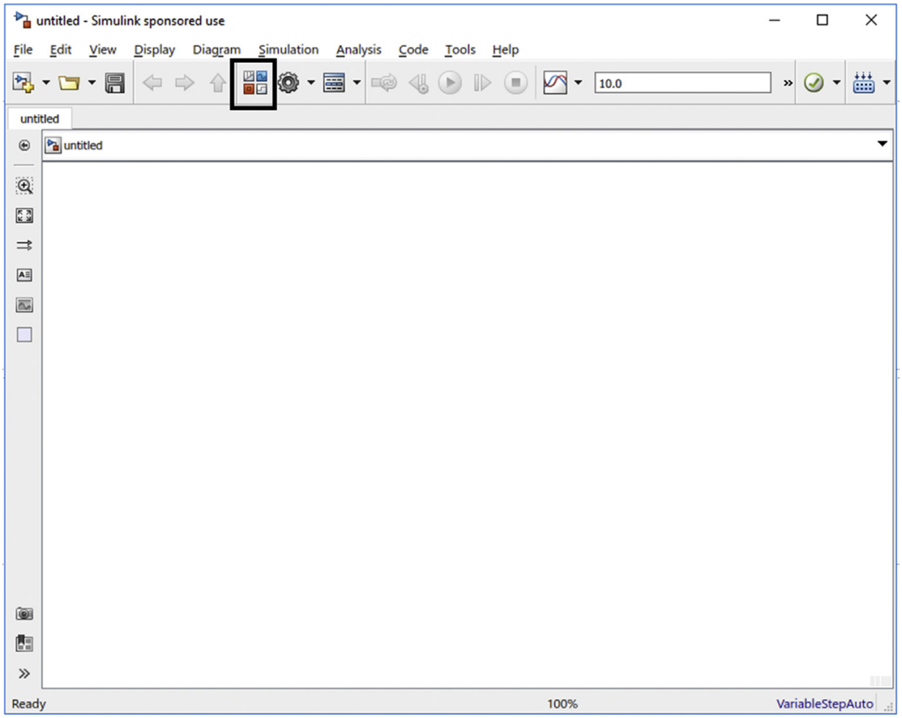

Figure 7.5 Simulink library browser.

3. Navigate to **Simscape > Electronics > Semiconductor Devices** and add **N-channel IGBT** block to the model as shown in Fig. 7.6. Update the block parameters for N-channel IGBT as shown in Fig. 7.7.
4. Go back to **Simscape > Electronics > Actuators and Drivers > Drivers** and add **Gate Driver** block (Fig. 7.8).
5. Go to Simscape > Utilities and add Simulink-PS Converter block and Connection Port block (Fig. 7.9).
6. Go to **Simulink > Signal Attributes** and add **Data Type Conversion** block to the model (Fig. 7.10).
7. Go to **Simulink > Sources** and add **In1** (input port) to the model (Fig. 7.11).
8. Add two physical modeling connection ports into the model from **Simscape > Utilities** as shown in Fig. 7.12.
9. Make all the connections with all the added blocks as shown in Fig. 7.13.
10. Select all the blocks as shown in Fig. 7.14 and right click and select “Create Subsystem from Selection.” This will create a subsystem with all the blocks in it and with one input and two output ports as shown in Fig. 7.15. Name the subsystem as “Switch 1.”
11. Obtain the remaining 11 switches of three-phase inverter by making 11 copies of the subsystem “Switch 1.” Also replace the input port connected to the switch subsystem with “From” blocks as shown in Fig. 7.16.
12. Go to **Simscape > Foundation Library > Electrical > Electrical Sources** and add four **DC Voltage Source** blocks, two for each leg (Fig. 7.17).

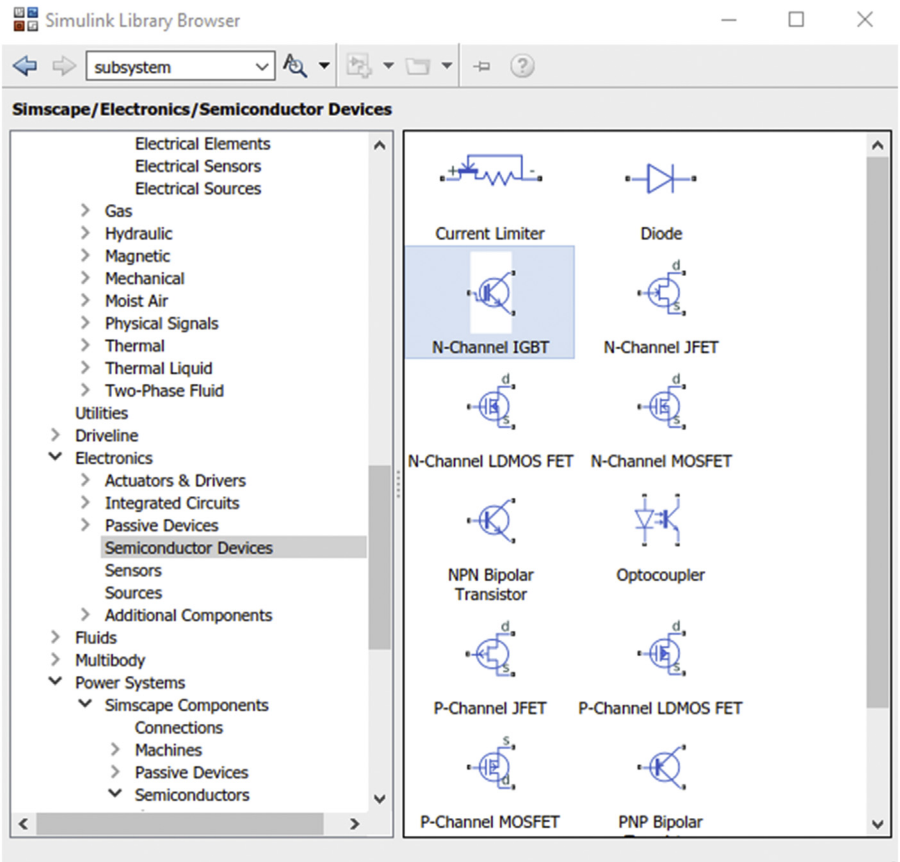

Figure 7.6 IGBT block.

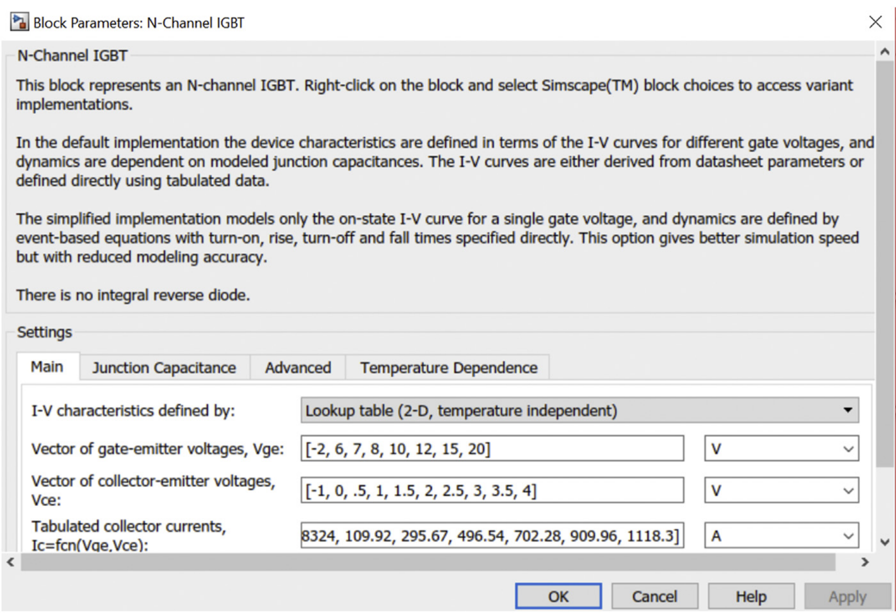

Figure 7.7 Block parameters for N-channel IGBT.

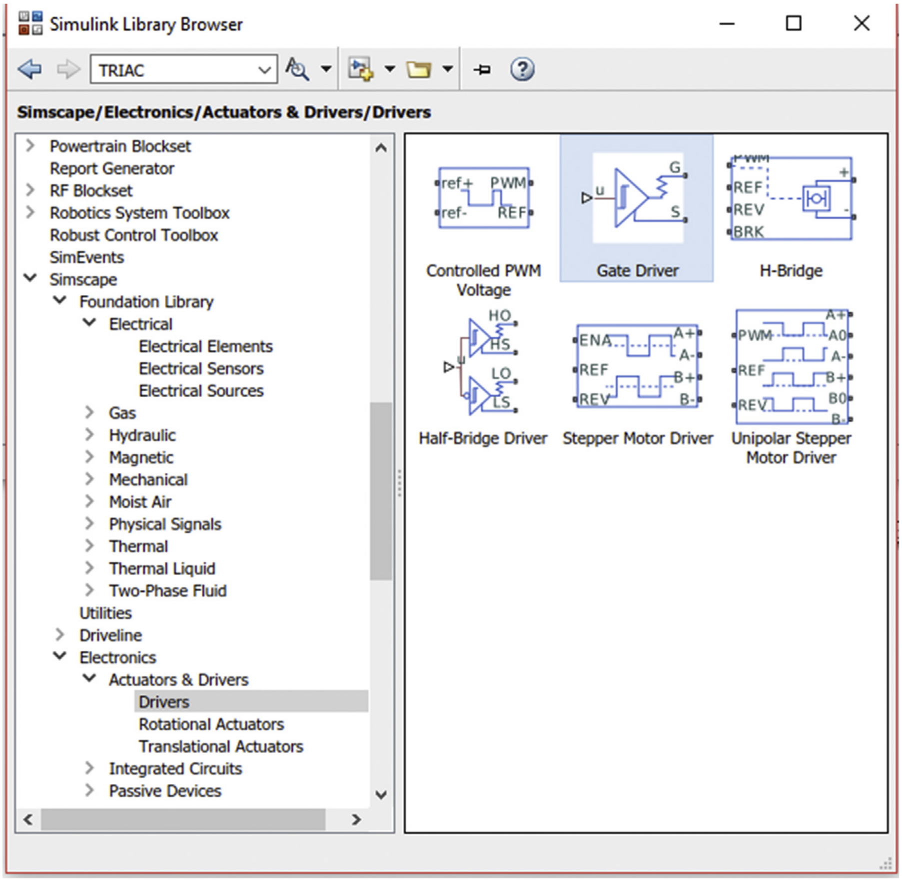

Figure 7.8 Gate driver block.

13. Setup the constant voltage parameter as 50 V for each voltage source block by double clicking on each DC Voltage Source (Fig. 7.18).
14. Connect the voltage sources to the switches as shown in Fig. 7.19.
15. Go to **Simscape > Electronics > Semiconductor Devices** and **add** 12 **Diode blocks** (Fig. 7.20) and make the connections as shown in Fig. 7.21. Update the block parameters as shown in Figs. 7.22 and 7.23.
16. Add and connect resistors and inductors to the model by selecting them from **Simscape > Foundation Library > Electrical > Electrical Elements** (Figs. 7.24 and 7.25). This RL circuit basically is considered as the load for the inverter circuit.
17. Set up the resistance and inductance at desired value for each resistor. For this model, resistance is set as 5 Ω for each resistor and inductance is set as 1e-6 H.
18. Go to **Simscape > Foundation Library > Electrical > Electrical Sensors** and add current sensors and voltage sensors to the model for reading output current and output voltage (Figs. 7.26–7.28). Also connect the sensors to Simulink® scopes by connecting the output

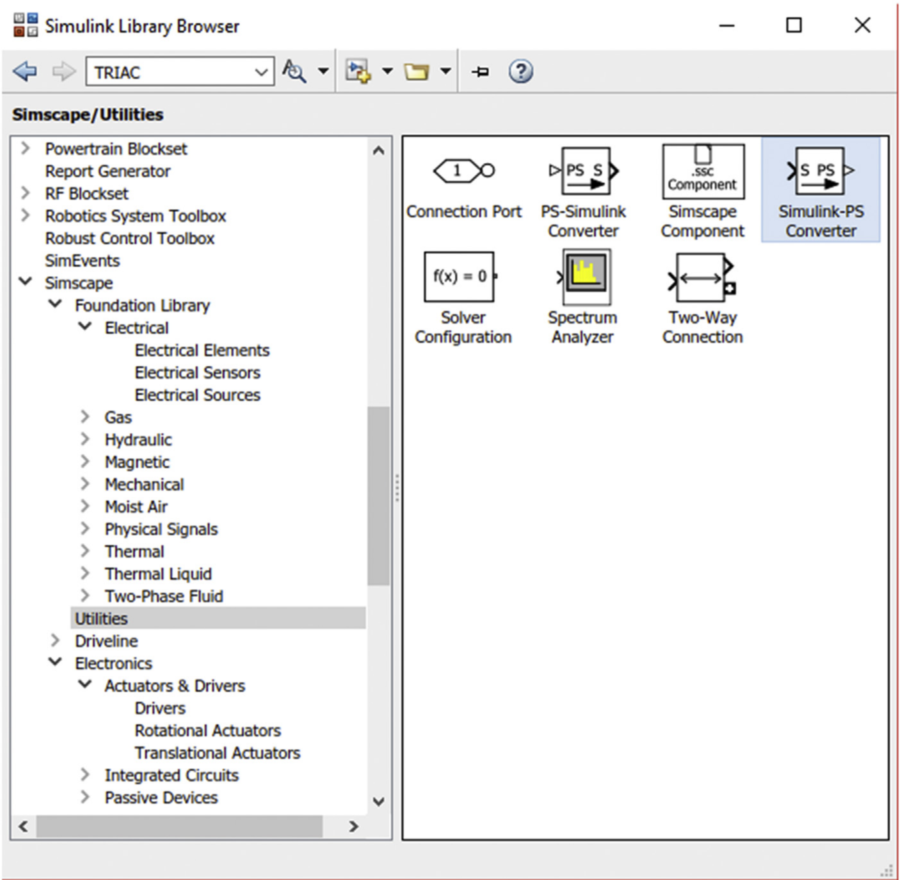

Figure 7.9 Simulink-PS converter.

from sensor to the PS-Simulink converter block which can be found at **Simscape > Utilities** (Fig. 7.27).

19. Add solver and Electrical Reference blocks to the model from **Simscape > Utilities** and **Simscape > Foundation Library > Electrical > Electrical Elements** (Figs. 7.29 and 7.30).

20. Set the sample time as 2e-6 for the solver block (Fig. 7.31).

21. Connect the solver and electrical terminator blocks as shown in Fig. 7.32.

22. Now we have to generate the gate pulse signals for firing the IGBT switches for the inverter. A PWM generator subsystem is created to generate the gate signals for each IGBT switches in the inverter model. Create a new subsystem and add digital clock to the model from **Simulink > Sources**(Fig. 7.33).

23. Add constant, gain, trigonometric function, i.e., sine, and sum blocks to the model accordingly and enter the values as shown in Fig. 7.34. This model generates the sinusoidal signals.

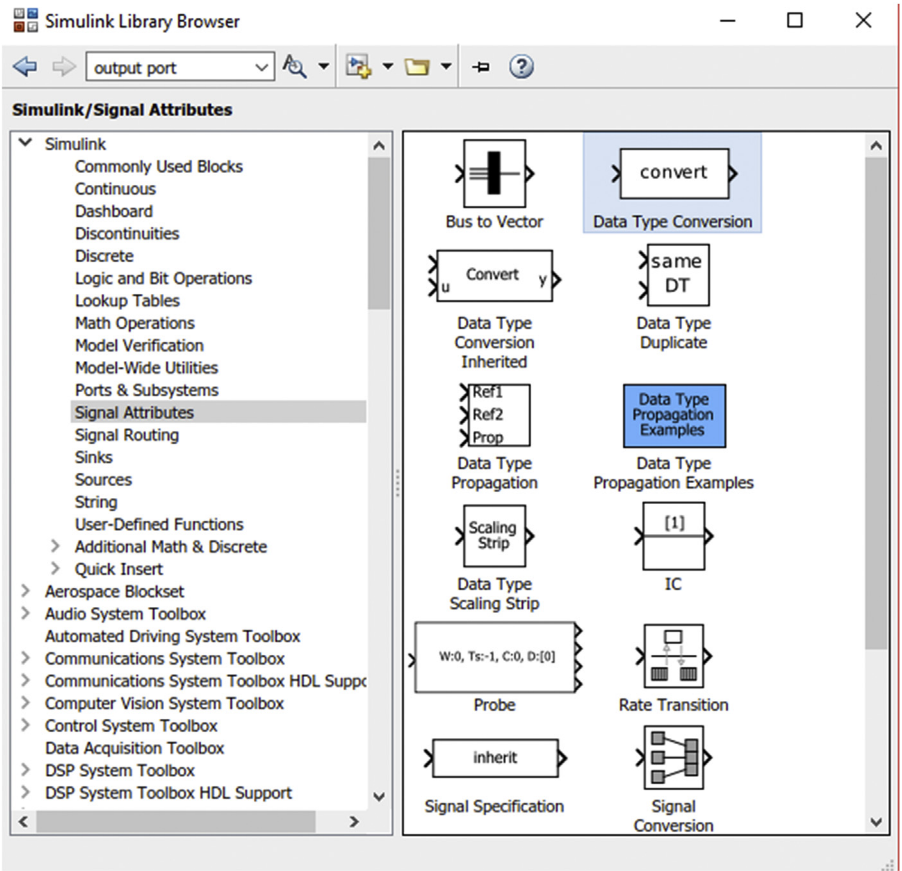

Figure 7.10 Data type conversion block.

24. Gate signals for each switches in the inverter is generated by using a PWM strategy where two high-frequency triangular waves are compared with a sinusoidal waveform. This resulted in generating output voltage with eight levels. “PWM Generator” subsystem can be created by removing the output port from the subsystem “Sin wt” and adding gain, logical operators, and triangle blocks to the model as shown in Fig. 7.35.
25. Assign the block parameter values for Triangle1 and Triangle2 blocks as shown in Figs. 7.36 and 7.37.
26. Create a subsystem and name it as PWM Generator, which outputs the gate pulses for inverter 1 and 2 as shown in Fig. 7.38.
27. The Simscape™ model design is ready. Save the model, and on the model configuration parameters window, set the simulation end time as 0.2 s, Solver Type to be Fixed, and Fixed Step Size to be 2e-6 as shown in Fig. 7.39. A fully simulatable working model is available in the attachment section under folder **Motor_Drive_System_Inverter_Model** for reference.
28. Run simulation and observe the Output Current and Output Voltage Scope blocks added in step 18. The simulated output currents and voltages for all three phases are shown in Figs. 7.40 and 7.41, respectively.

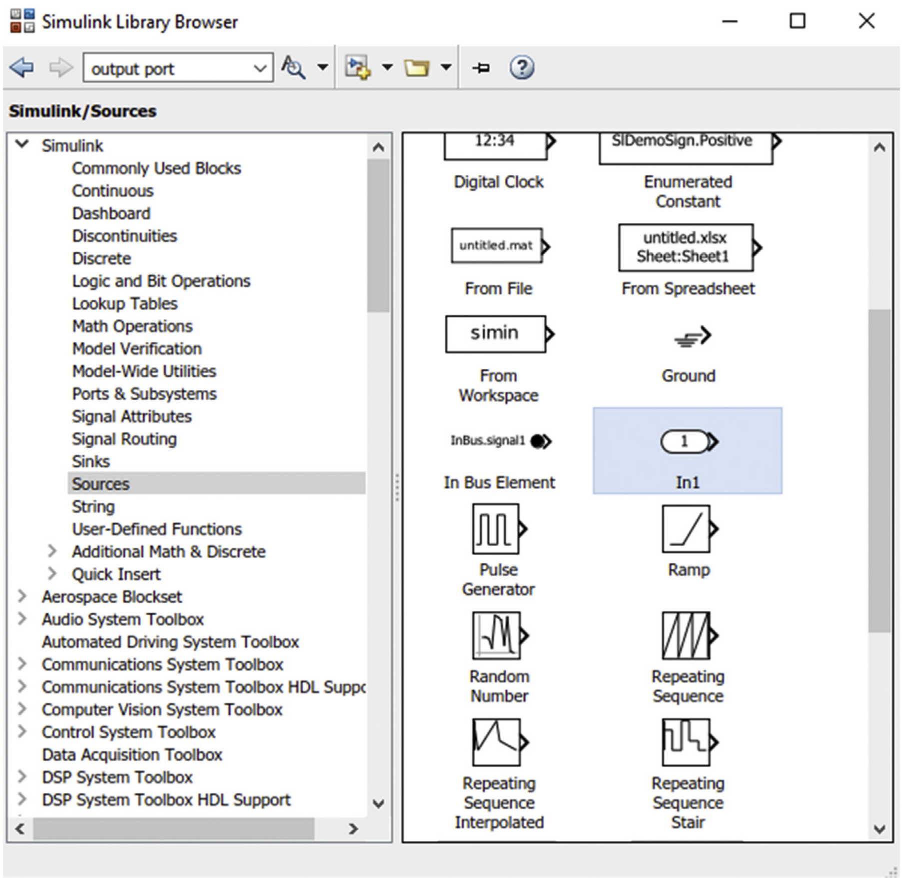

Figure 7.11 In1 (input port) block.

7.5 Fault injection and diagnostic algorithm development

In this section, we will introduce an open-circuit failure condition to one of the legs of the inverter circuit in the Simulink model and first analyze the impact of the failure on the functionality of the inverter.

1. Save the model we tested in the previous section with a different name.
2. As shown highlighted in Fig. 7.42, disconnect the line between Switch 10 and Switch 9 of the second inverter leg. Add a Step block, Simulink-PS Converter block, and a Switch block and make the connections as shown in Fig. 7.42. Configure the Step block with initial condition of 1 and a final value of 0 at time 0.06 s as shown Fig. 7.43. And also configure the Switch block with values as shown in Fig. 7.44. So initially, since the step block output is 1, it will

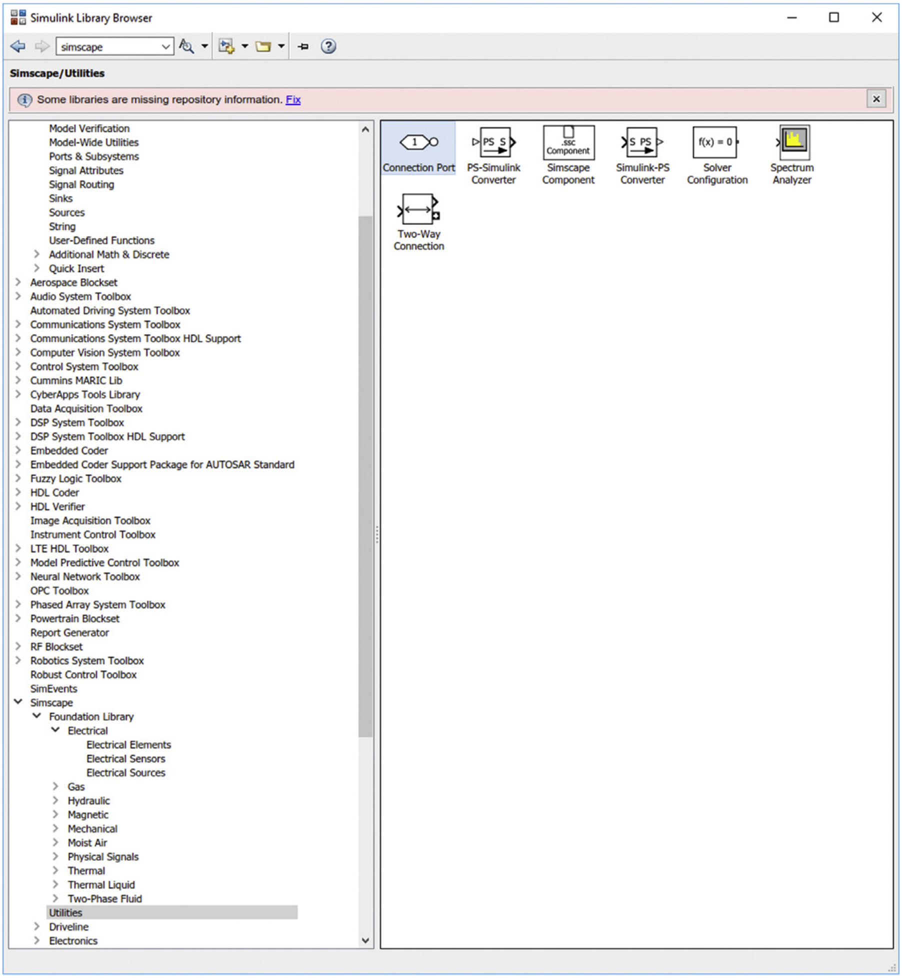

Figure 7.12 Physical modeling connection port.

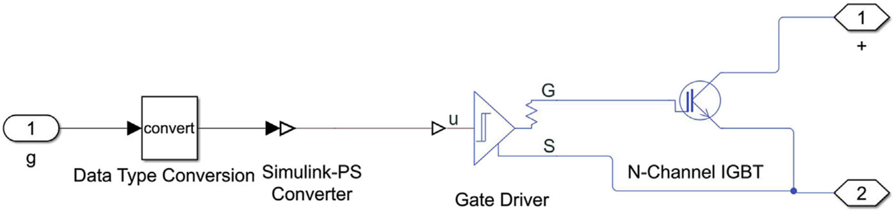

Figure 7.13 Connecting all the blocks.

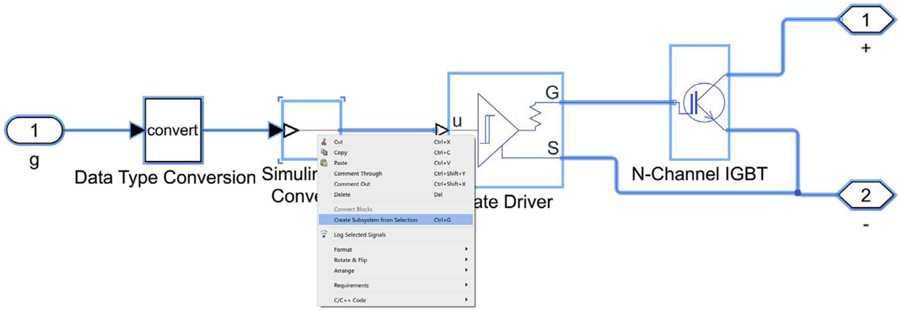

Figure 7.14 Creating subsystem with selected blocks.

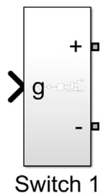

Figure 7.15 Subsystem created for switch 1.

make the switch to be closed, but at time t = 0.06 s, because the step block value becomes 0, this opens the switch and the connection between the IGBT 10 and IGBT 9 will be open.

3. A fully simulatable working model with this failure condition introduced is available in the attachment section under folder **Motor_Drive_System_Inverter_Model_with_OC_Fault** for reference.
4. Run simulation and observe the Output Current and Output Voltage Scope blocks added in step 18 of Section 7.3. The simulated output currents and voltages for all three phases are shown in Figs. 7.45 and 7.46, respectively. Note that because of the open circuit at time t = 0.06 s, the current and voltage of the second phase is significantly affected.

7.6 Application problem

1. Introduce a failure condition for a short circuit between the + and − terminals of one of the IGBT switches, using the same Step block, and switch block strategy discussed earlier in this chapter and observe the output voltage and current of the inverter and compare it to the no-fault condition.

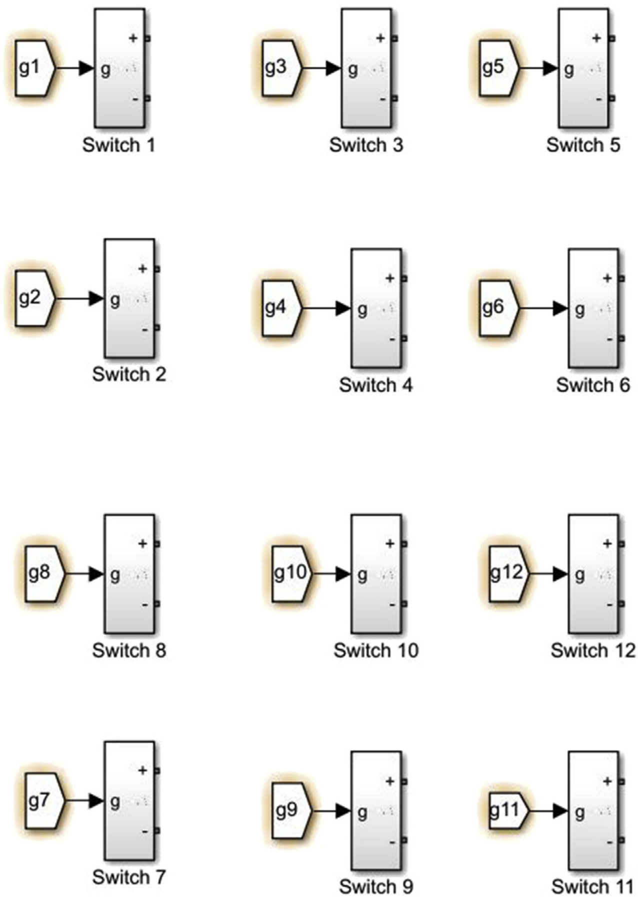

Figure 7.16 All 12 switches added.

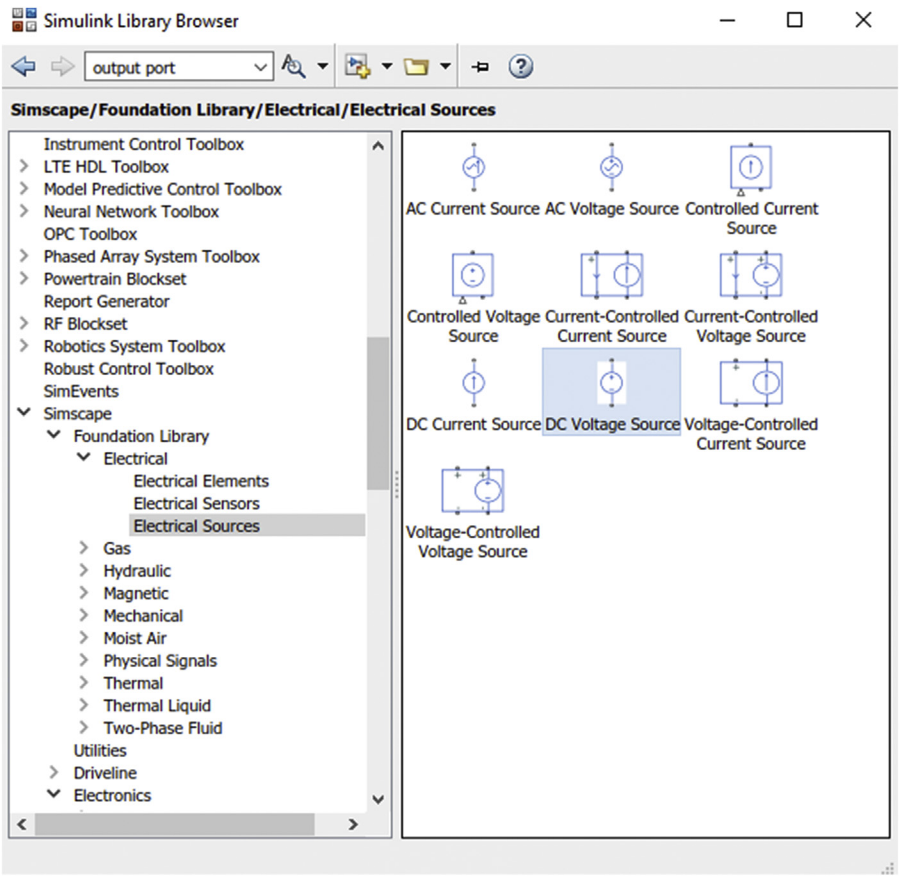

Figure 7.17 DC voltage source.

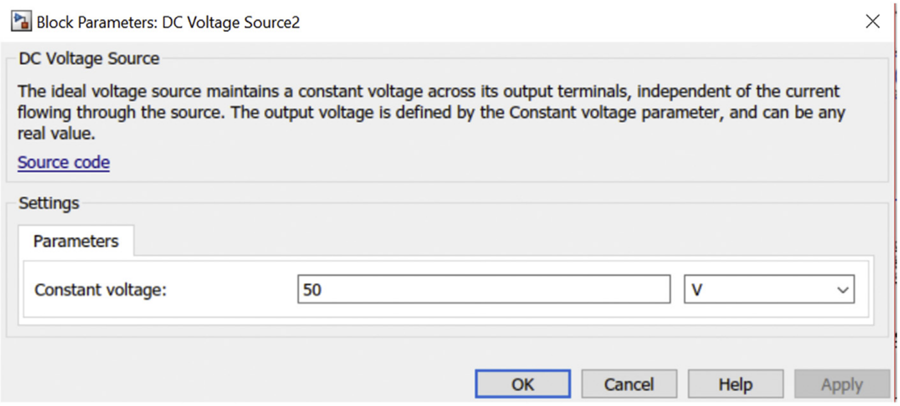

Figure 7.18 Parameter setting for DC voltage source.

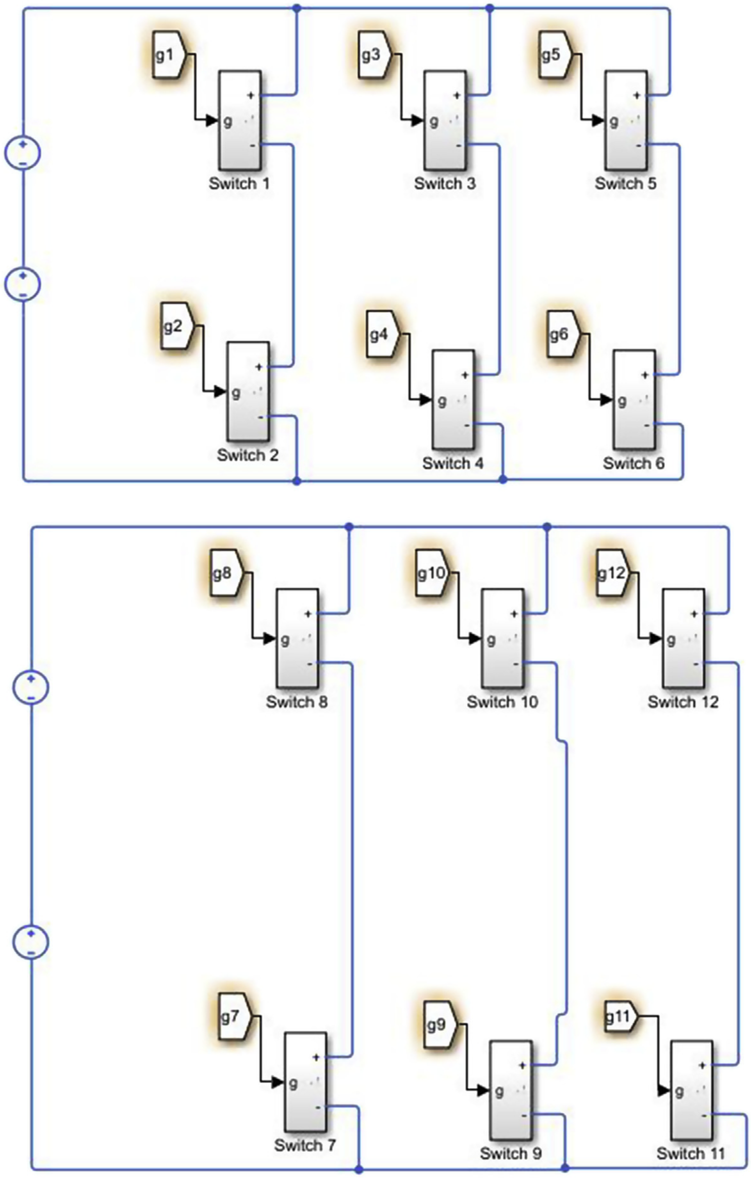

Figure 7.19 Voltage source connection to the switches.

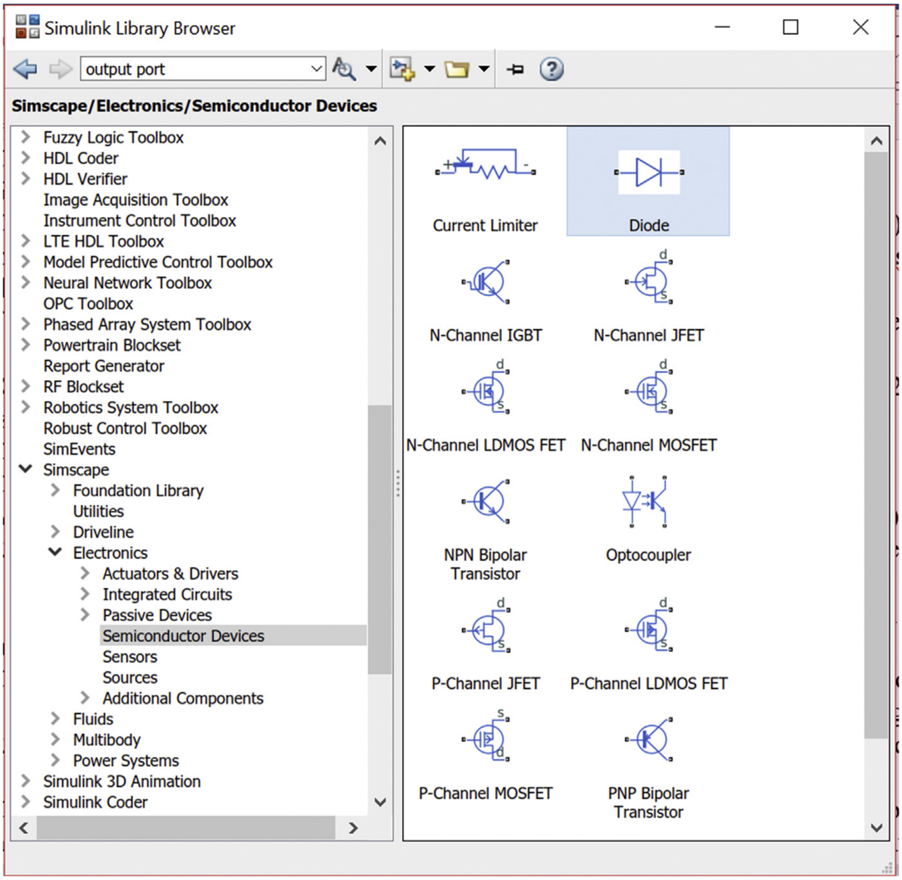

Figure 7.20 Diode block.

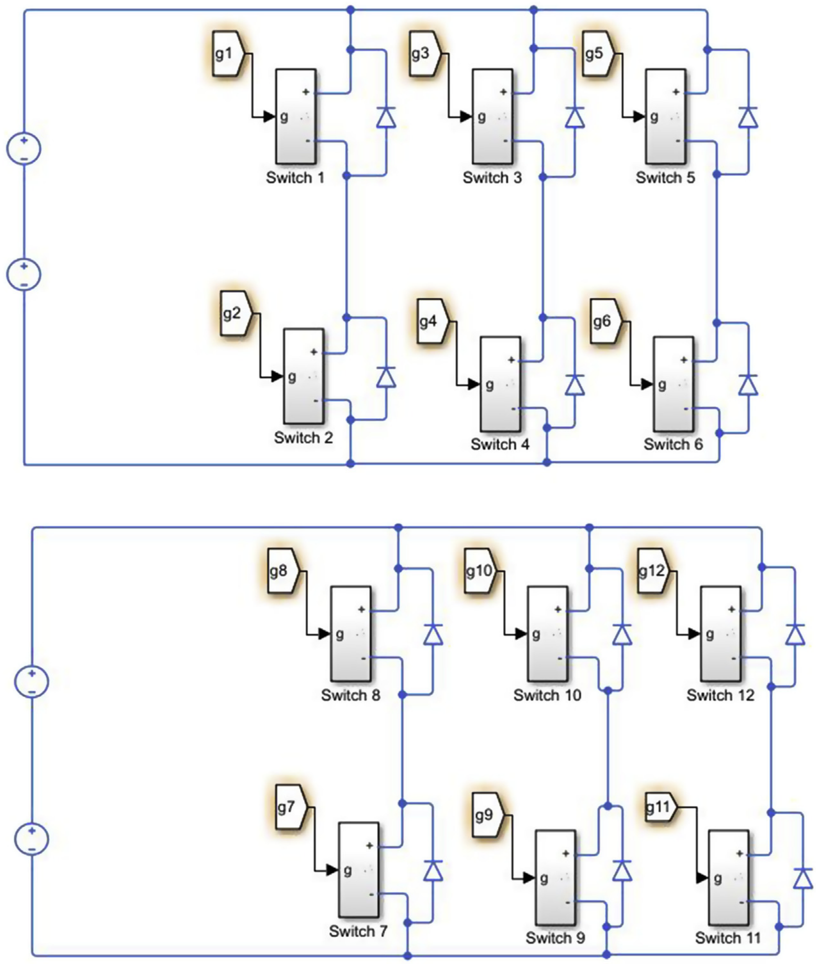

Figure 7.21 Connecting diodes antiparallel to the switches.

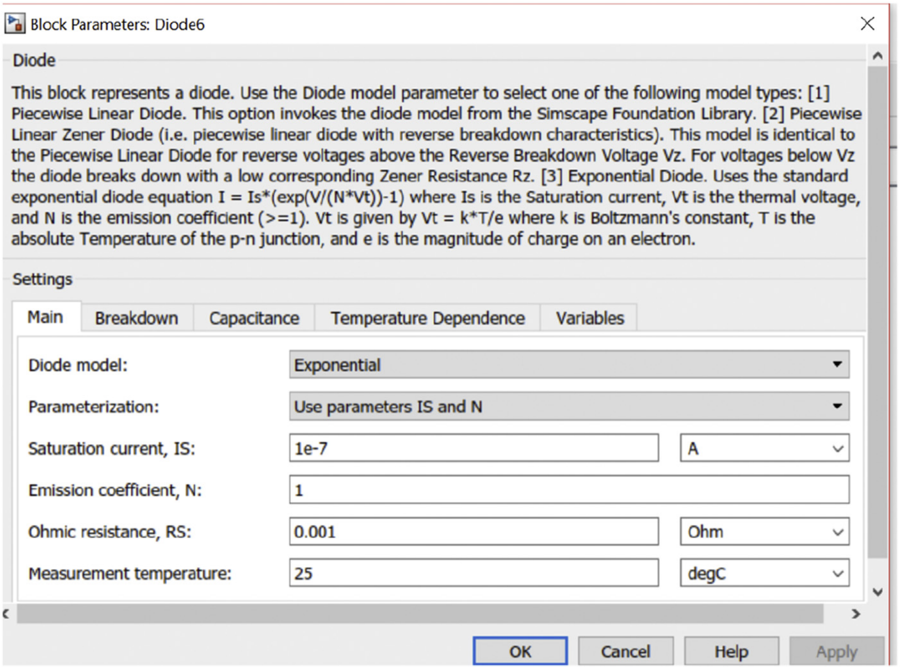

Figure 7.22 Block parameters for diode 1

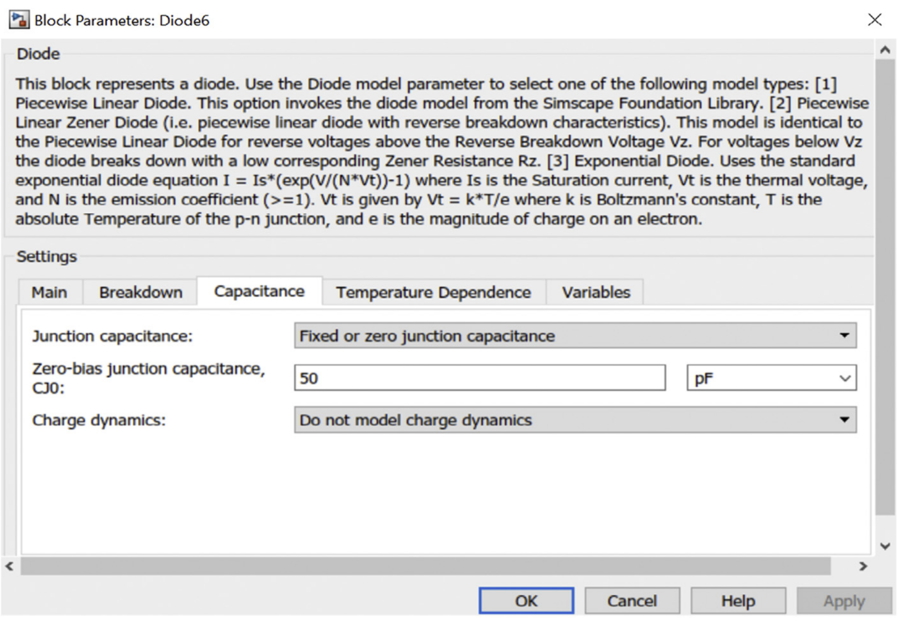

Figure 7.23 Block parameters for diode 2.

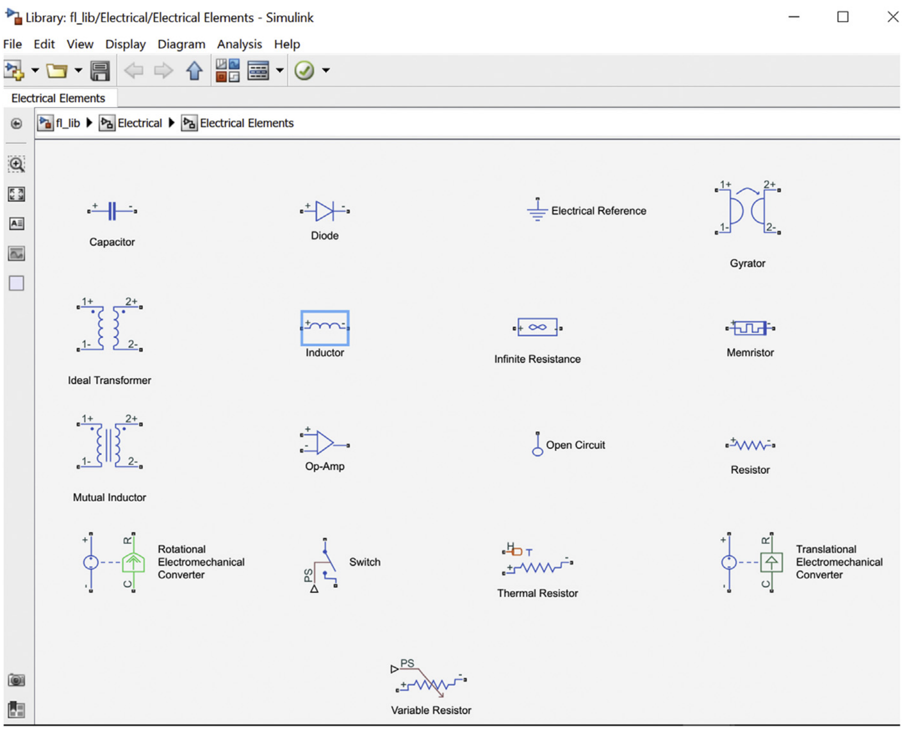

Figure 7.24 Inductor and resistor blocks.

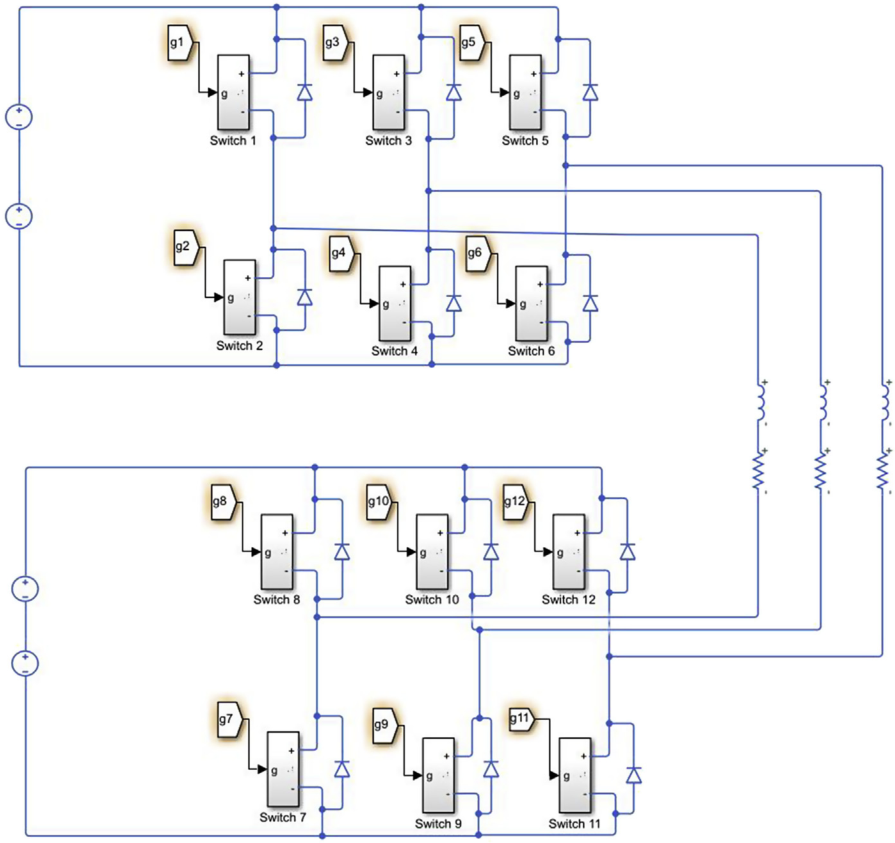

Figure 7.25 Connecting resistor and inductor blocks to the inverter model.

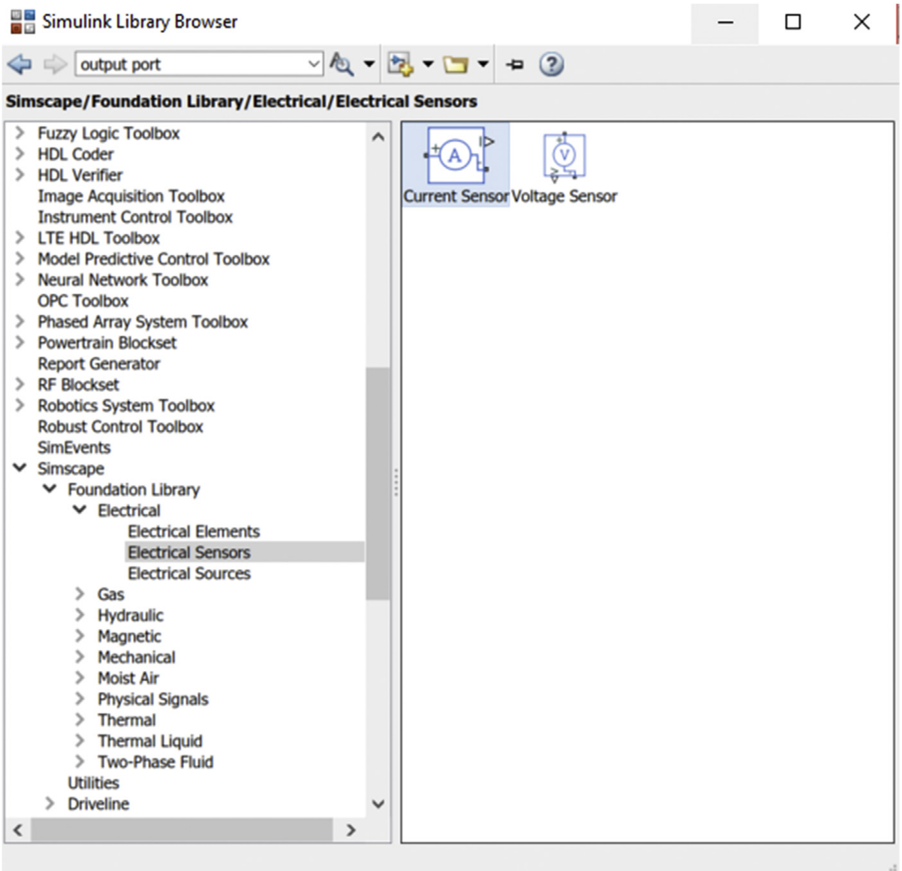

Figure 7.26 Current sensor and voltage ensor blocks.

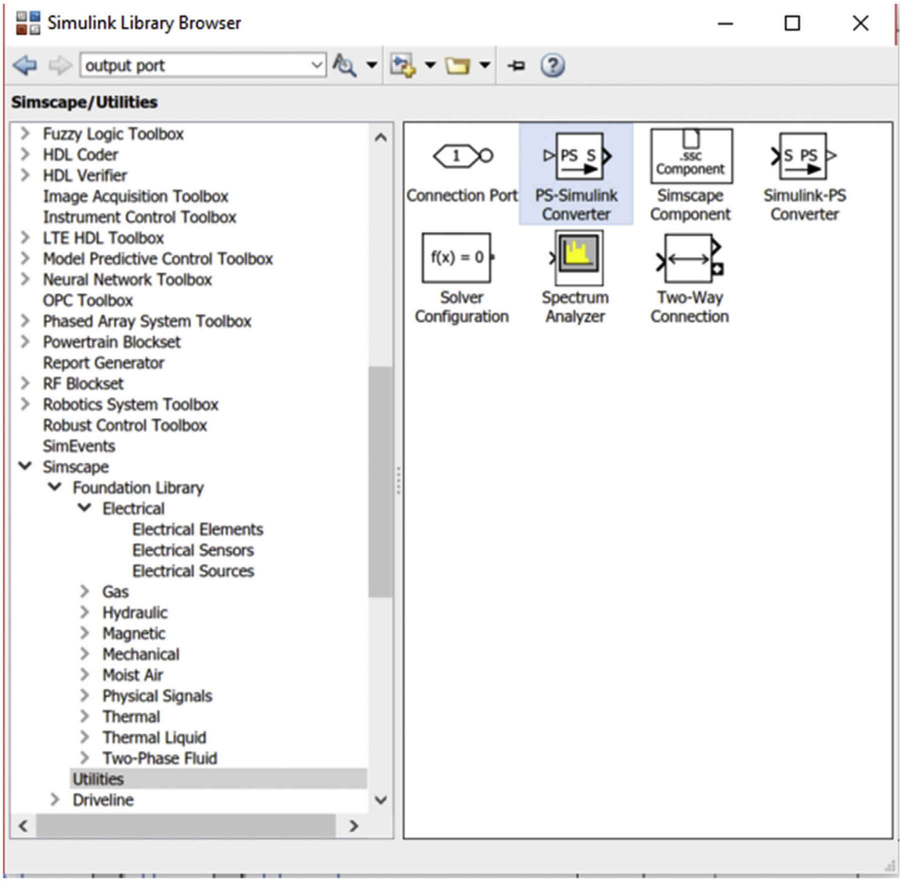

Figure 7.27 PS-simulink converter.

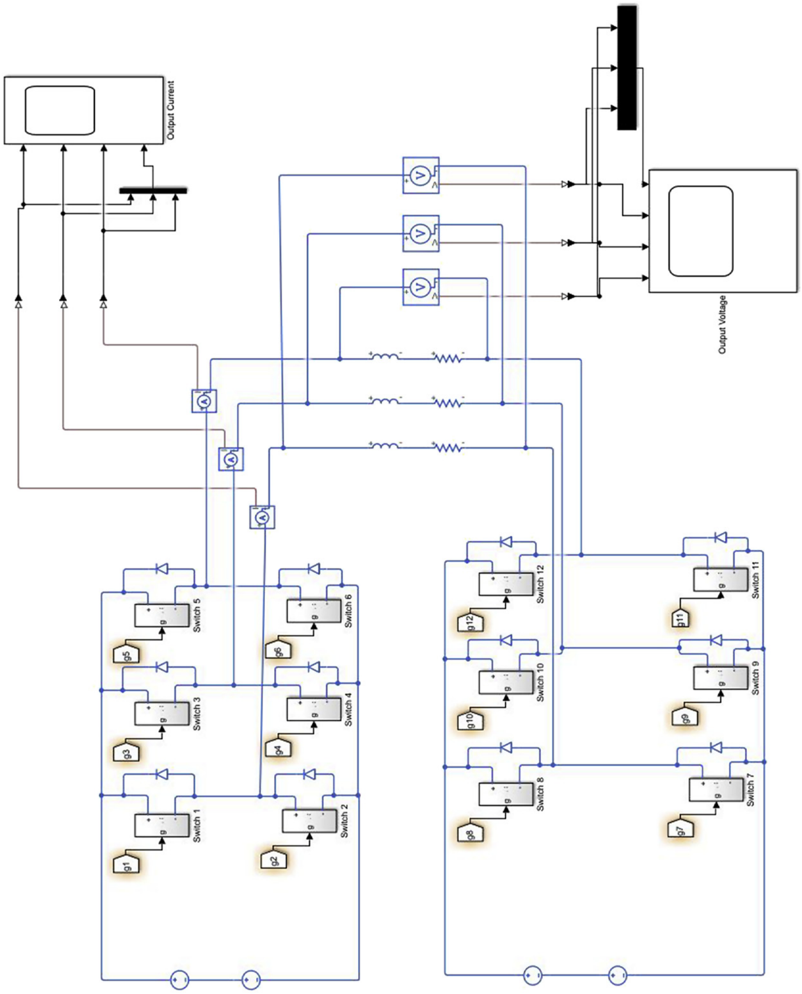

Figure 7.28 Connecting voltage and current sensors to the model.

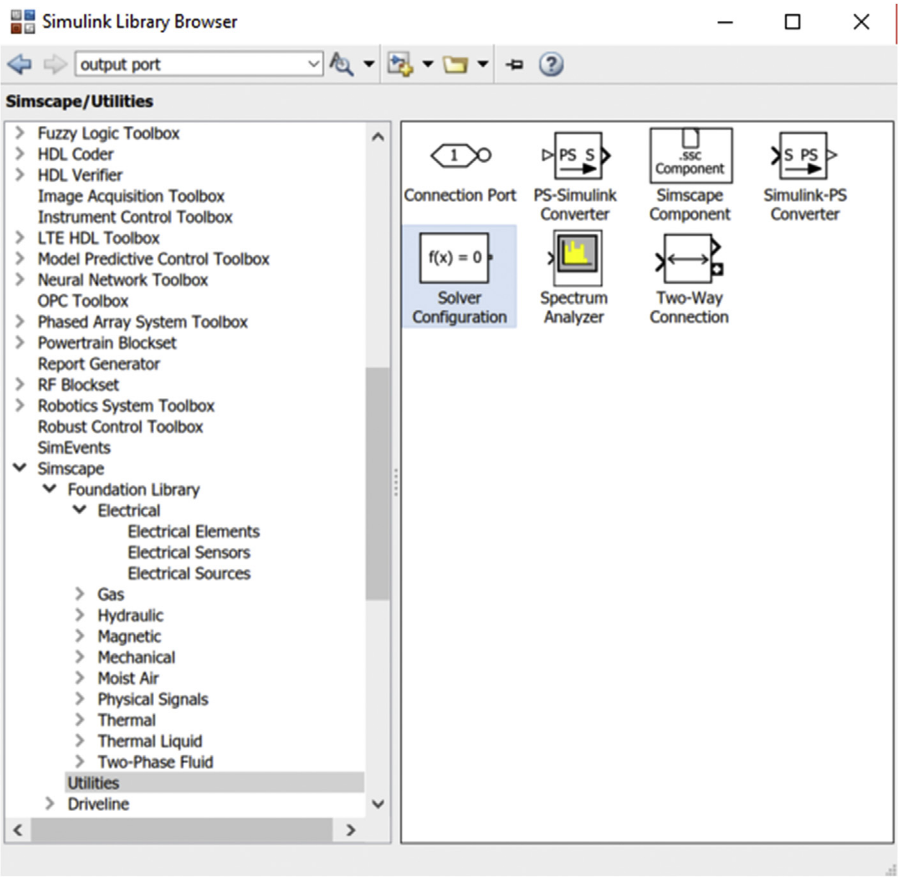

Figure 7.29 Solver block

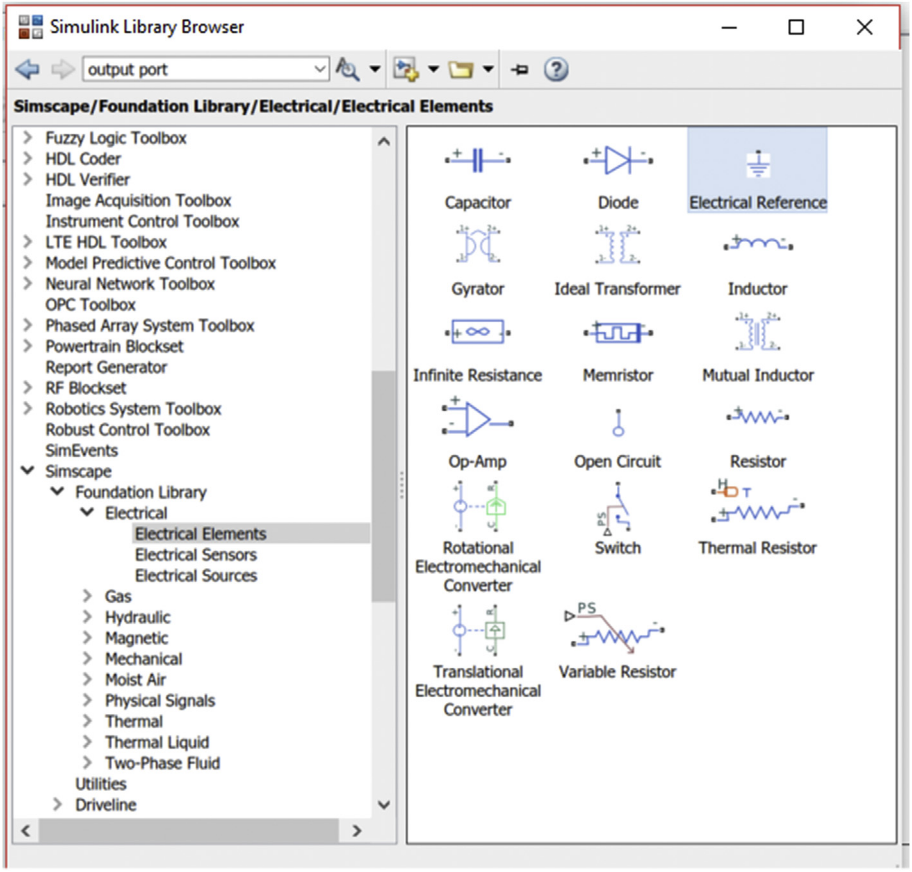

Figure 7.30 Electrical reference block.

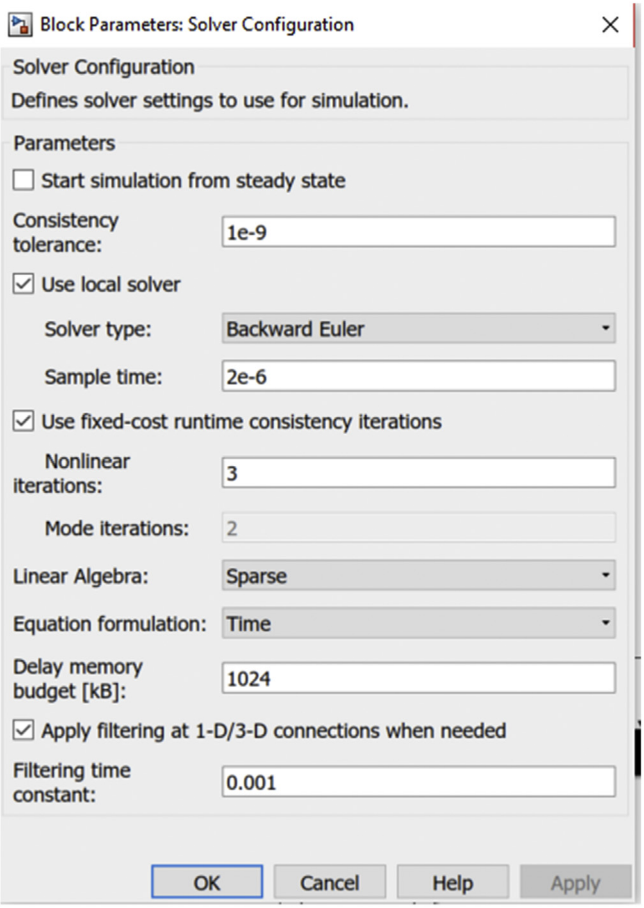

Figure 7.31 Setting up the sample time parameter for the Solver block.

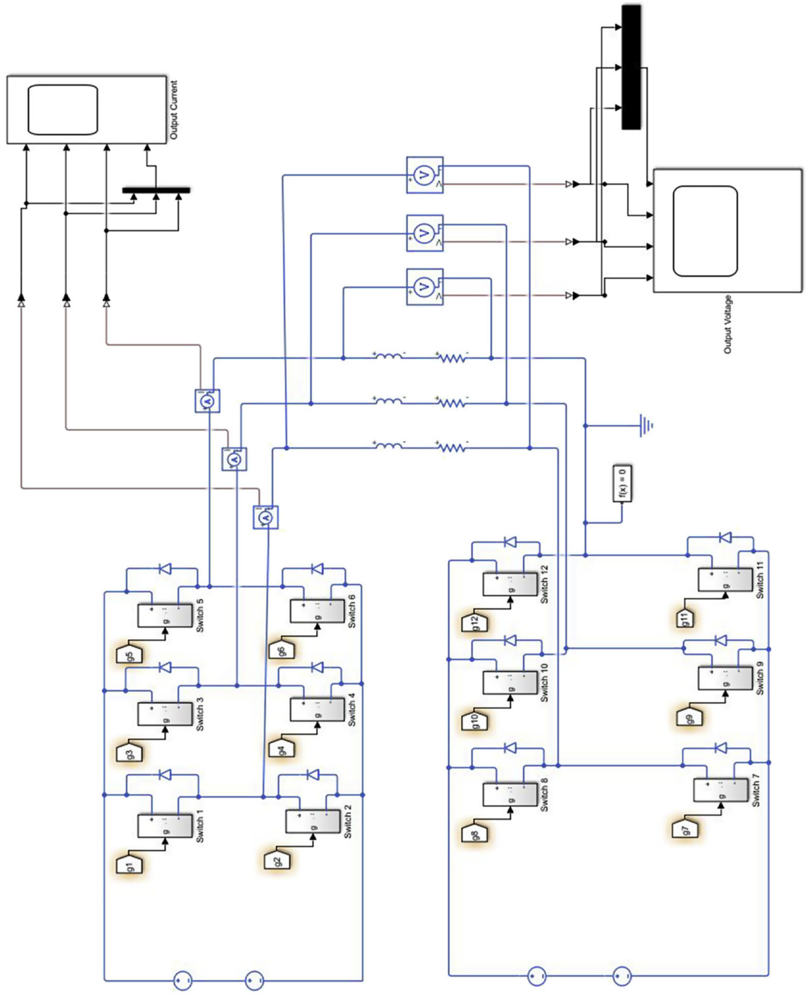

Figure 7.32 Solver and the electrical terminator block connection.

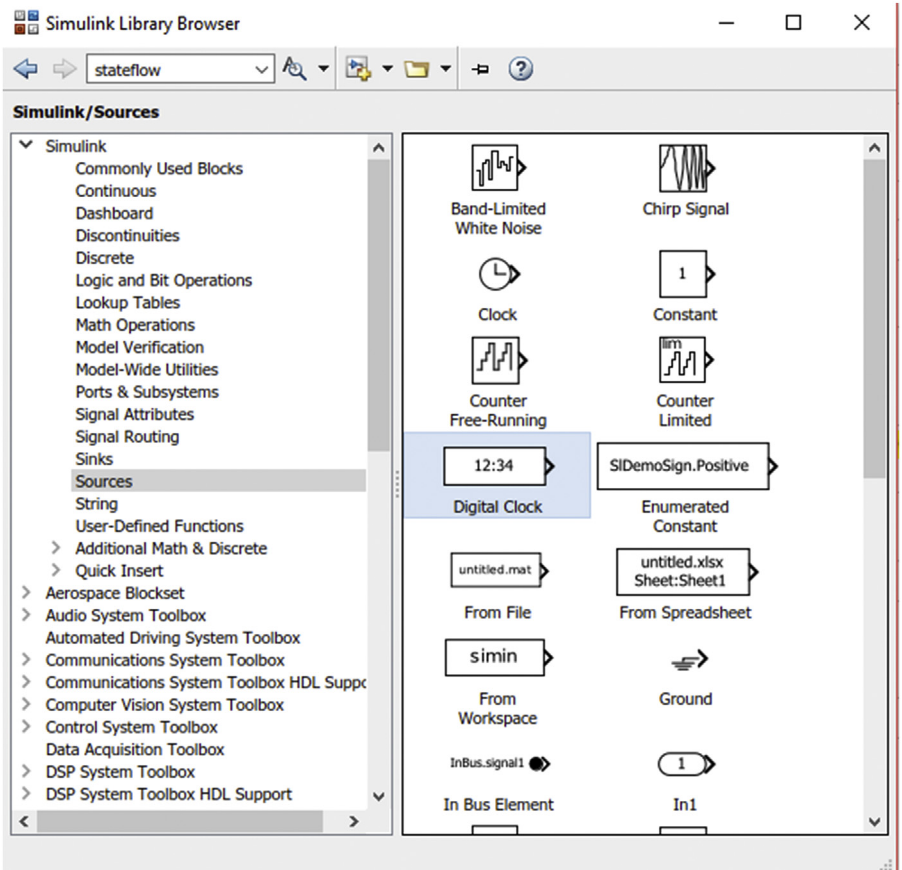

Figure 7.33 Adding digital clock block to the model.

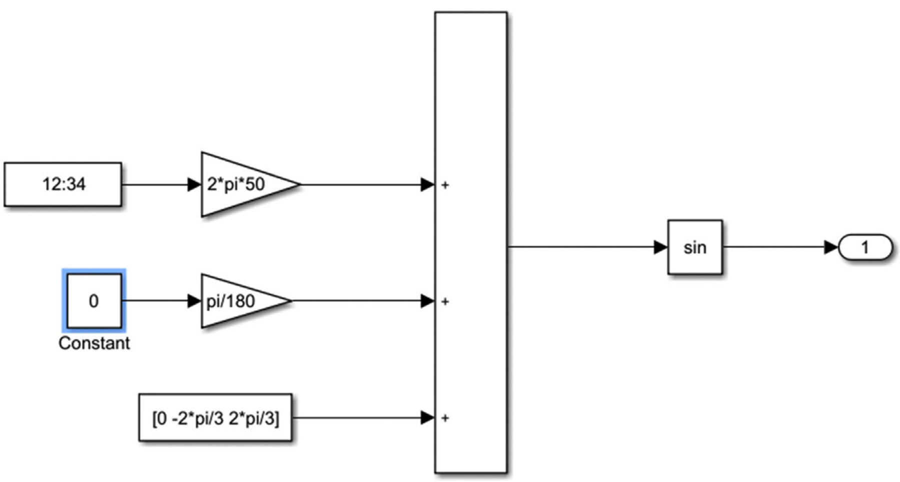

Figure 7.34 Model to generate sinusoidal signals.

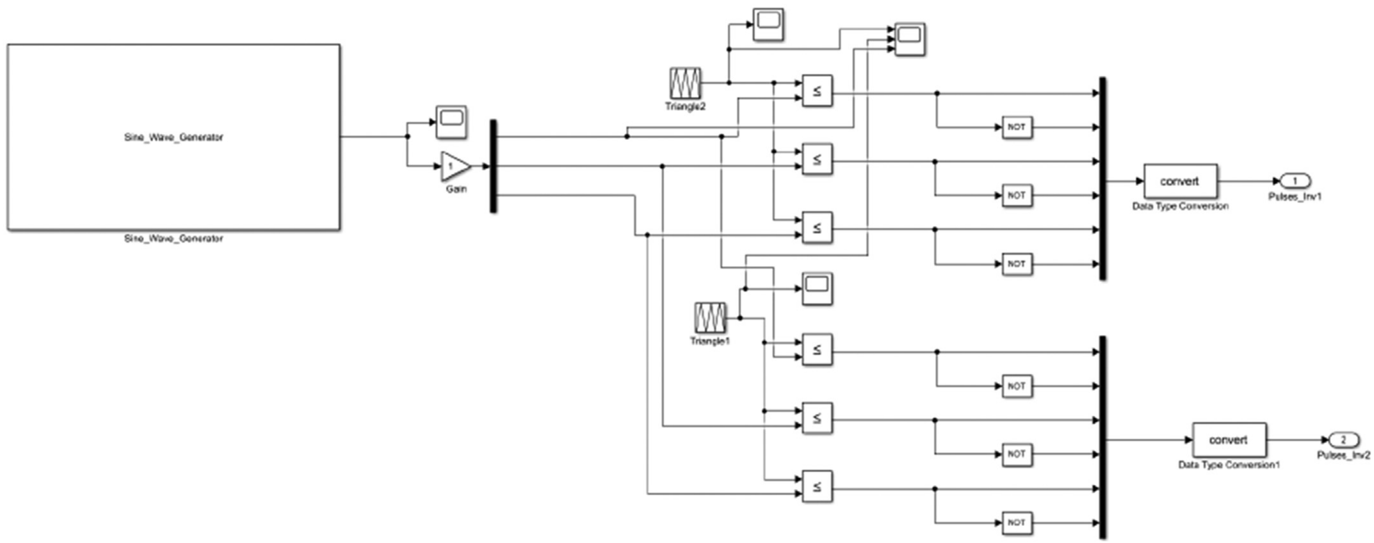

Figure 7.35 PWM generator.

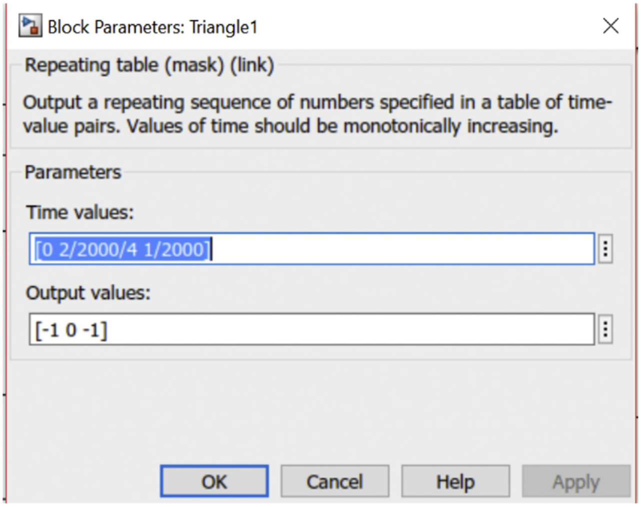

Figure 7.36 Assigning block parameter values for triangle1 block repeating sequence block.

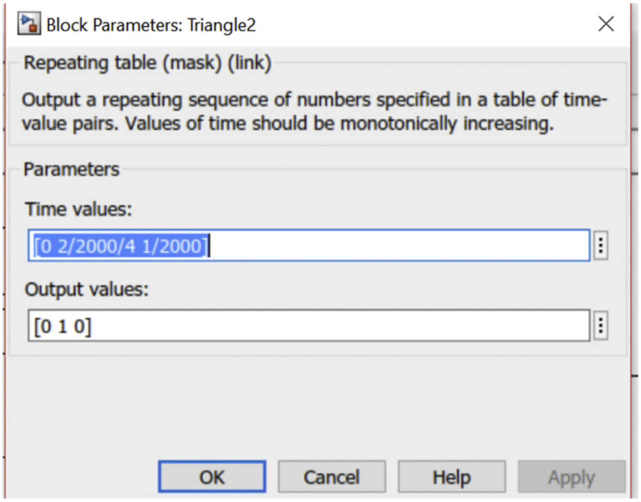

Figure 7.37 Assigning block parameter values for triangle2 block repeating sequence block.

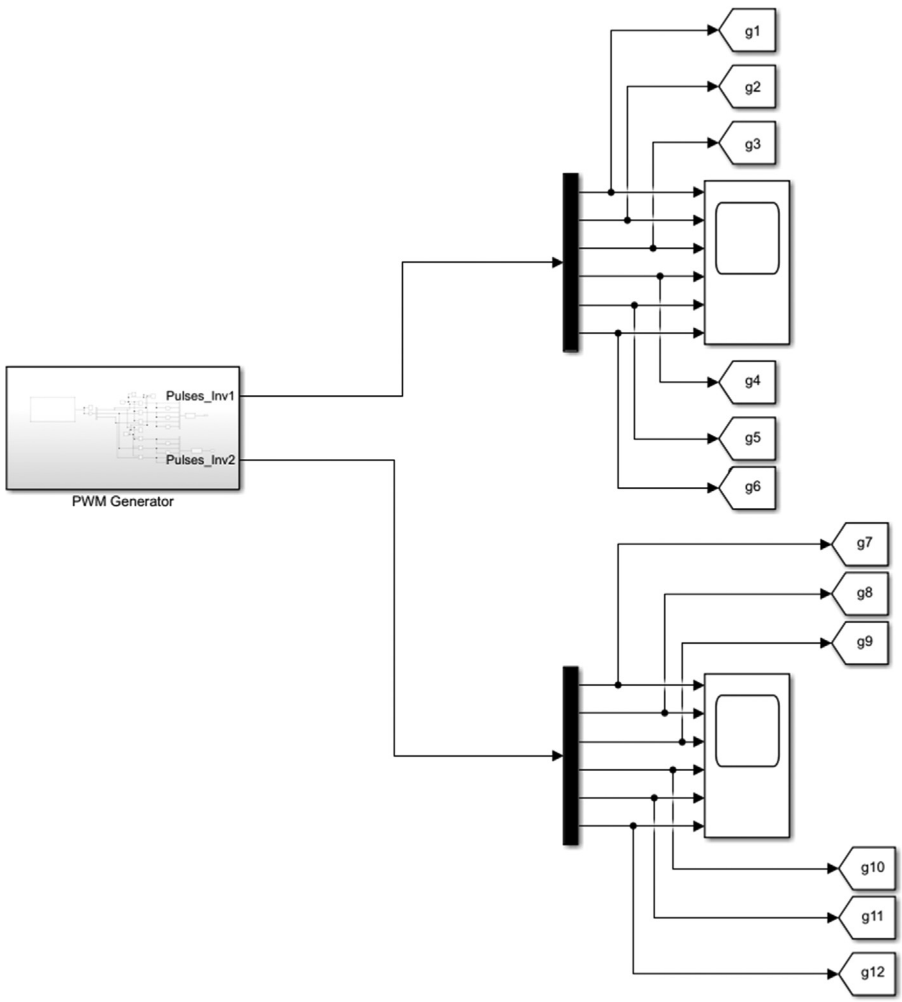

Figure 7.38 PWM generator subsystem.

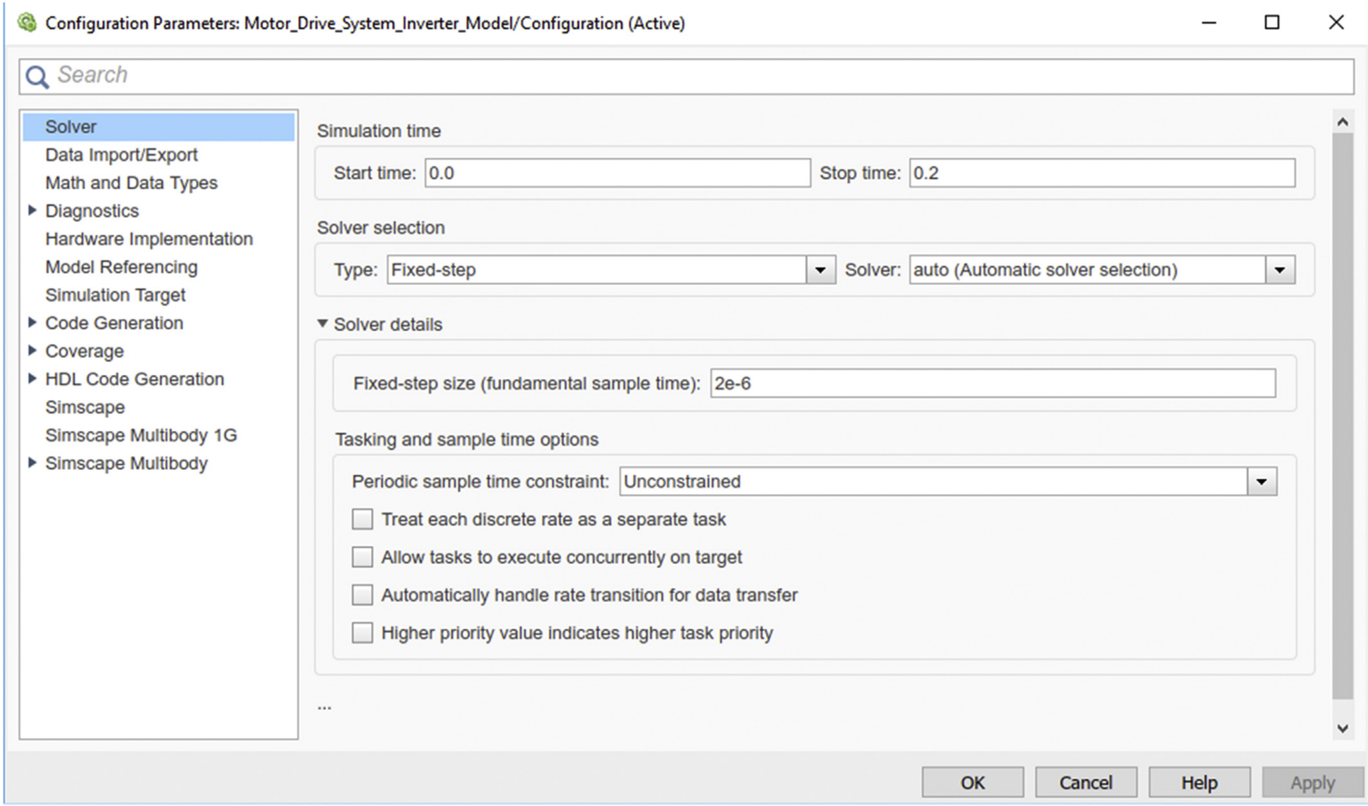

Figure 7.39 Model configuration parameters.

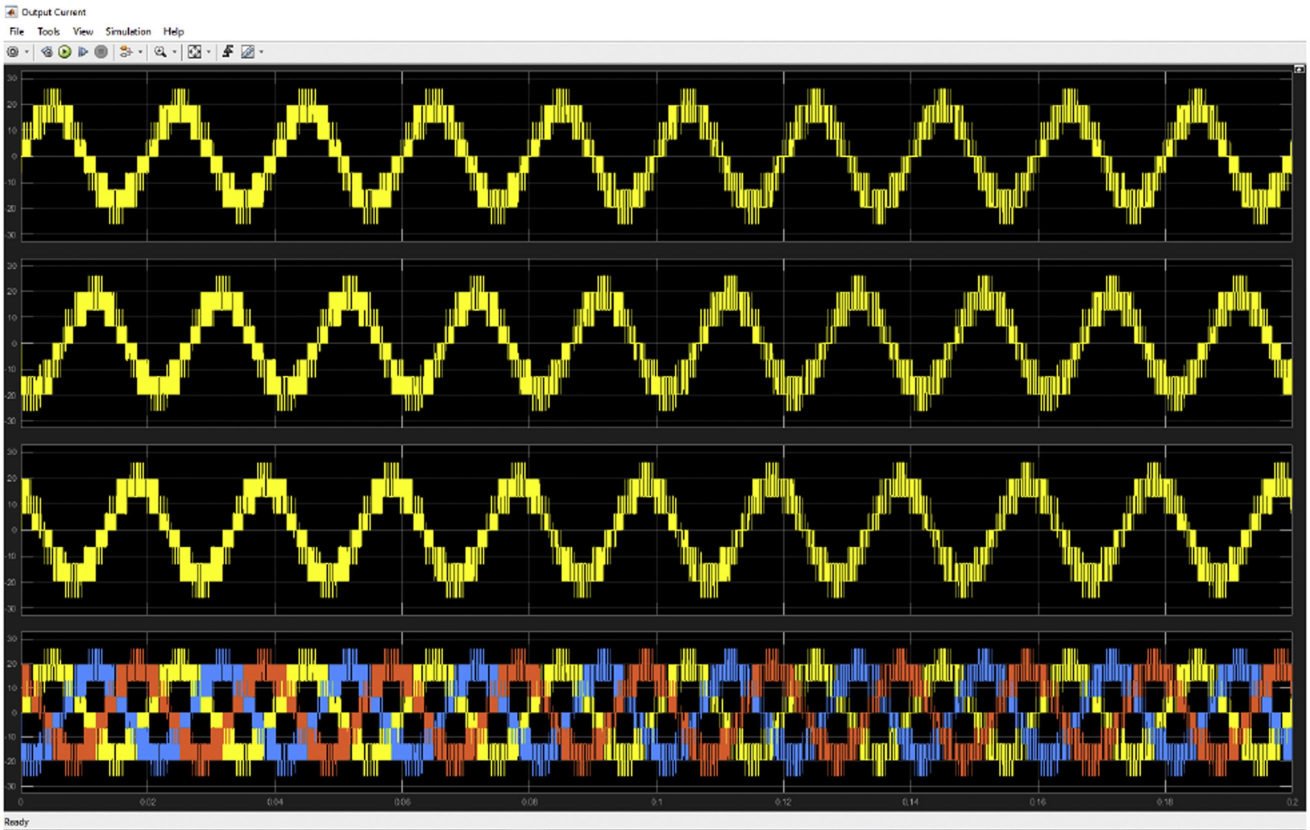

Figure 7.40 Inverter output currents from simulation.

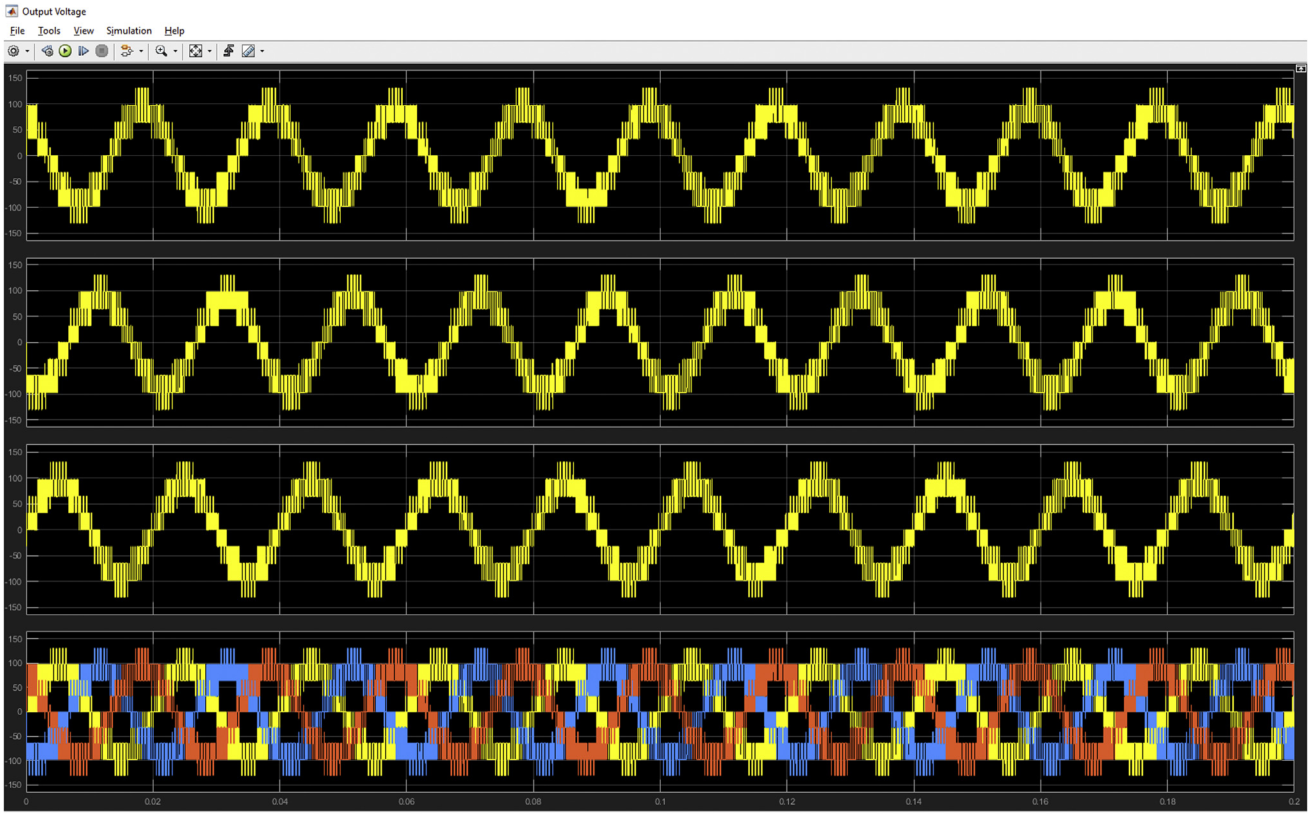

Figure 7.41 Inverter output voltages from simulation.

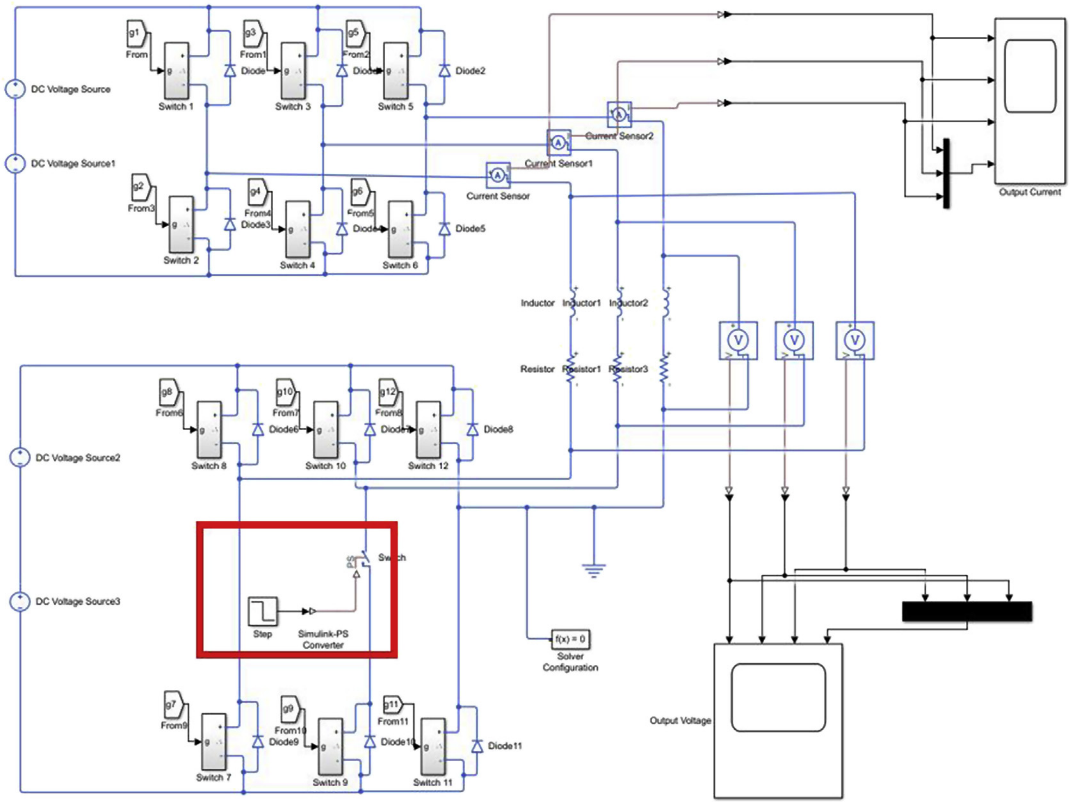

Figure 7.42 Introducing open-circuit failure to the inverter circuit.

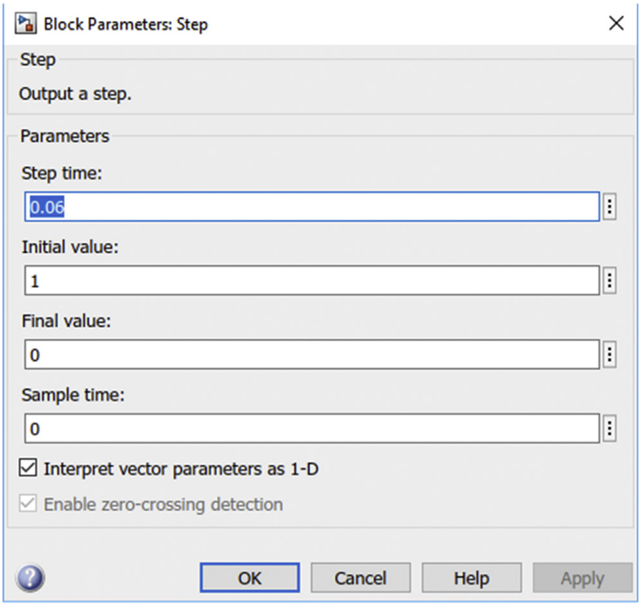

Figure 7.43 Configuring step input block for open-circuit failure.

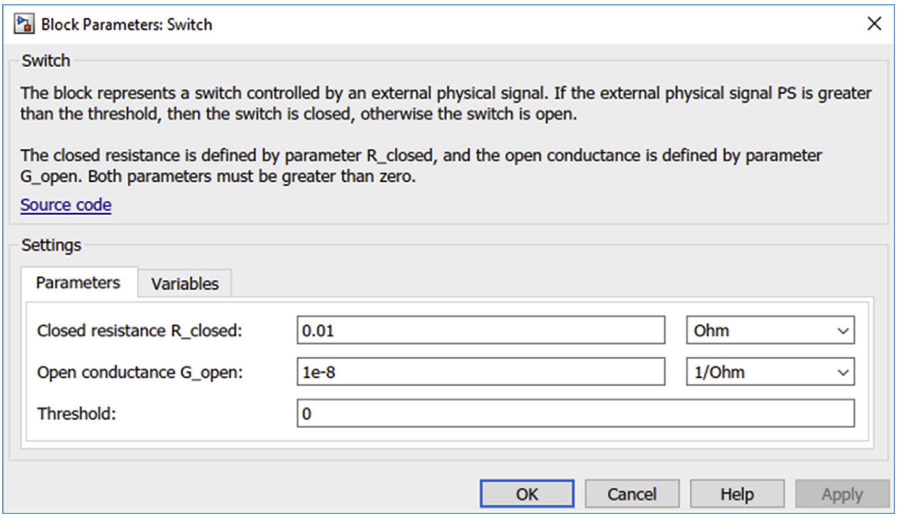

Figure 7.44 Configuring the switch block for open-circuit failure.

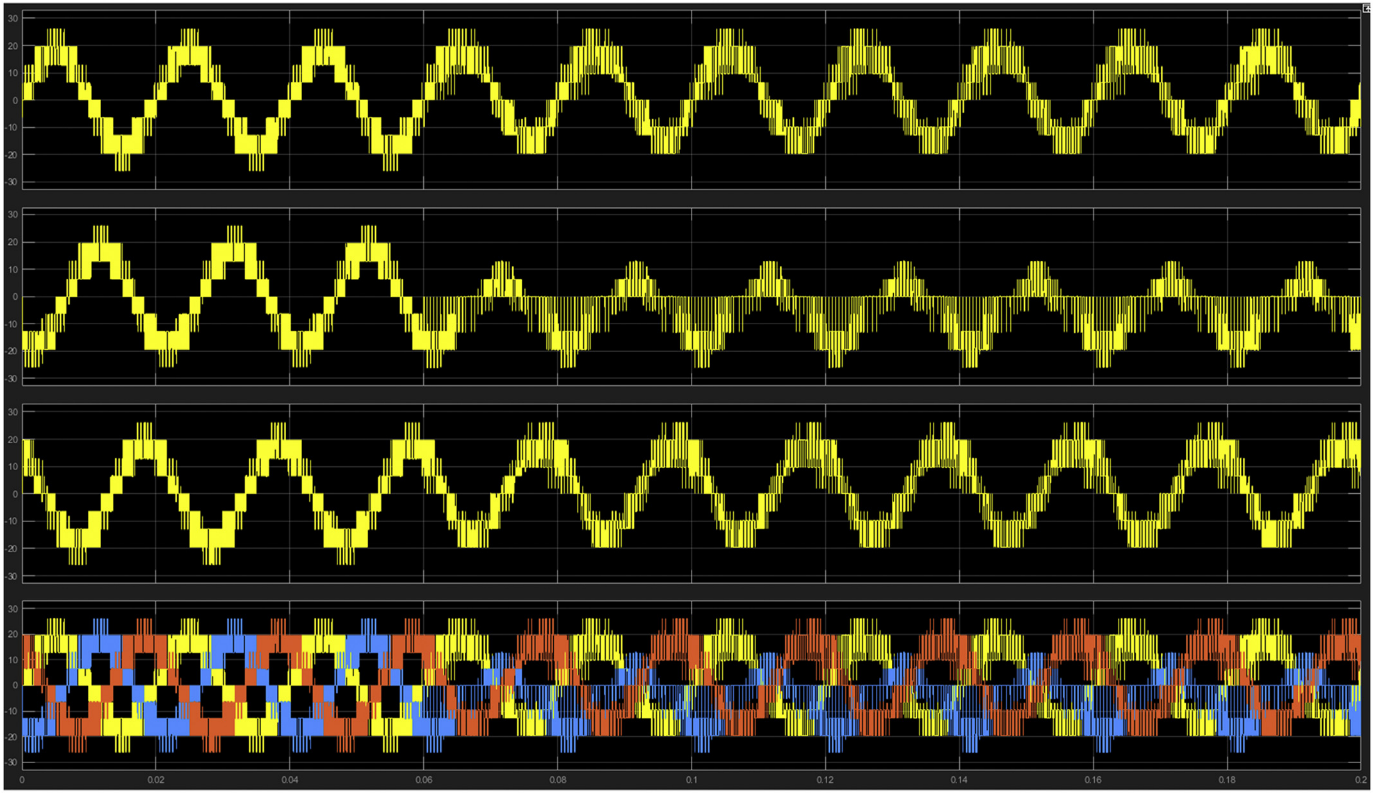

Figure 7.45 Inverter output currents from simulation with open-circuit failure.

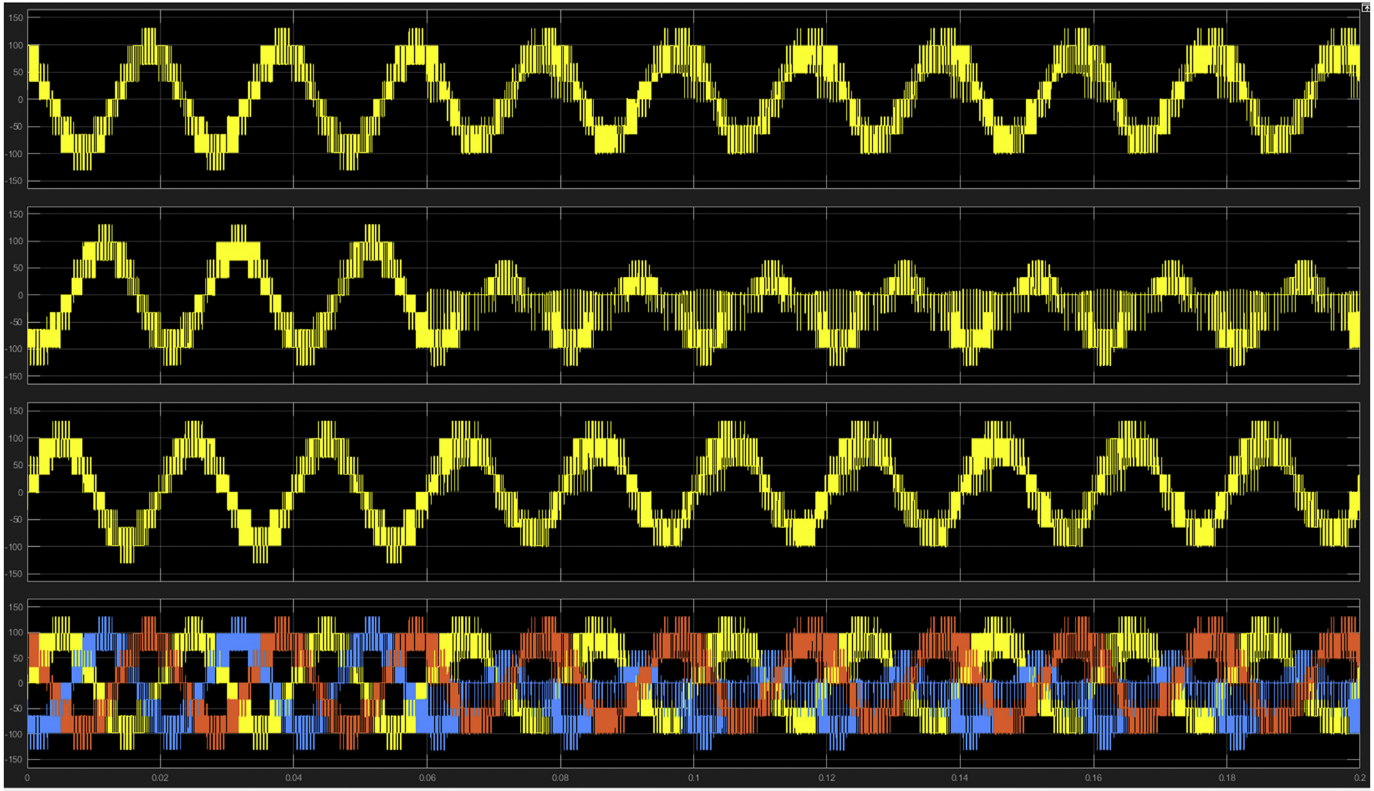

Figure 7.46 Inverter output voltages from simulation with open-circuit failure.

Reference

[1] E.C. dos Santos, E.R. da Silva, Cascade configuration, in: Advanced Power Electronics Converters: PWM Converters Processing AC Voltage, Wiley, 2014, pp. 125−171, ch. 5, sec.7.