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Modeling and User's Documentation

For

Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers

U.S. DEPARTMENT OF
ENERGY
Electricity Delivery
& Energy Reliability

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REVISION HISTORY

Revision	Date	Description	Editor
1	10/16/2015	Initial version	Salcedo
2	10/19/2015 -to- 10/23/2015	Added the following sections: Cables Circuit Breaker Transformers Loads (time-varying and static) System Topology – Case#1: Boston Symposium 2015 Irradiance Profile Load Profiles Test Circuits	Salcedo Corbett
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4	10/26/2015	Added Smith-10/23/2015 sections	Salcedo
5	11/06/2015	Added text from TCO for package release Added text and logo for sponsor	Salcedo Corbett Limpaecher
6	11/09/2015	Added relay section	Salcedo
7	11/12/2015	Added generator and Woodward section Finalize relay section	Nowocin Salcedo

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1. SYSTEM TOPOLOGY – CASE#1: OCT. 1ST SYMPOSIUM

Library: *N/A*

1.1 DESCRIPTION

The Radial distribution systems are widely implemented due to their simplicity and relatively low cost. The feeders leave a substation and distribute electrical power in the designated zone without connections to other points of supply. This configuration is popular in rural areas with long feeders supplying remote loads. To increase reliability, damaged parts of the feeders may be isolated and alternative power sources (i.e. nearby substations or local generation) can be connected by means of manual or automatic tie switches.

The test feeder used for the study consists of one (out-of-three) radial feeder supplying a real-life industrial park, see Figure 1.1. The overall electrical demand of the feeder ranges from 4.2 MW to 12 MW for minimum and maximum load, respectively. The system is rated for a medium voltage of 13.8 kV and low voltages of 4.16 kV, 2.4 kV, 460 V, and 208 V. There are 10 loads continuously supplied by the feeder (2 critical, 4 priority, and 4 interruptible). Critical loads are categorized by the high requirements of continuous electrical service, power quality, and reliability (i.e. hospitals, sensitive equipment labs, etc.). Priority loads are buildings that ideally are always served, but in case of contingencies, or islanding with lack of generation, may be disconnected. Interruptible loads are buildings not necessarily required to be served during contingencies or islanded conditions. Furthermore, there are two large induction motors of 250 horsepower, one of the largest sizes recommended by the 2011 National Electric Code (NEC) for full voltage start-up. Even though these motors are not part of the actual site, the units were added to evaluate the microgrid controller's ability to perform islanded-load-balancing while having a large motors start-up.

Each of the system loads is modeled as a time-varying dynamic load based on electrical demand profiles extracted from smart metering equipment. There are two simulated Caterpillar diesel generators in the system corresponding to a 1000 kVA (CAT 32) and a 4000 kVA (CAT C175-20), operated at nominal voltages of 480 V and 13.8 kV, respectively. Both generators are controlled and protected using the commercially available Woodward EasYgen 3500 generator controllers. During simulations, the Woodward controllers are entirely controlled by the microgrid controllers without operator intervention unless the alarms deem necessary. There are 13 distribution transformers serving the area. Two of these transformers interconnect a simulated 3500 kW PV system with maximum power point tracking (MPPT), and a 4000 kVA energy storage system (ESS). The PV system is supplied with a varying irradiance profile that begins with a sunny day followed by a storm-type cloud. Note that any irradiance profile may be applied to the PV system. The ESS is fully controlled by the microgrid controller enabling the evaluation of power factor correction, peak shaving/smoothing, and possibly power export. The total system demand, and the available generation and storage were sized to evaluate the microgrid controller's ability to perform smart load shedding prior and during islanded conditions.

The conventional system fault protection is provided by simulated relays modeled to approximate a Schweitzer SEL-787 transformer protection relay. These units can be remotely actuated by the microgrid controller, and provide sensor values. All settings are based on a moderate inverse time curve. The simulated relay functions are the following: synchronizing or synchronism-check (ANSI Std. Dev. No. 25), phase instantaneous overcurrent (ANSI Std. Dev. No. 50P), AC inverse time overcurrent (ANSI Std. Dev. No. 51P), undervoltage relay (ANSI

Std. Dev. No. 27), and overvoltage relay (ANSI Std. Dev. No. 59). Addition of other relay functions may be a topic for future development. This document provides a more detailed discussion of each of the components used in the system, their operation modes, and interfaces.

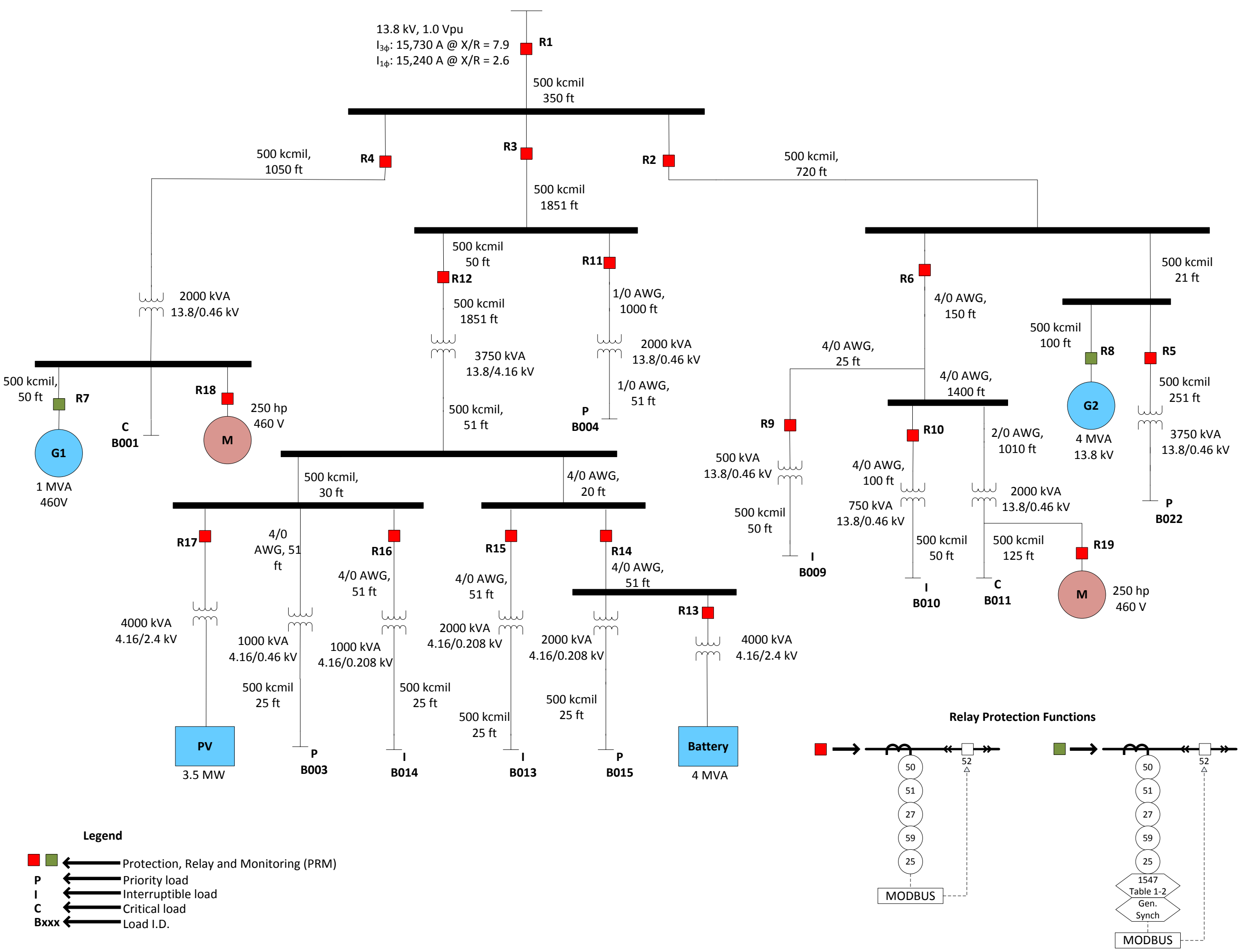


Figure 1.1 System Topology – Test feeder one-line diagram

Since distribution systems consist of a large number of similar elements, the following modeling approach was adopted. The GUI of MATLAB-Simulink is used to derive detailed prototype models for each group of electrical component (i.e., one base model for all network transformers, one base model for all breakers, and so forth). These models are parametrized in order to adapt to different voltages, kVA ratings, operation settings, and impedances. Applying this technique, the following prototype models were derived:

- Cables;
- Breakers;

- Network transformers;
- Time-varying loads;
- Generators;
- PV system;
- Energy storage system (ESS);
- Relays simulating functions of the commercial SEL-787

In addition, some built-in models in the MATLAB-Simulink libraries were adopted, such as three-phase series RL branches, ideal switches, measurement probes, among others. The created prototype models were placed into the system replicating the one-line diagram. Then, the corresponding parameters of the prototype models were updated to reproduce the real-life system architecture. The resulting distribution system is then loaded into the real-time simulator which is hardware-interfaced with two commercial Woodward EasYgen 3500 controllers and the commercial microgrid controller under evaluation. This document describes the prototype models in more detail to provide more information on model complexity.

1.2 OPAL-RT REQUIREMENTS

The following tools are required to simulate cases in the test-bed: Simulink-Simscape, Simulink-SimPowerSystems, Matlab Coder, and Opal-RT Lab (an interface to the real-time simulator).

After the electrical component were modeled and tested, the one-line diagram was used as a reference to build the simulation model in the Simulink environment. Due to the high computing demand of the logic components and the system size, three Opal-RT cores were required for the simulations. Since this development had a three-month timeline, the models were not fully optimized. Therefore, it is likely that only two Opal-RT cores could be sufficient to simulate the system. Core# 1 and core# 2 are used to simulate the distribution system, and core# 3 is used to simulate all the relay logics. Each of these cores communicates to each other in real-time. The Opal-RT provides a fifth order, highly accurate, and efficient solver called ARTEMiS. For more information, visit the Opal-RT website. Future work includes the modeling of this system with fully optimized components, and the leverage of other real-time simulators in the market.

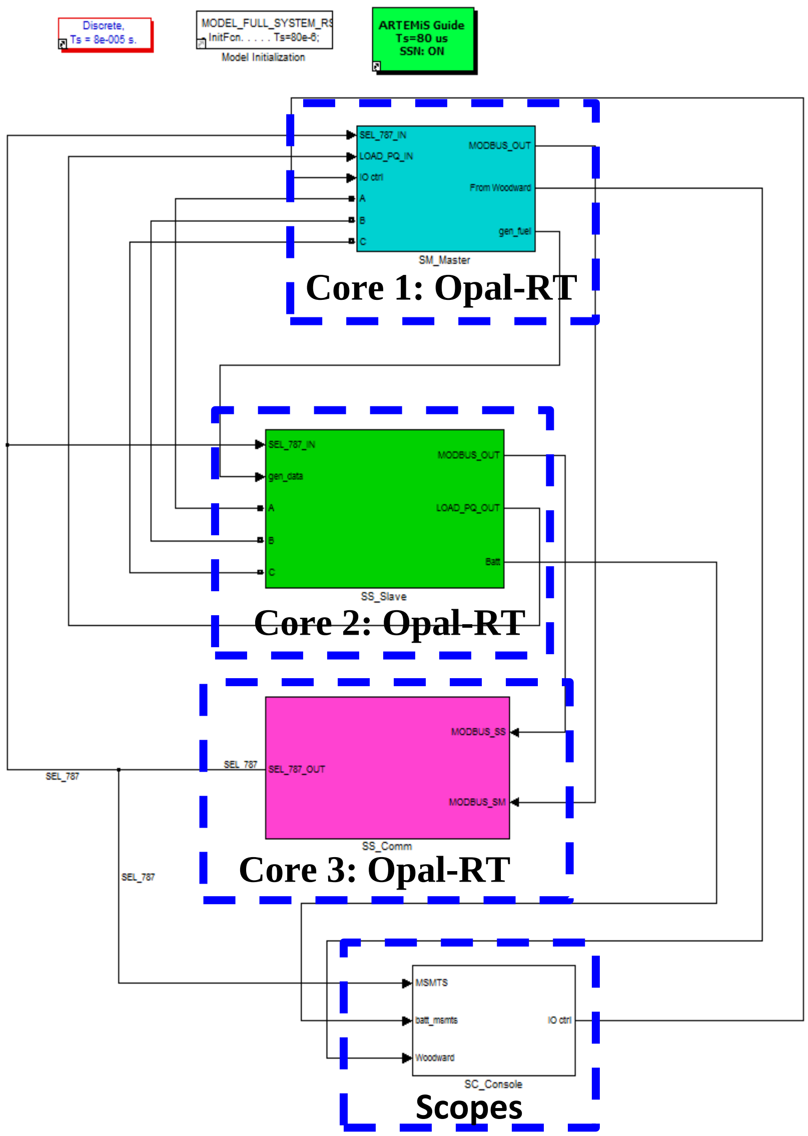
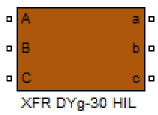


Figure 1.2 System Topology – Opal-RT Cores layout

2. TRANSFORMER

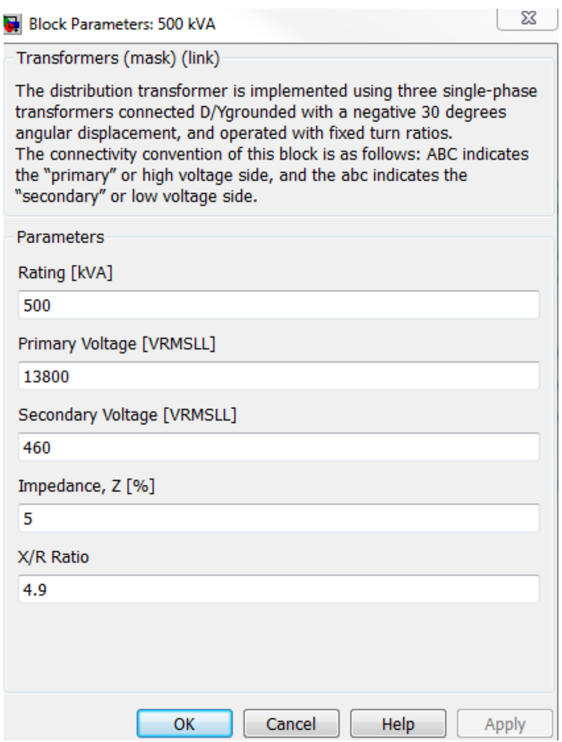
Library: *transformer_lib.mdl*

2.1 DESCRIPTION



The network transformer is implemented using three single-phase transformers connected D/Ygrounded with a negative 30 degrees angular displacement, and operated with fixed turn ratios. The impedances and X/R ratios were obtained from the actual site one-line diagram.

2.2 DIALOG BLOCK AND INPUT PARAMETERS



The connectivity convention adopted for this block is as follows: *ABC* indicates the "primary" or high voltage side, and the *abc* indicates the "secondary" or low voltage side.

The required parameters for the transformer are the kVA rating, primary and secondary voltages in RMS line-to-line, the percent impedance, and the X/R ratio. The model was created to work using the typical data available in conventional power flow programs.

Rating

The transformer the kVA rating

Primary Voltage

Primary winding nominal voltage in RMS line-to-line

Secondary Voltage

Secondary winding nominal voltage in RMS line-to-line

Impedance

Percent leakage impedance of the transformer

X/R Ratio

Equivalent X/R ratio

2.3 MODEL SCOPE AND LIMITATIONS

Due to the short timeline of the effort, the units were modeled as linear transformers with magnetizing branches represented by constant per unit values of resistance and inductance. Although this assumption was not influential in the presented demos during the symposium, future work involving transient overvoltages, unbalanced short circuits, and self-healing switching may require the transformers to be modeled considering non-linear magnetizing branches.

2.4 EXAMPLE

This example shows basic transformer setup for the real-time HIL simulation platform to evaluate microgrid controllers. The diagram shows a simple case consisting of a source, two 500-kcmil cables, a 500 kVA transformer, and a 300 kVA static load.

- The data and parameters used in the HIL test-bed were extracted from an actual operating industrial area. The transformer model was validated against fundamental calculations.

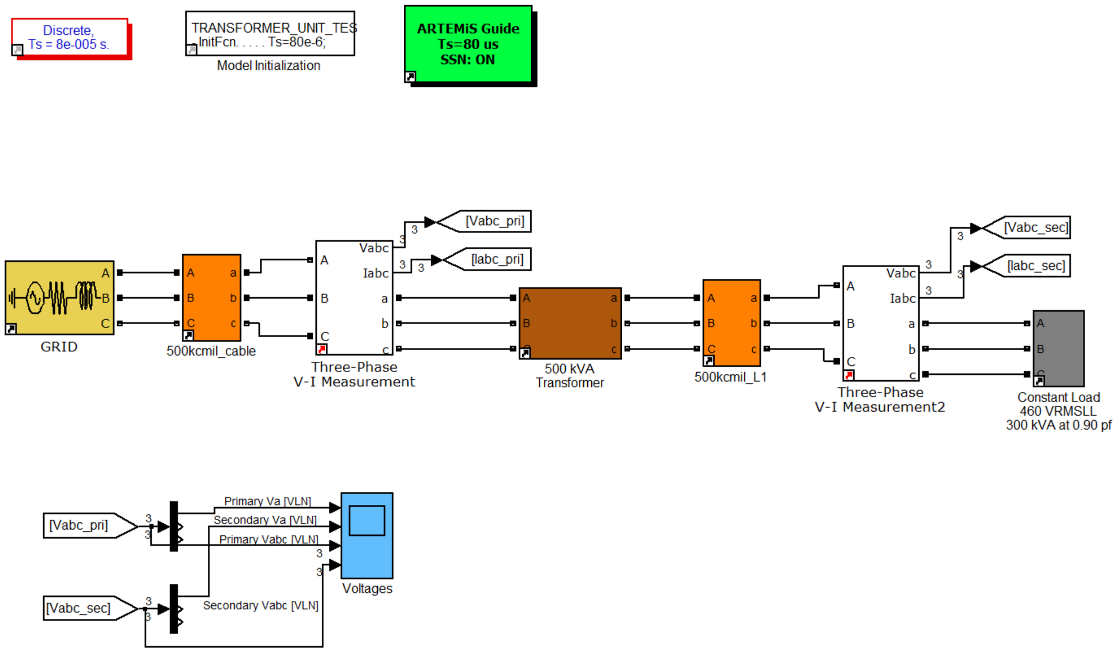


Figure 2.1. Transformer Unit Test – Sample Diagram

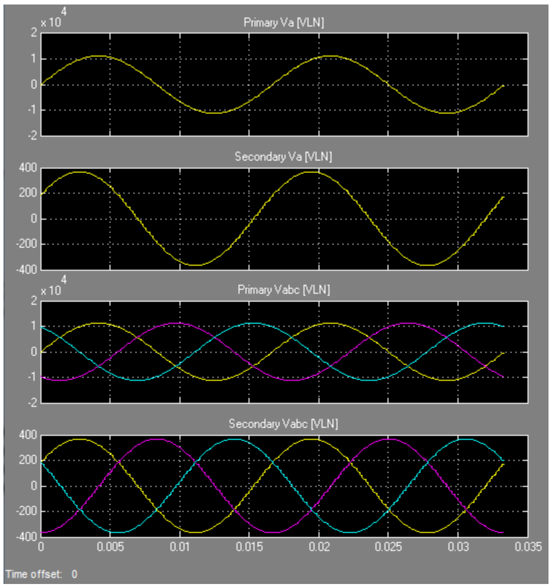
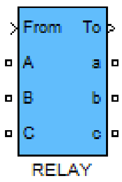


Figure 2.2. Transformer Unit Test – Voltage waveforms

3. CIRCUIT BREAKER

Library: *modbus_lib.mdl*

3.1 DESCRIPTION



The circuit breakers are represented as controlled three-phase switches with measurement probes to monitor the system. Their control logic is provided by external relays. As can be seen in this figure, measured values of the phase currents flowing through the breaker and terminal voltages are compared with the selected overcurrent settings (instantaneous overcurrent or ac-time overcurrent) and under/over-voltage settings. Once tripping conditions are satisfied, the logic waits for current zero-crossing to issue the trip command.

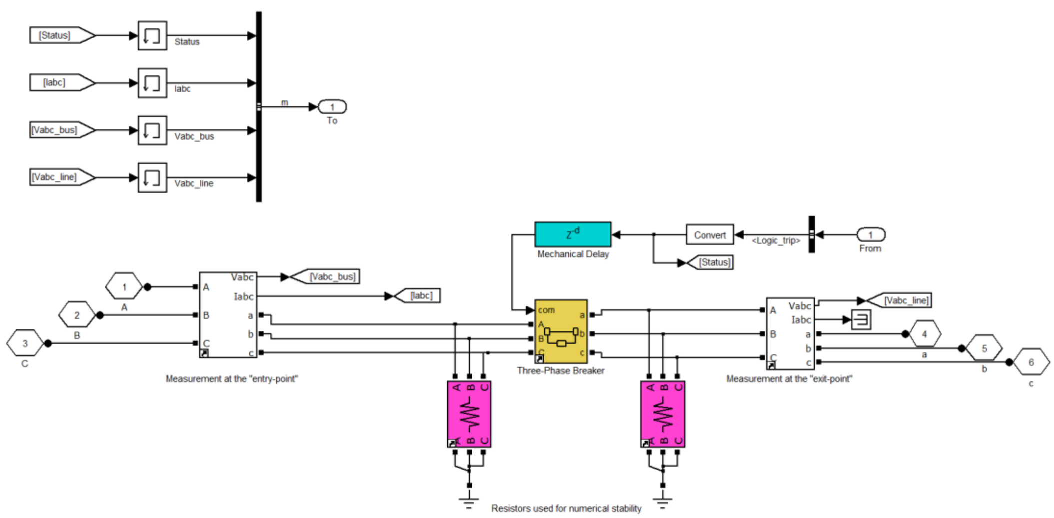
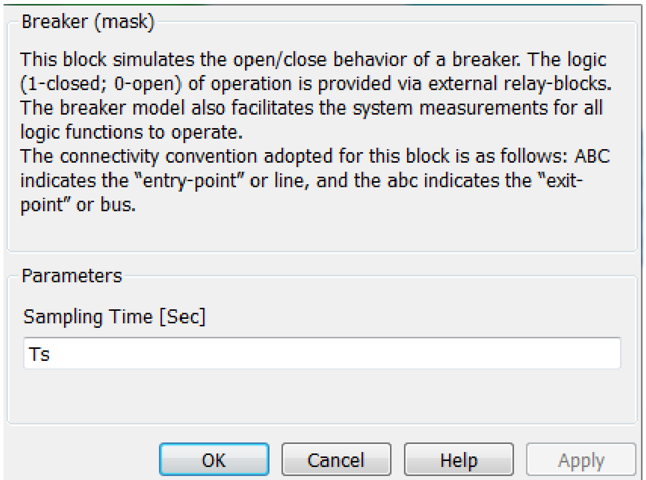


Figure 3.1 Breaker Unit Test – Internal scheme

3.2 DIALOG BLOCK AND INPUT PARAMETERS



The connectivity convention adopted for this block is as follows: *ABC* indicates the “entry-point” or line side, and the *abc* indicates the “exit-point” or bus. The only required parameter is the simulation sampling time.

Sampling Time

The simulation sampling time (or time-step) in second

3.3 EXAMPLE

This example shows basic operation of the breaker model. The test system is composed of a source, two 500-kcmil cables, a 500 kVA transformer, a 300 kVA static load, and the circuit breaker. The circuit breaker is controlled using a step sequence. The commanded operations are as follows: first, the breaker is initially closed; then, sends an open command; lastly, the commands force the breaker to reclose causing a current asymmetry.

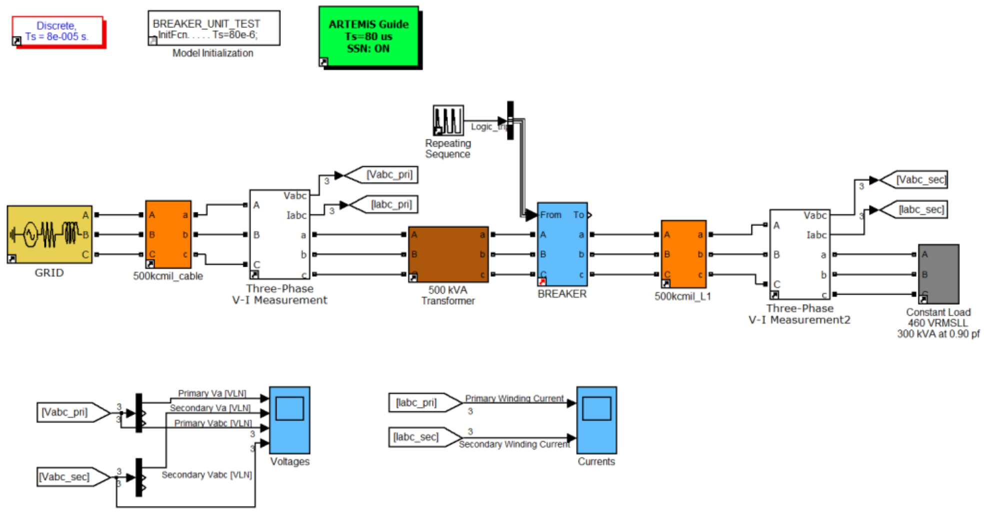


Figure 3.2 Breaker Unit Test – Sample Diagram

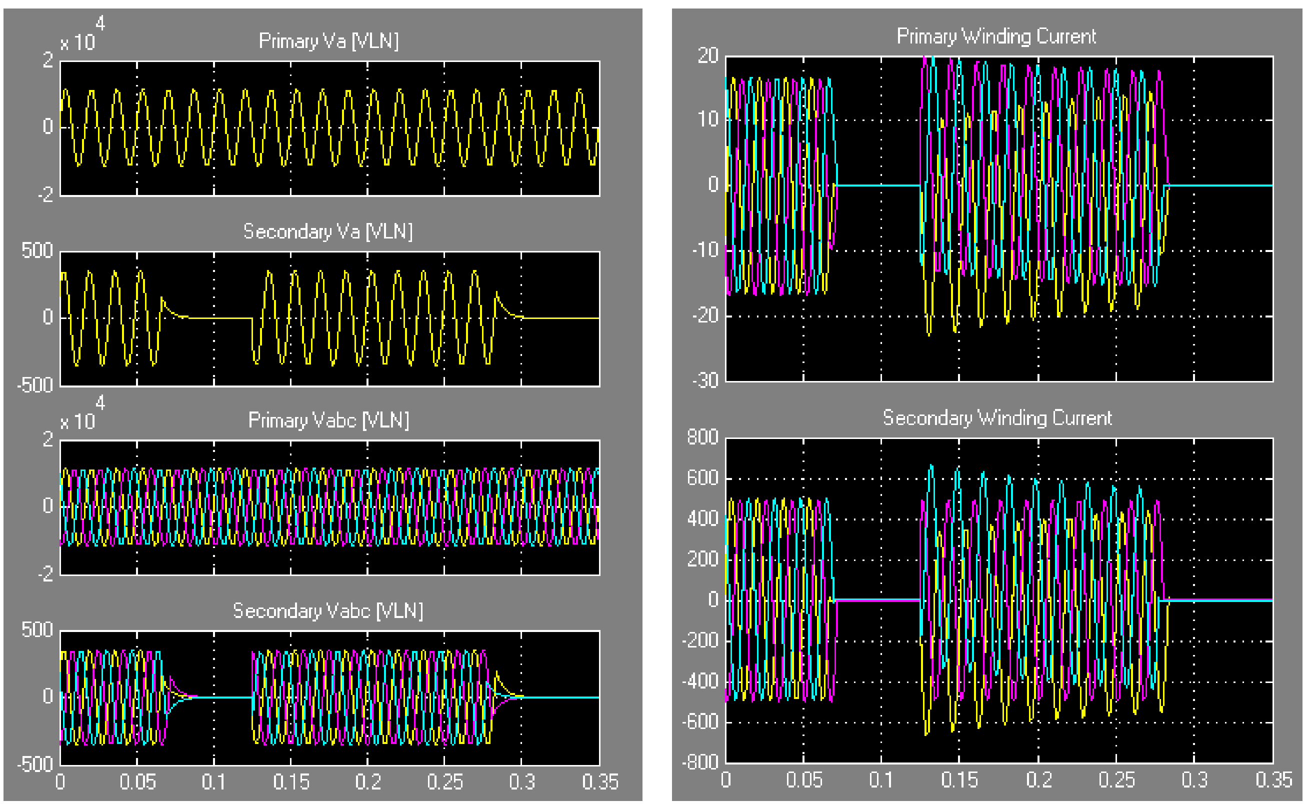
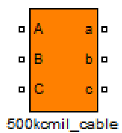


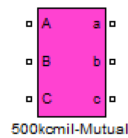
Figure 3.3 Breaker Unit Test – Voltage and current waveforms

4. CABLES

Library: *cables_lib.mdl*

4.1 DESCRIPTION

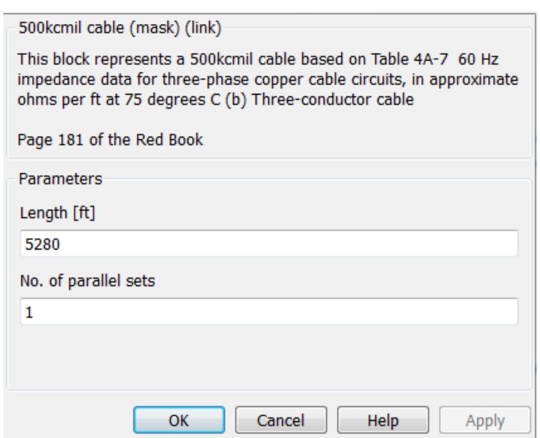




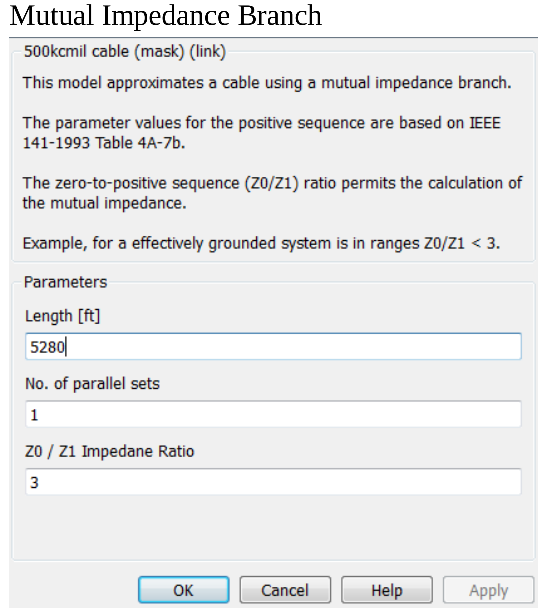
The Feeder conductors and secondary mains are modeled using Simulink positive sequences three-phase series RL branches (orange). Additionally, mirror models where developed using a Simulink positive-and-zero sequence mutual impedance branch to consider the coupling between phases (magenta). However, these coupled branches do not account for cable capacitances. Parameters of each cable section were calculated using impedances obtained from IEEE 141-1993 Table 4A-7b [1] and the length of the cables extracted from the actual site one-line diagram. Table 2 shows the most typical cables in the system.

4.2 DIALOG BLOCK AND INPUT PARAMETERS

Series RL Branch



Mutual Impedance Branch



Length

The length of the cable in feet

No. of parallel sets

Number of parallel cable sets of the same type and with common connection terminals

Z0/Z1 ratio

The zero-sequence-to-positive-sequence impedance ratio. Although the ratios of resistance (R0/R1) and reactance (X0/X1) may not be the same, only one ratio is used for simplicity. Since the cables in a power system are mostly inductances, it can be assumed that Z0/Z1 is approximately X0/X1.

4.3 MODEL SCOPE AND LIMITATIONS

The available branches do not account for cable capacitances. Future work will involve cable modeling using PI sections with mutual inductances and capacitances between the phases. This will enable the accurate simulation of unbalanced system conditions such as the influence of single phase short circuits on unfaulted phases.

4.4 EXAMPLE

This example simple shows the influence of cable mutual impedances during asymmetric events. The diagram is composed of two identical sources, two cables with 5280ft length, measurements, and a controlled fault. Initially, the measurements observe the same quantities from each circuit. The per-phase voltage waveform comparison is given below to demonstrate the influence of the mutual impedances on overvoltage. The yellow line represents the RL series branch without mutual coupling, and the magenta line represents the mutually coupled branch. The Z0/Z1 equals to 3, corresponding to an effectively grounded system. At 1 cycle of simulation, a single-phase fault (phase A) is introduced to the system. The unfaulted phases (phase B and phase C) show a slight increase in voltage caused by the mutual inductance. In a larger system that includes capacitances and longer cables, the voltage increase may be significant and should be taken into consideration.

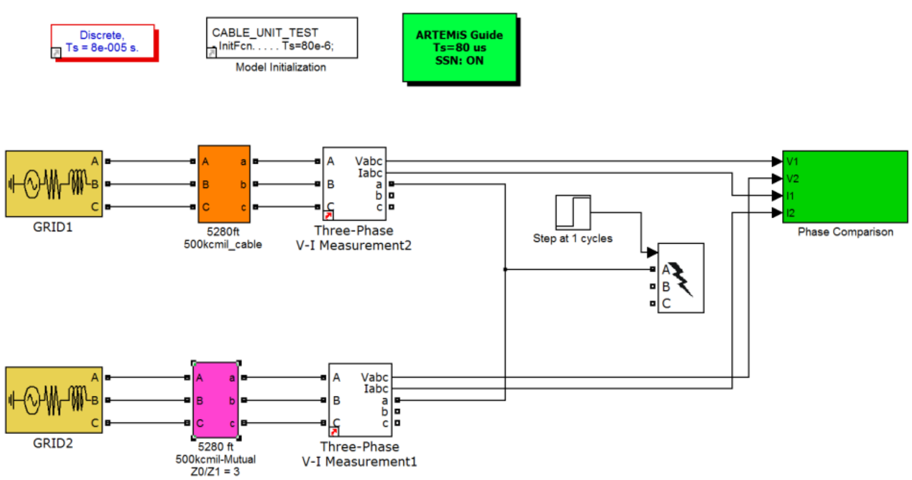


Figure 4.1. Cable Unit Test – Sample Diagram

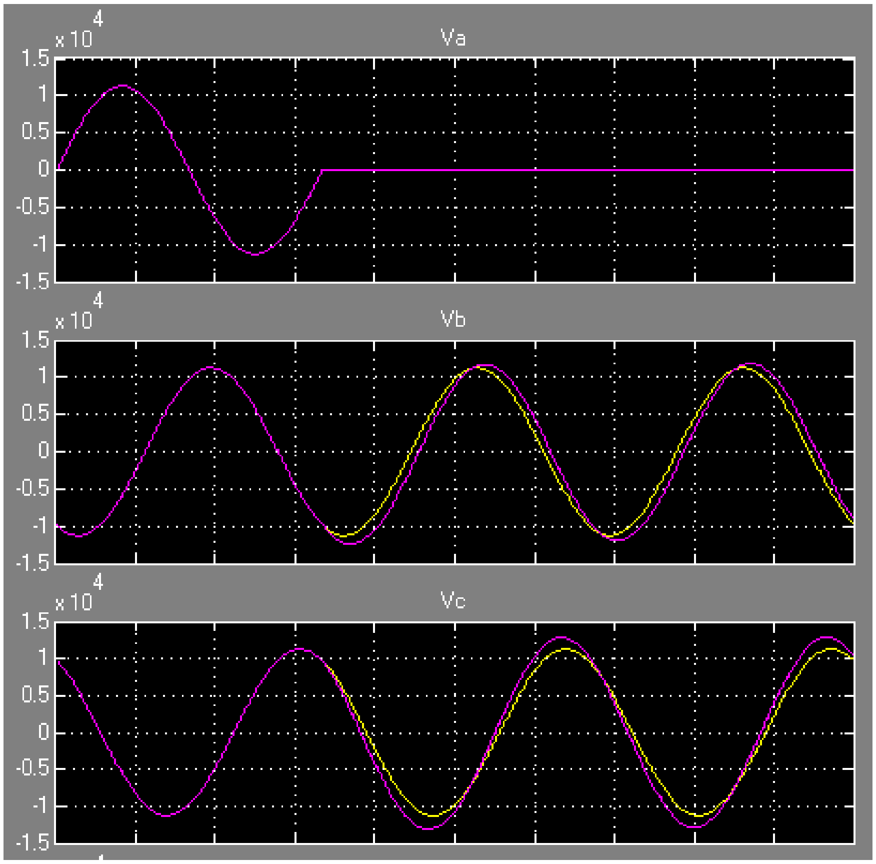


Figure 4.2. Cable Unit Test – Voltage waveforms

5. VARIABLE LOAD

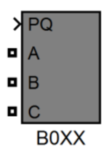
Library: dynamic_load_lib

5.1 DESCRIPTION

Two different block types are used to implement dynamic or static 3-phase load subject to mask parameters. The dynamic load block uses a 3-phase controlled current source to apply time-varying load to the A, B, and C terminals of the block. The load can be positive real power and either negative or positive reactive power as defined by the values of an input array and the current simulation time. The power can be scaled parametrically at the mask level.

The static load block implements static 3-phase load subject to mask parameters.

Dynamic PQ Load



The Dynamic PQ Load block applies a dynamic 3-phase balanced load to inputs A, B and C. The magnitude and power factor of the load are determined by the array variable input “PQ” which is comprised of 3 rows:

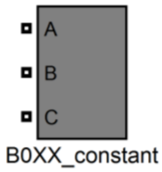
Row 1: Time at which P (row 2) and Q (row 3) are applied.

Row 2: Positive real power “P” in kW

Row 3: Positive or negative reactive power “Q” in kVAr

Operation	Conditions
The load is continuously applied to the voltage source feeding A B and C. During simulation the load data points are interpolated at each time step as necessary.	The applied constant load can only be inductive or purely resistive. Time step is inherited from the model. The dynamic load will pull more current if the voltage at A, B and C decreases. Initially, a nominal voltage is used to determine the amount of current drawn.

Static PQ Load



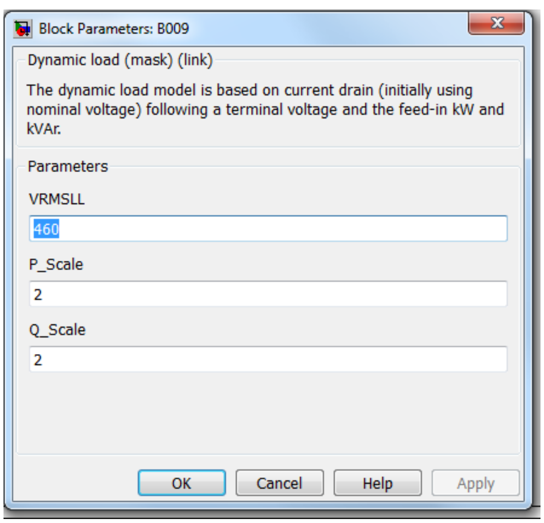
The Static PQ Load block applies a constant 3-phase balanced impedance to inputs A, B and C.

Operation	Conditions
The load is continuously applied to the voltage source feeding A B and C	The applied constant load can only be inductive or purely resistive. Time step is inherited from the model.

5.2 DIALOG BLOCK AND INPUT PARAMETERS

Dynamic Load:

The block is a masked subsystem for which the parameter entry pane appears thus:



VRMSLL

Nominal balanced 3-phase input voltage line-to-line RMS applied to terminals A, B and C. This value is used initially and during out-of-tolerance conditions for the bus voltage.

P_Scale

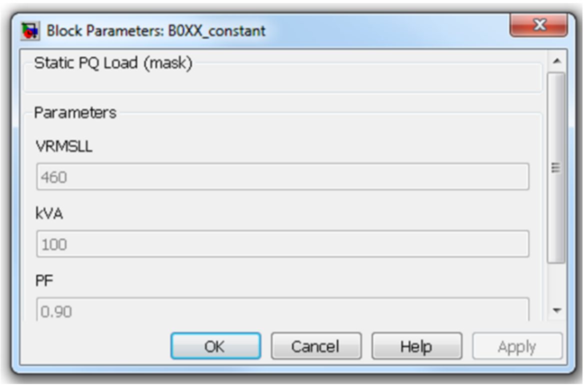
Scale factor applied to “P”, the second row of the input variable

Q_Scale

Scale factor applied to “Q”, the second row of the input variable

Static Load:

The block is a masked subsystem for which the parameter entry pane appears thus:



VRMSLL

Balanced 3-phase input voltage line-to-line RMS applied to terminals A, B and C.

KVA

Load kVA demand

PF

Load power factor (always lagging), applied load is always inductive or real (i.e. pf=1.0).

5.3 MODEL SCOPE AND LIMITATIONS

The dynamic load block can be used to represent a time-varying active load to a balanced 3-phase source connected to terminals A, B and C. The power drawn will be nominally independent of terminal voltage as long as bus voltage is maintained within nominal constraints, e.g., +/- 50% of nominal voltage. The static load can be used to represent a constant (i.e., non-time varying and linear) load impedance to a balanced 3-phase source connected to terminals A, B and C. The power drawn will vary with varying terminal voltage according to (Vrms)^2/Z

5.4 EXAMPLE

This example shows basic load setup for the real-time HIL simulation platform to evaluate microgrid controllers. The diagram shows a simple case consisting of a source, three 500-kcmil cables, a transformer, and two loads (one static and one dynamic).

In this particular case, the unit test was developed using the input data file reader built-in to the Opal-RT (real-time simulator) toolboxes. However, the values to active and reactive power may be supplied to the load any available means including vectors, or the read-in block of Simulink.

The trend lines illustrate the consumption of the system. The blue line shows the power consumed by the dynamic load which replicates the fed-in demand profile. Note that the only changes in the system are caused by load dynamics. The magenta line represents the constant load. And the yellow line shows the total power supplies by the source.

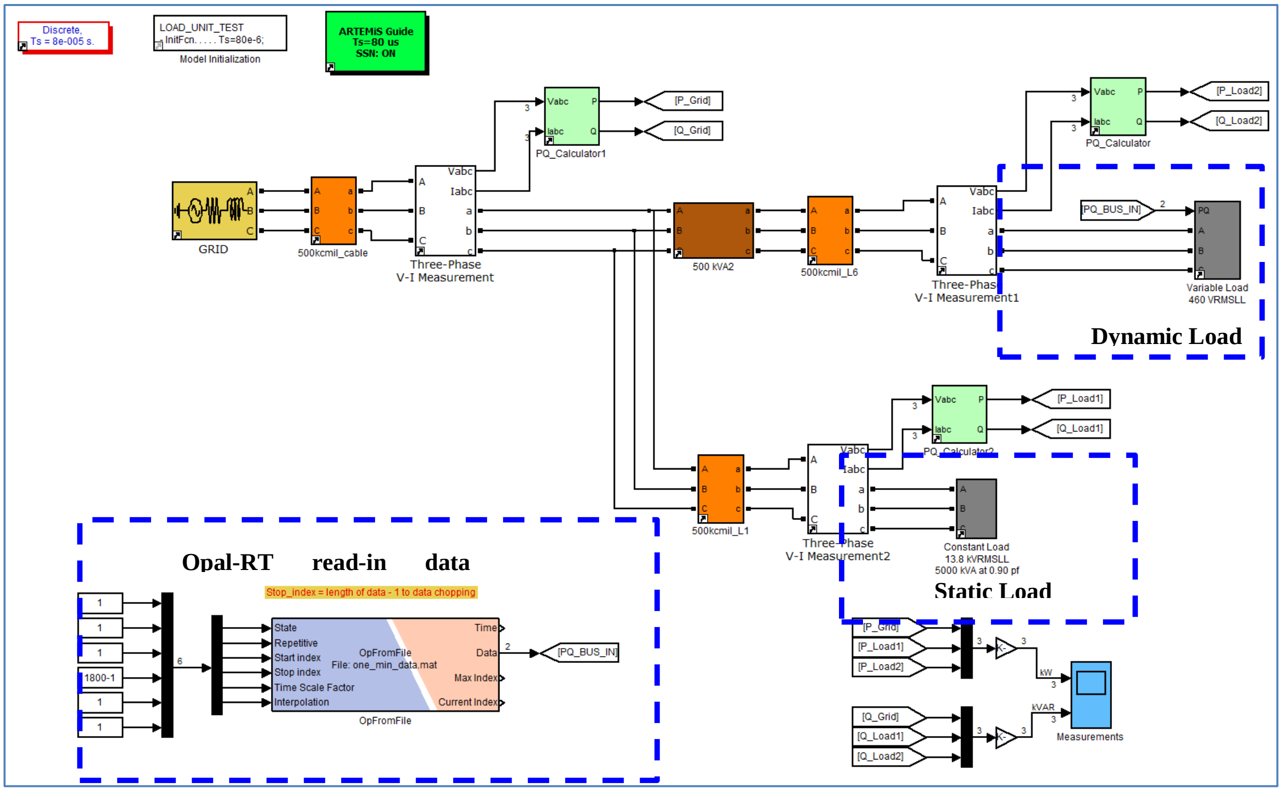


Figure 5.1. Load Unit Test – Sample Diagram

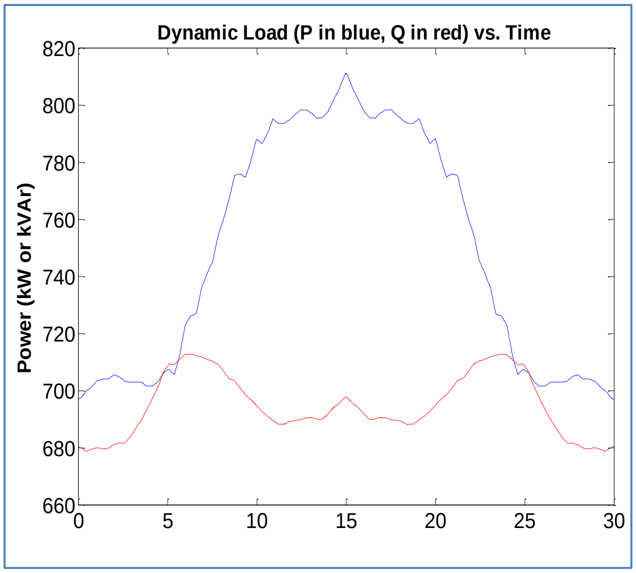


Figure 5.2. Load Unit Test – Example load profile

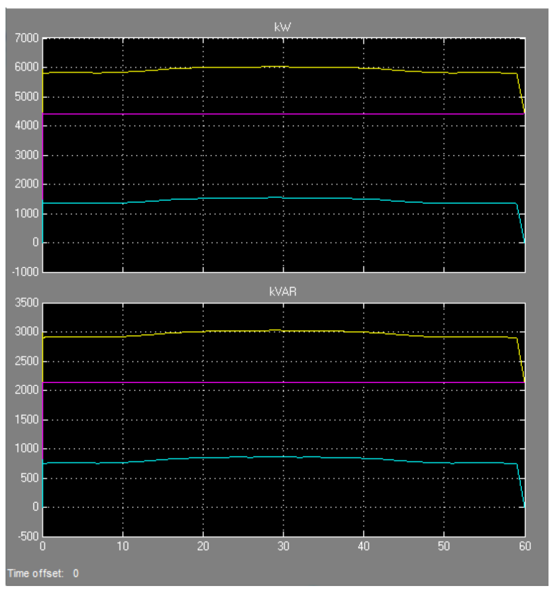


Figure 5.3. Load Unit Test - Active and reactive power consumption

6. BATTERY

<u>Library</u>: *Batt_lib*
Block: Battery

6.1 DESCRIPTION

This block represents a simple battery DC source. It is essentially an energy integrator with an equivalent series resistance on the output. When energy is present in the battery, i.e., the battery state of charge (SoC) not zero, the battery will source or sink current based on the difference in its nominal voltage and the terminal voltage divided by the equivalent series resistance (ESR). When it is empty it outputs no current.

6.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Vout: This is the voltage present on the battery terminal voltages when the load is applied.

Outputs:

Iout: Battery output current. Positive is current flow in amps out of the battery.

Capacity: State of Charge of the battery at present (0-1).

Saturation: A value of 1 indicates the battery is full, -1 indicates it is empty. Otherwise this port will output 0.

Parameters:

Capacity (kWh): Energy storage capability.
Output Resistance (Ohms): The battery is modeled with voltage source behind an equivalent series resistance. This resistance dictates how much current will flow when a DC voltage is connected to the battery.
Open Circuit Voltage: This is the battery voltage when no load is applied.

6.3 MODEL SCOPE AND LIMITATIONS

The battery model can be used to model a DC energy source with a fixed capacity and a limited output power. The model does not model any changing battery voltage due to state of charge.

6.4 EXAMPLE

In this example the battery model is tied to several other blocks to feed a controlled grid tied inverter.

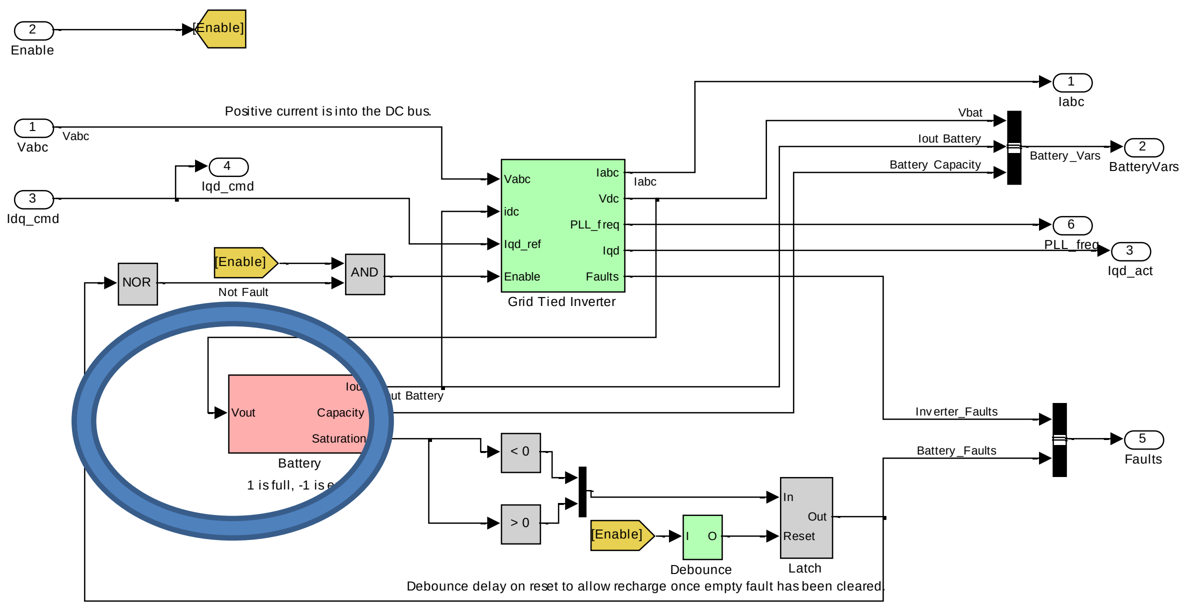


Figure 6.1. Battery Block

7. BOOST RECTIFIER

Library: *Batt_lib*
Block: Boost_rectifier_average_model_disc

7.1 DESCRIPTION

The block implements the plant model for the power electronics, DC bus cap, and output filter utilized in a grid tied inverter. The boost rectifier topology is modeled according to the following standard equations:

$$\frac{d}{dt}\begin{bmatrix}\bar{i}_d\\ \bar{i}_q\end{bmatrix} = \frac{1}{3L}\begin{bmatrix}\bar{v}_d\\ \bar{v}_q\end{bmatrix} - \begin{bmatrix}0 & -\omega\\ \omega & 0\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_d\\ \bar{i}_q\end{bmatrix} - \frac{1}{3L}\begin{bmatrix}d_d\\ d_q\end{bmatrix}\cdot\bar{v}_{dc}$$

$$\frac{d\bar{v}_{dc}}{dt} = \frac{1}{C}\begin{bmatrix}d_d & d_q\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_d\\ \bar{i}_q\end{bmatrix} - \frac{\bar{v}_{dc}}{RC}$$

Real power is in the d axis, reactive in the q axis. Additional information can be found here:

> Hiti, S., Boroyevich, D., and Cuadros, C., "*Small-signal modeling and control of three-phase PWM converters*," in Industry Applications Society Annual Meeting, 1994., Conference Record of the 1994 IEEE , vol., no., pp.1143-1150 vol.2, 2-6 Oct 1994.

The model is further improved by not linearizing around a single operating point but allowing all inputs to change in a non-linear time invariant way. This adjustment gives small signal level performance and correct operation over a wide operating range. The R parameter is replaced with a dc current which is time-varying. Lastly, the model includes an enable signal that effectively zeroes the inductor current when the inverter is disabled.

Diode clamping when AC input voltages are above the DC voltage is not modeled. The bock relies on some initialization details in BES_init.m.

7.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Vqd: Grid voltage in Q and D, a 2 signal wide vector. The units are peak volts.

dqd: Duty cycle inputs in the Q and D, a 2 signal wide vector. The input should range from positive 1 to -1 for realistic performance of the circuit.

idc: DC current into the DC bus in amps. Positive current is out of the inverter.

En: Enable signal which allows current to flow into or out of the inverter. The enable signal sets the duty cycle input to a default value of zero.

Outputs:

Iqd: phase currents in Q and D peak.

Vdc: DC bus voltage in volts.

Parameters:

DC Bus Capacitance: The capacitor across the DC side of the inverter in [F] from the equations above.
Boost Inductor: The inductor in series with each phase in Henries from the equations above.
Switch resistance when off: The amount of resistance (in ohms) a switch will have when the inverter is disabled. Typical values are 10MOhm, but the larger the value the slower simulation will progress.
Nominal DC Bus Voltage: The normal DC bus voltage in volts. This is used to initialize the capacitor state to prevent any inrush transients.

7.3 MODEL SCOPE AND LIMITATIONS

The model can be used to approximate currents and voltages at the several switching cycle time scale. Transient behavior during inverter disable is somewhat inaccurate as the phase currents are clamped at zero instead of returned to DC bus.

7.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

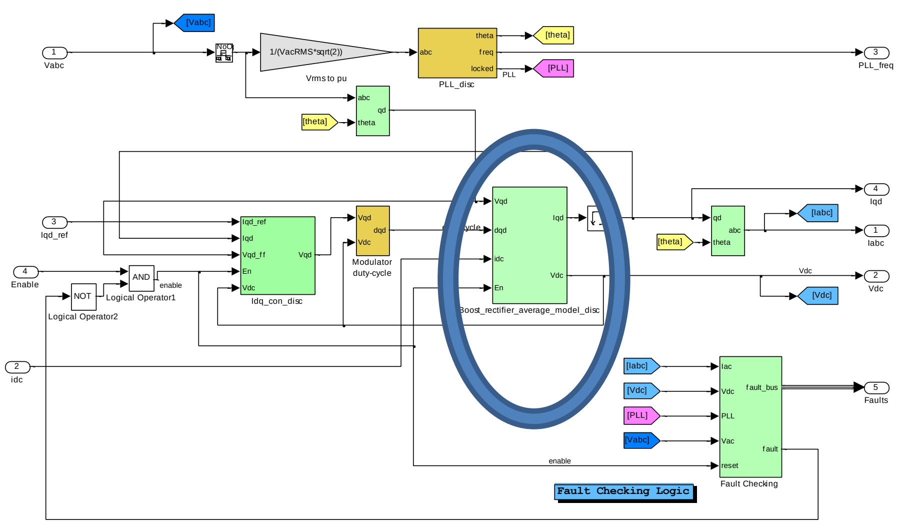


Figure 7.1. Boost Rectifier

8. COORDINATES TRANSFORM

Library: *Batt_lib*
Block: Park Transform

8.1 DESCRIPTION

This block is used to transform ABC quantities into the rotating coordinate frame of reference. The three-phase quantity is mapped into a real and reactive component depending on the angle at which the reference frame is aligned.

The basic equation used is as follows:

Vabc * P = Vqd0

$$P = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

The third term of the conversion matrix yields an output known as the zero components. In a balanced three phase system this is always zero so is not used here.

8.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

abc: Three-phase quantity in a 3 signal wide vector.

theta: Phase angle for the frame of reference (0-2*pi).

Outputs:

qd: Transformed signal output.

Parameters:

none

8.3 MODEL SCOPE AND LIMITATIONS

The block can be used to transform the coordinate space for any three-phase quantity. Voltage, current, or flux for instance. If an unbalanced system is needed the coordinate transform that outputs a zero component may be needed.

8.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

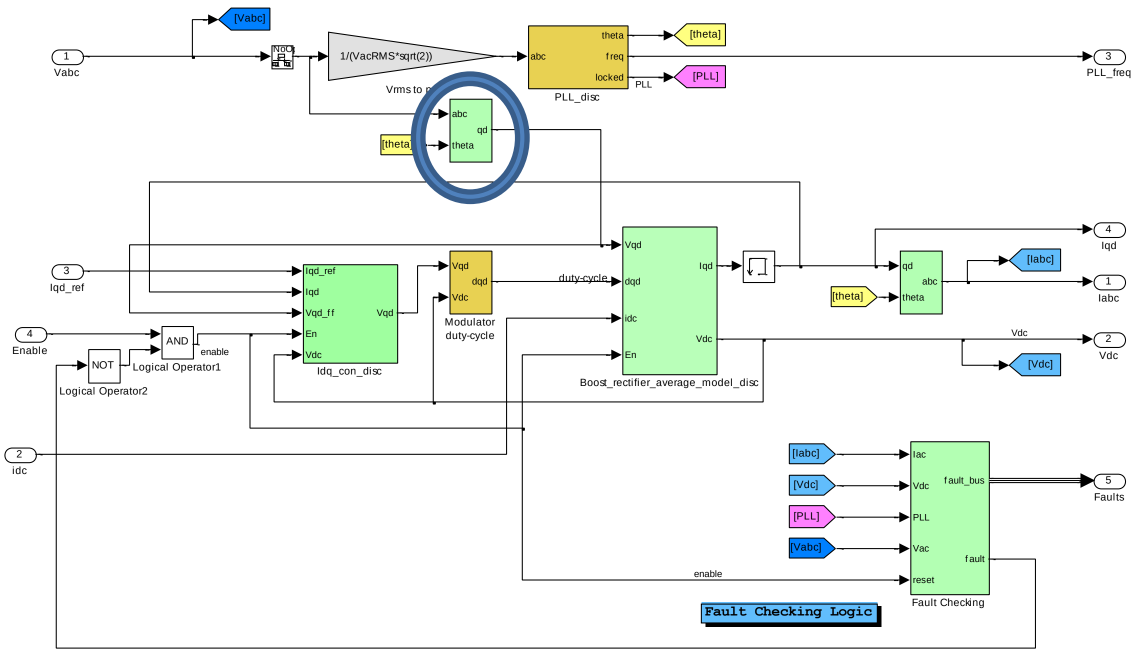


Figure 8.1. Coordinates Transform

9. DQ CONTROLLER

Library: *Batt_lib*
Block: Idq_con_disc

9.1 DESCRIPTION

This block implements a DQ axis current controller. It measures actual DQ currents and adjusts voltage to achieve the desired current. It is represented by two cross coupled PI loops. The voltage output of these controllers is then subtracted from the feedforward voltage from the grid. This allows the controller to react even quicker to fast grid dynamics. Lastly, a vector saturation block decides which axis gets priority when the DC voltage limits the output voltage which can be achieved. Anti-windup protection in also used when saturation is active.

Additional documentation can be found here:

Sizhan Zhou, Jinjun Liu, Linyuan Zhou, and Hongwei She, "*Cross-coupling and decoupling techniques in the current control of grid-connected voltage source converter,*" in Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE, pp.2821-2827, 15-19 March 2015.

The bock relies on some initialization details in BES_init.m.

9.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Idq_ref: Desired Q and D current in amps peak.
Iqd: Actual measured Q and D current.
Vqd_ff: Measured Q and D grid voltage for feedforward correction in volts.
En: Enable signal (0/1). This will clear any Vqd output to zero and zero the PI controller states when set to 0.
Vdc: Available DC bus voltage in volts. This is used to control the output voltage limitation which at most can only be sqrt(3/2)*Vdc.

Outputs:

Vqd: AC side voltage output in the Q and D axis.

Parameters:

Boost Inductor: Per phase inductance [H] of the boost rectifier to be controlled.
Maximum Iq: Any input Q reference current above this maximum value that will be clamped (amps).
Maximum Id: Any input Q reference current above this maximum value that will be clamped (amps).
Proportional Gain: PI regulator proportional gain in both axis.
Integral Gain: PI regulator integral gain in both axis.
Nominal DC Bus Voltage: DC bus voltage that is normally seen at steady state in volts.

9.3 MODEL SCOPE AND LIMITATIONS

The controller can be used to control current in a three phase six-switch inverter. Switching or non-switching plan models are appropriate with the proper duty cycle modulation or PWM generation unit.

9.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

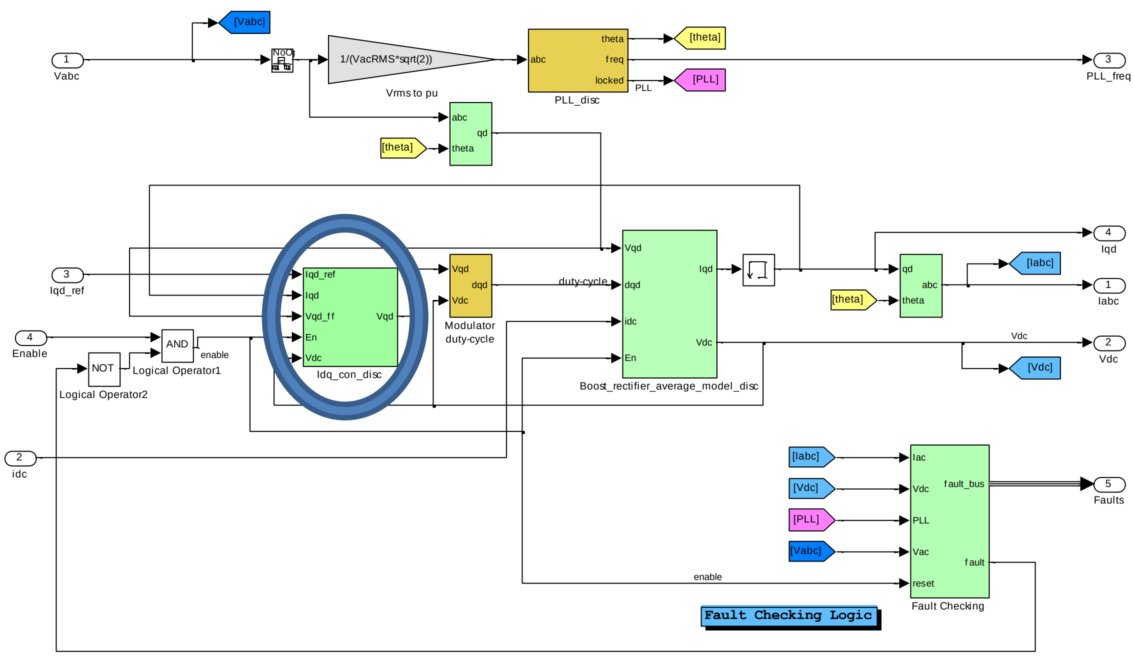


Figure 9.1. dq-controller

10. INVERSE TRANSFORM

Library: *Batt_lib*
Block: Inverse Park Transform

10.1 DESCRIPTION

This block is used to transform ABC quantities into the rotating coordinate frame of reference. The three-phase quantity is mapped into a real and reactive component depending on the angle at which the reference frame is aligned.
The basic equation used is as follows:

$$Vqd0 * P^{-1} = Vabc$$

$$P^{-1} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix}$$

The third term of the conversion matrix yields an output known as the zero component. In a balanced three phase system this is always zero so is not used here.

10.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

qd: Q and D signals in a 2 signal wide vector.
theta: Phase angle for the frame of reference (0-2*pi).

Outputs:

abc: Transformed signal output.

Parameters:
none

10.3 MODEL SCOPE AND LIMITATIONS

The block can be used to transform the coordinate space for any three-phase quantity. Voltage, current, or flux for instance. If an unbalanced system is needed the coordinate transform that outputs a zero component may be needed.

10.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

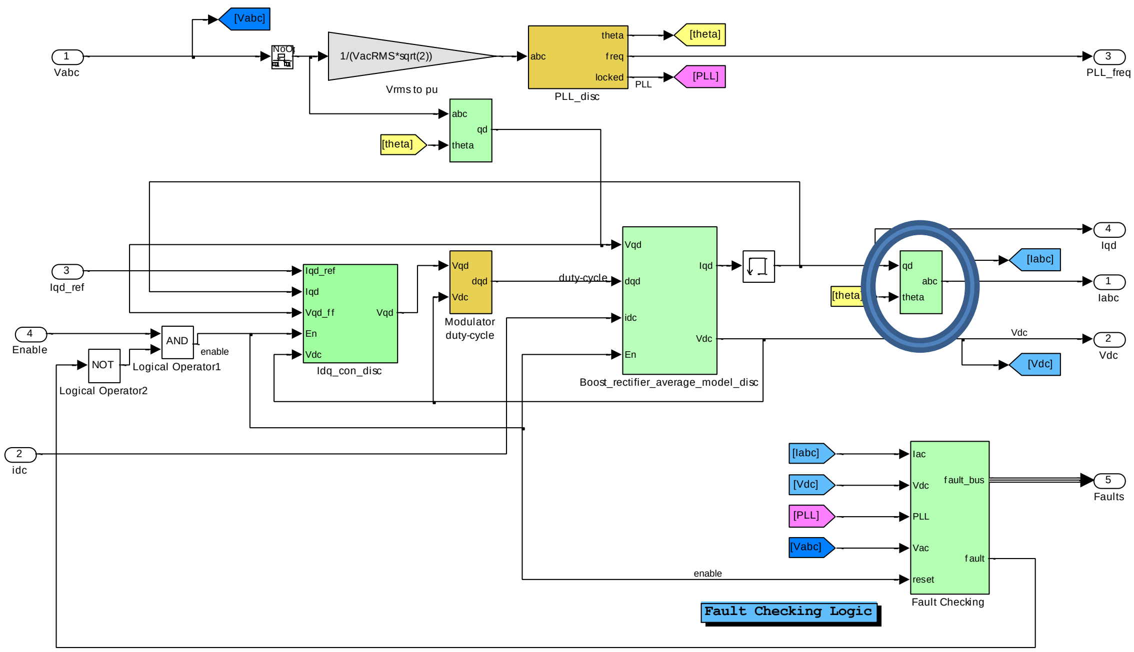


Figure 10.1. Inverse Transform

11. MODULATOR

Library: *Batt_lib*
Block: Modulator

11.1 DESCRIPTION

This block tranforms a requested AC output voltage to the needed duty cycles to achieve that. The basic law used is Vqd/Vdc. A saturation block is also included which limits the output to +1 to -1. Lastly a unit delay is included to model duty cycles which can typically only be updated once per switching cycle.

11.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Vqd: Requested AC voltages (on an inverter output).
Vdc: Available DC bus voltage in volts.

Outputs:

dqd: Duty cycle outputs.

Parameters:

None used but Vdc_nom and Td_es_min must be defined.
Vdc_nom is nominal DC bus voltage. Td_es_min is the switching frequency.

11.3 MODEL SCOPE AND LIMITATIONS

The model can be used to approximate the available output voltage for a three phase six-switch inverter.

11.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

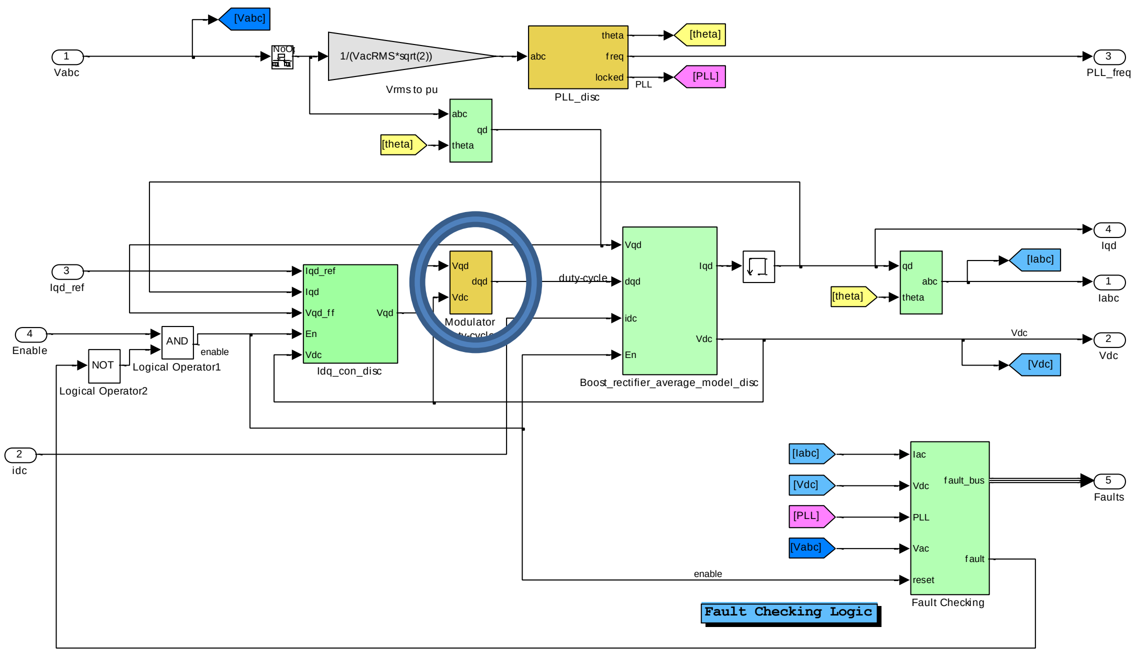


Figure 11.1. Modulator

12. DISCRITE PLL

Library: *Batt_lib*
Block: PLL_disc

12.1 DESCRIPTION

This block implements a discrete phase lock loop for a three phase power system. A 3 signal wide ABC vector is measured to align an internal oscillator with the proper phase angle theta. The block also outputs an instantaneous frequency measurement.

The control loop is designed to track slowly changing grid voltages that are typically seen in power systems, particularly those utilizing rotating machines with inertia. If the AC waveform frequency is varying too much the lock output may go low to indicate the oscillator cannot be synced. The PLL uses a coordinate transform to DQ space, a PI controller which varies the frequency, and variable frequency oscillator to generate theta for the original coordinate transform. The PI parameters can be adjusted if tracking isn't as desired.

The bock relies on some initialization details in BES_init.m.

12.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

abc: Three-phase signal to be sampled for determination of phase and frequency. The input is in PU and should vary between +1 and -1.

Outputs:

theta: Phase angle of the three-phase system on abc input in radians (0-2*pi). Theta is aligned to phase A and is zero output at input zero crossing but relies on all three phases to achieve the best match.

freq: Instantaneous frequency of internal oscillator (in radians).

Locked: Output indicates if PLL is locked to input waveform. During transients or widely varying input this output may go low which indicates the theta and freq outputs cannot be trusted. The frequency must be within the proper range and the PI regulator must have a small tracking error. In addition there is a leaky bucket fitler which will only indicate a lock when the system remains locked for 0.5 sec.

Parameters:

Proportional Gain: PI regulator proportional gain. Typical value of 0.03 may be used.

Integral Gain: PI regulator integral gain. Typical value of 0.03 may be used.

PLL Frequency Range: The value here offset by 1 and multiplied by the grid frequency to obtain the allowable frequency tolerance for the internal oscillator. If the oscillator is above this range the lock output will go low to indicate an out of range condition.

PLL Lock Window: A value between 0-1 which indicates how much misalignment is tolerable in both the positive and negative directions. 0.1 is a typical value. The misalignment is also filtered with a low pass filter at twice the grid frequency to suppress any momentary glitches.

The PLL_time_step variable must be defined and it defines the discrete time for the PI controller and filters. This should be at least 10x the grid frequency.

12.3 MODEL SCOPE AND LIMITATIONS

The PLL can be used to track any set of three-phase waveforms. It is fairly immune to grid harmonics and will produce a result that weights each phase evenly as opposed to just sampling one particular phase.

12.4 EXAMPLE

In this example the model is tied to several other blocks to form a controlled grid tied inverter.

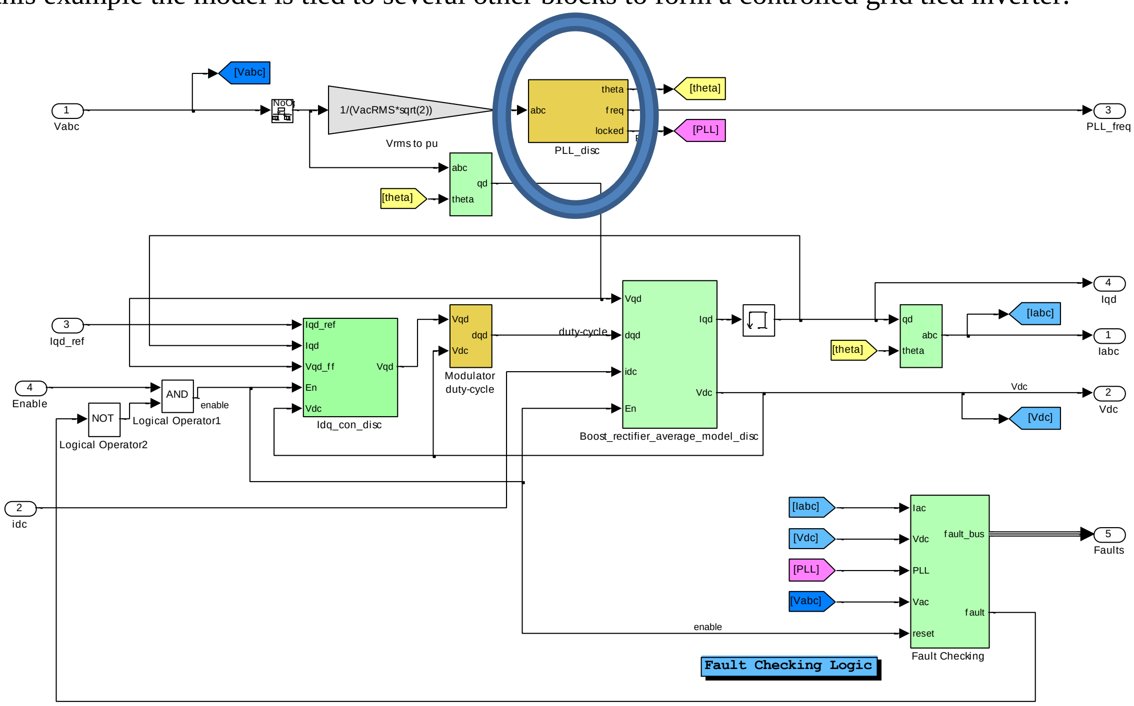


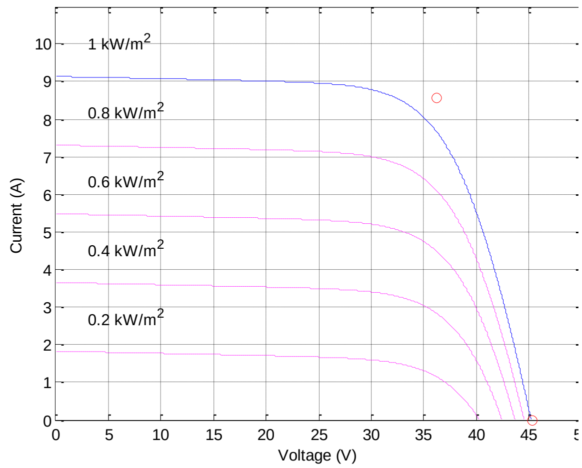
Figure 12.1. Discrete PLL

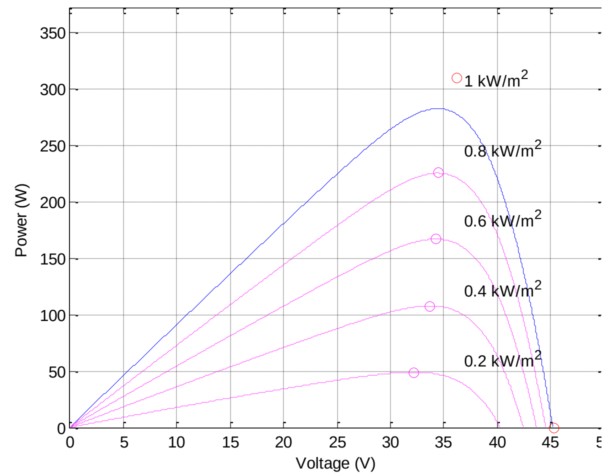
13. PV ARRAYS

Library: *PV_lib*
Block: PV

13.1 DESCRIPTION

This block implements a series and parallel string of PV panels. Given the input conditions it produces a DC current which can be utilized in power systems. The resultant DC voltage is typically fed back to the PV block from the higher level system which given its load will dictate the resultant voltage. The panel characteristics are given from the block parameters. The check boxes in the mask will produce the curves shown below.





13.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Irradiance: A value between 0-1000 [W/m^2] describing the amount of sunlight the panels are exposed to.
Temp: Degrees Celsius the panels are operating in.
Vpv: Total string voltage the panels are connected to.

Outputs:

m: A measurement bus which contains the following signals.

V_PV: Total string voltage.
I_PV: String output current in amps.
P_PV: String output power in watts.
Temperature: String temperature in degrees Celsius.
Irradiance: String irradiance in (W/m^2)

Ipv: String output current in amps.

Parameters:

Number of cells per module: The number of solar cells in one PV panel module.

Number of series-connected module per string: The number of panels connected in series.

Number of parallel strings: The number of strings of modules which are connected in parallel to form the entire PV source.

Open circuit voltage Voc (V): Panel voltage with no load applied and full irradiance.

Short circuit current Isc (A): Panel current with a short applied to the load terminals.

Band gap energy of crystalline silicon (eV): Silicon electron volts characteristic.

Temperature coefficient of Voc (%/C): Amount of change in Voc per degrees C.

Temperature coefficient of Isc (%/C): Amount of change in Isc per degrees C.

Series resistance Rs (Ohms): Equivalent series resistance for each panel.

Shunt resistance Rsh (ohms): Equivalent parallel resistance for each panel.

Light-generated current IL (A): Current produced by photons.

Maximum Power Point Voltage Vmpp (V): Voltage which is present when the panels are producing the maximum power with full irradiance (1000).

Maximum Powe Point Current Impp (A): Current which is present when the panels are producing the maximum power with full irradiance (1000).

13.3 MODEL SCOPE AND LIMITATIONS

The PV model can be used to represent any set of PV panels connected through one central inverter. It does not do any power optimization on a per panel basis.

13.4 EXAMPLE

In this example the PV model is tied to several other blocks to form a controlled PV and grid tied inverter.

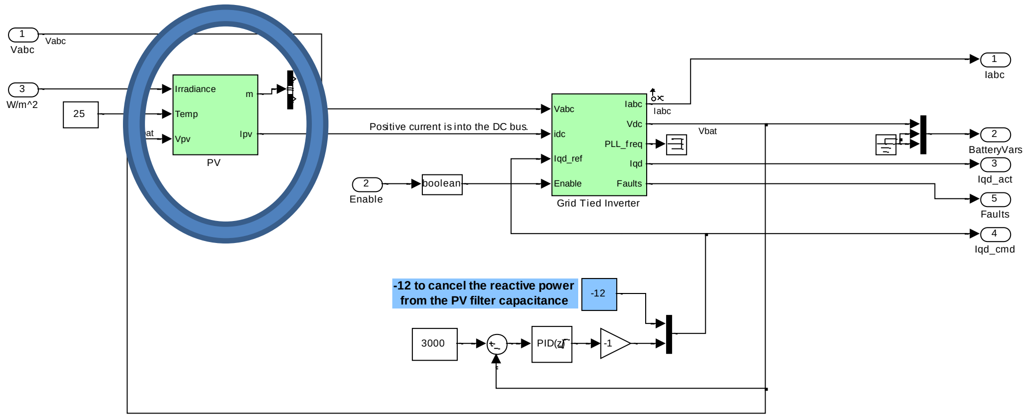


Figure 13.1. PV Array

14. GRID TIED BATTERY

Library: *Batt_lib*
Block: Grid tied battery

14.1 DESCRIPTION

This block represents a three phase connected grid tied battery energy storage system. It acts as a controlled current source to the grid and responds to current commands which cause the device to provide a given real and/or reactive power. It includes a DC energy source, three phase inverter, AC current controller, phase locked loop, and fault control logic. No loss mechanisms were modeled as the system assumed that any small inefficiency would be negligible.

The fault logic monitors several sub-system values to ensure the device is operating in a safe operating area. If a fault is present the system will shut-down and wait for a signal on enable line to clear fault.

The bock relies on some initialization details in BES_init.m.

14.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Vabc: AC three phase grid voltage as a three signal wide vector.

Enable: 0 or 1 input to turn the device on or off. If a fault is present this input can be cycled to clear the fault and attempt to restore operation.

Idq_cmd: Commanded D and Q axis current. The inverter attempts to produce this AC value given battery capacity and specified inverter capability.

Outputs:

Iabc: Current fed to the grid. The output is a 3 signal wide vector representing the instantaneous current in each of the 3 phases.

Battery_vars:

Battery voltage: Instantons DC voltage present on the battery.
Capacity: State of Charge of the energy storage battery (0-1).
Battery Iout: Output current of the battery into the inverter.

Iqd_cmd: Commanded Q and D current in amps.

Iqd_act: Actual Q and D current in amps.

Faults: A vector of several possible faults which could disable the inverter.

Phase A over current: A current has occurred in phase A which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

Phase B over current: A current has occurred in phase B which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

Phase C over current: A current has occurred in phase C which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

DC Link Overvoltage: A voltage has occurred on the DC side which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

PLL loss of sync: The internal oscillator cannot synchronize to the gird voltage. This often occurs because of instability in the grid.

Vrms out of spec: The grid voltage is outside of the specified acceptable range.

Battery Empty: The energy storage battery has been depleted and no more energy is available. The device should be charged.

Battery Full: The energy storage battery is full and can accept no more charge. The device should be discharged.

Freq: Measured grid frequency used to exchange power.

Parameters:

Peak Power (W): Inverter maximum charge or discharge power.

Capacity (kWh): Battery energy storage capacity.

Grid Tie Line to Neutral Voltage (RMS): Grid voltage of the system the battery is connected to in volts RMS.

Nominal DC Battery Voltage: Voltage used for the DC battery source.

14.3 MODEL SCOPE AND LIMITATIONS

The grid tied inverter model can be used to simulate an energy storage device attached to a three phase power system. It does not model switching level interactions but does model interactions at the sub-cycle level. It can be used for grid fault analysis and stability studies.

The model produces Simulink signals and not SimPowerSystems electrical node connections. Because of this an Simulink to SimPowerSystems interface block must be used. In addition depending on grid stiffness a set of capacitors are often needed for stability. The example below uses a set of 10uF capacitors.

The parameters are calculated for a specified power level. Values of several MW to 10s of kW have been tested.

14.4 EXAMPLE

In this example the battery model is tied to several other blocks to feed a controlled grid tied inverter.

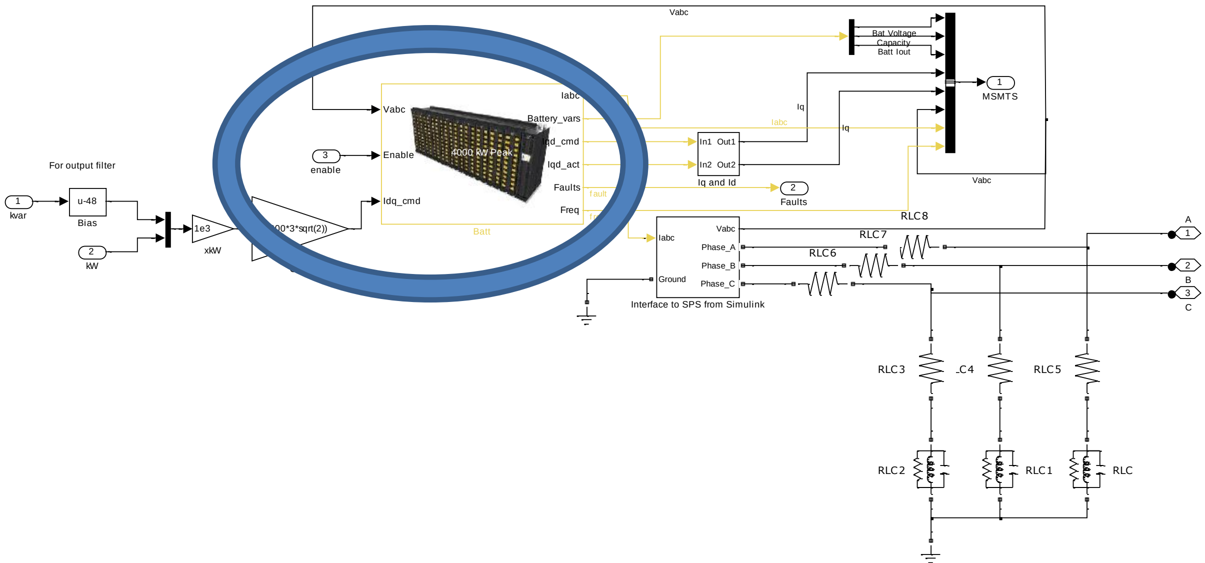


Figure 14.1. Grid-tied Battery

15. GRID TIED PV

Library: *PV_lib*
Block: Grid tied PV

15.1 DESCRIPTION

This block represents a three phase connected grid tied photovoltaic (PV) energy source system. It acts as a controlled current source to the grid and attempts to maximize the power it can draw from the PV for a given amount of irradiance. It includes a DC PV source, three phase inverter, AC current controller, phase locked loop, and fault control logic. No loss mechanisms were modeled as the system assumed that any small inefficiency would be negligible.
The fault logic monitors several sub-system values to ensure the device is operating in a safe operating area. If a fault is present the system will shut-down. When the fault has cleared it will restore operation.

The bock relies on some initialization details in BES_init.m.

15.2 DIALOG BLOCK AND INPUT PARAMETERS

Inputs:

Vabc: AC three phase grid voltage as a three signal wide vector.

Enable: 0 or 1 input to turn the device on or off.

W/m^2: Irradiance present on the surface of the panels.

Outputs:

Iabc: Current fed to the grid. The output is a 3 signal wide vector representing the instantaneous current in each of the 3 phases.

Battery_vars:

Battery voltage: Instantons voltage present on the PV.
Capacity: Not used
Battery Iout: Not used

Iqd_act: Actual Q and D current in amps.

Faults: A vector of several possible faults which could disable the inverter.

Phase A over current: A current has occurred in phase A which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

Phase B over current: A current has occurred in phase B which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

Phase C over current: A current has occurred in phase C which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

DC Link Overvoltage: A voltage has occurred on the DC side which is greater than the rated power devices. This should not occur if the controller is able to successfully control power.

PLL loss of sync: The internal oscillator cannot synchronize to the gird voltage. This often occurs because of instability in the grid.

Vrms out of spec: The grid voltage is outside of the specified acceptable range.

Parameters:

Peak Power (W): Inverter maximum power.

Grid Tie Line to Neutral Voltage (RMS): Grid voltage of the system the battery is connected to.

VacRMS Limit [Hi Low] (pu L-N): Maximum and minimum voltage that the PV will operate in a per unit line to neutral form.

15.3 MODEL SCOPE AND LIMITATIONS

The grid tied PV model can be used to simulate a PV system attached to a three phase power system. It does not model switching level interactions but does model interactions at the sub-cycle level. It can be used for grid fault analysis and stability studies. The model always attempts to output a unity power factor and does not provide any reactive power.

The model produces Simulink signals and not SimPowerSystems electrical node connections. Because of this a Simulink to SimPowerSystems interface block must be used. In addition depending on grid stiffness a set of capacitors are often needed for stability. The example below uses a set of 10uF capacitors.

The parameters are calculated for a specified power level. Values of several MW to 10s of kW have been tested, but the user must ensure that the PV model at the lower level has the power to produce the specified power.

15.4 EXAMPLE

In this example the PV model is tied to several other blocks to form a controlled grid tied inverter.

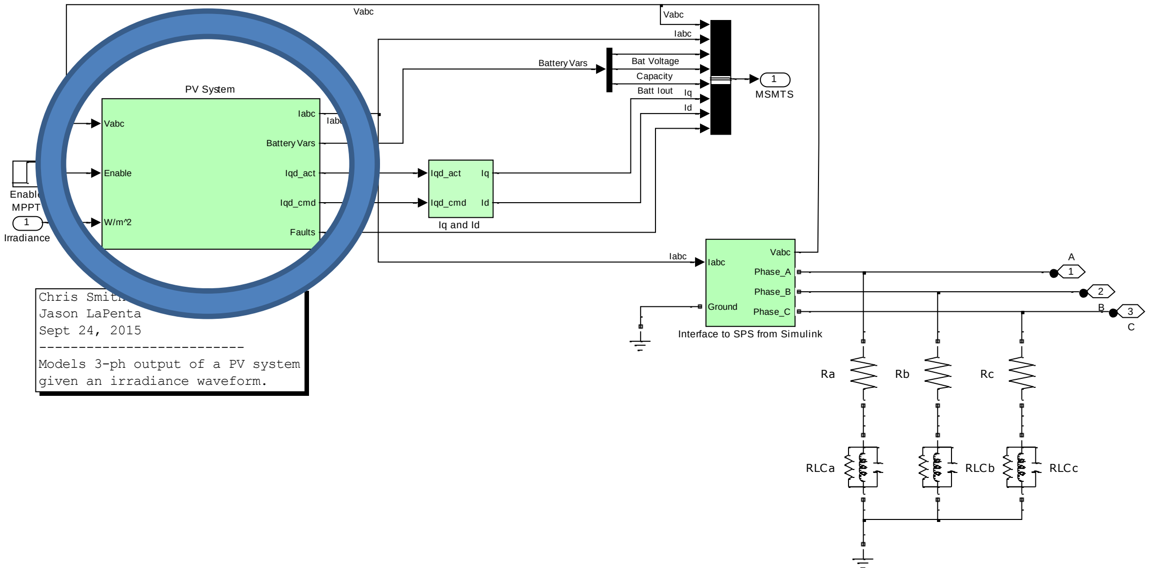
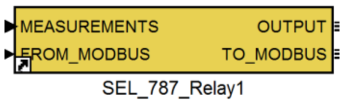


Figure 15.1. Grid-tied PV

16. RELAY

Library: Modbus_lib.mdl

16.1 DESCRIPTION



Relays perform the control logic required by the circuit breakers to open or close its contacts. For this work, relays are also used to gather system measurements and status. The base model was developed to approximate a Schweitzer SEL-787 Transformer Protection relay, see Figure 16.1. Figure 16.3 provides a high level overview of the logic blocks arrangement for the relay. The highlighted zones include preliminary calculations of active and reactive power, rms quantities, among other parameters; the register mapping for the information sent via Modbus; the preprogrammed relay functions; and, the selected data to be logged for each simulation. The register mapping assumed the actual mapping of SEL-787 relay. These units can be remotely actuated by the microgrid controller, and provide sensor values. All settings are based on a moderate inverse time curve. The simulated relay functions are the following: synchronizing or synchronism-check (25), phase instantaneous overcurrent (50P), AC inverse time overcurrent (51P), undervoltage relay (27), and overvoltage relay (59). Each breaker in the distribution system has its own tripping current and delay settings. The under/over-voltage settings are set to ±15% of nominal voltage. Addition of other relay functions may be a topic for future development.

The main protection functions are illustrated schematically in Figure 16.2. The measured values of phase currents through the breaker and terminal voltages are compared with the selected overcurrent settings (instantaneous overcurrent or ac-time overcurrent) and under/over-voltage settings. The rms values are computed using a built-in Simulink block which calculates true rms by means of numerical integration over a sliding window. A time integrator is used to ensure that the tripping command is generated only if one of the phase currents or voltage exceeds the threshold for a predefined period of time. These times are calculated based on a moderate inverse-time curve. Furthermore, the logic waits for current zero-crossing to issue the trip command.

To enable the reclosing of breakers when both terminals are energized, relays were modeled with synchronizing-check (ANSI Std. Dev. No. 25) capabilities. The time-domain voltages at the breaker terminals are compared for magnitude, angle, and frequency to determine whether the predefined conditions are acceptable to reclose the breaker contacts without causing reclosing-transient problems in the system. The angle difference between the two voltages must be within 12° degrees, the magnitude difference should be within 3%, and the frequency difference must be within 0.5 Hz. These parameters are flexible and may be adjusted by the user. Furthermore, dead-bus logic was implemented to allow the breaker to be remotely reclosed when any or both terminals has a voltage of less than 1% of the nominal value. Figure 16.4 shows the Simulink block diagram used to implement the synchronism-check function to the relay.

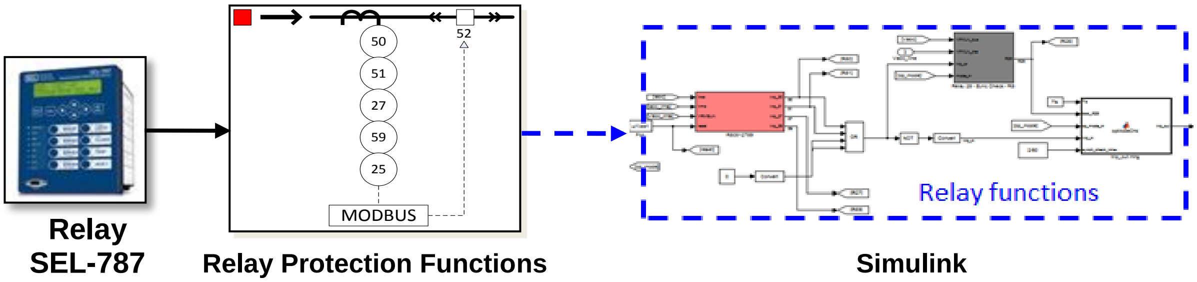


Figure 16.1. Relay modeling base-scheme

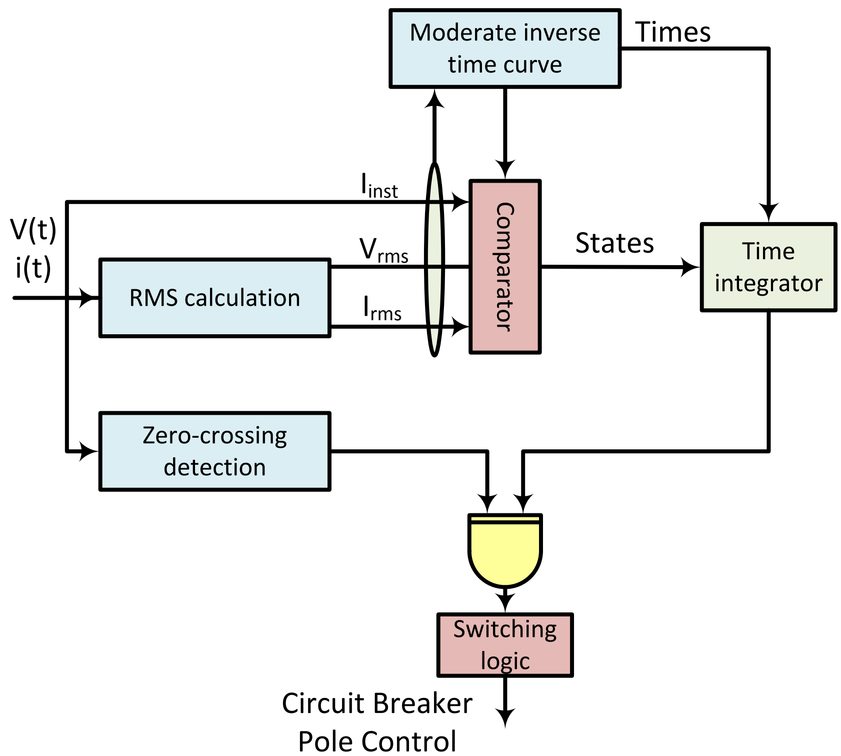


Figure 16.2. Scheme of functions: undervoltage relay (27), AC inverse time overcurrent relay (50), instantaneous overcurrent relay (51), and overvoltage relay (59)

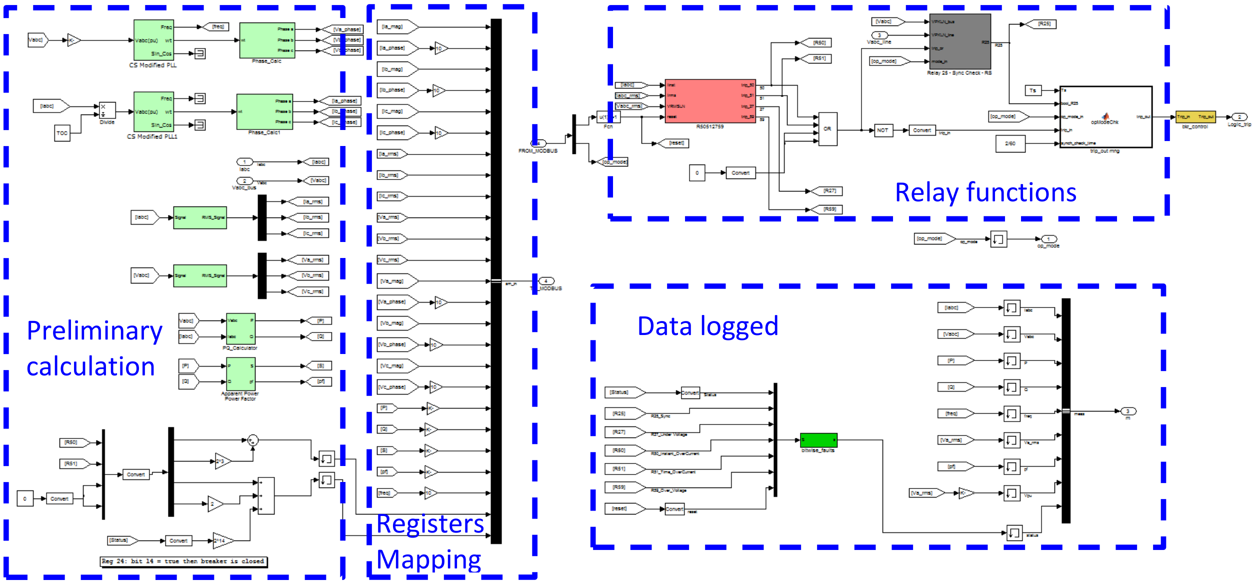


Figure 16.3. Simulink model of the relay

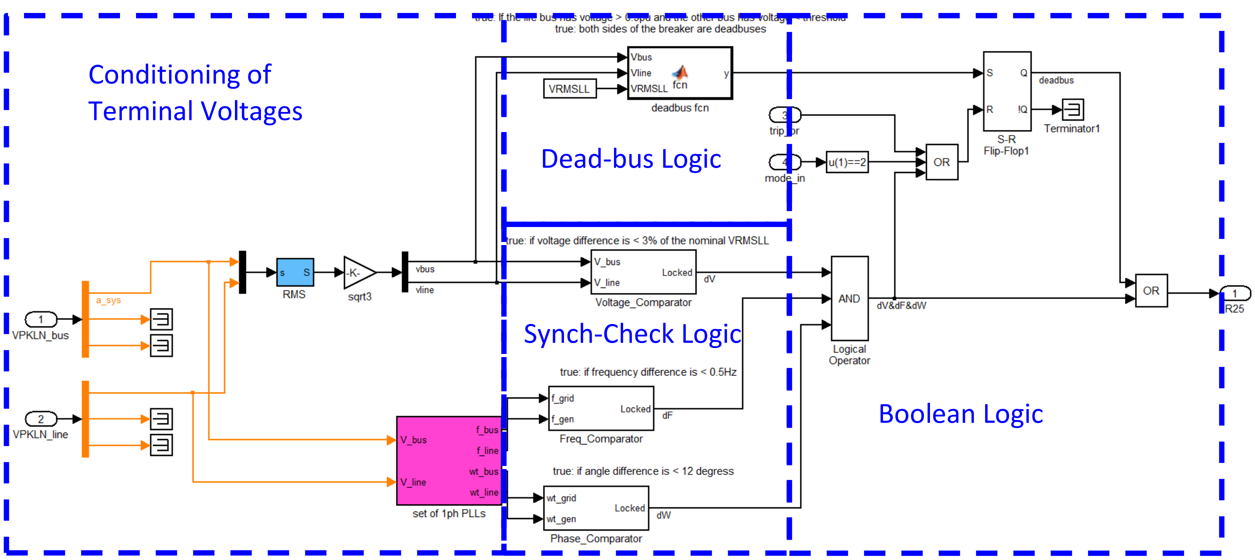
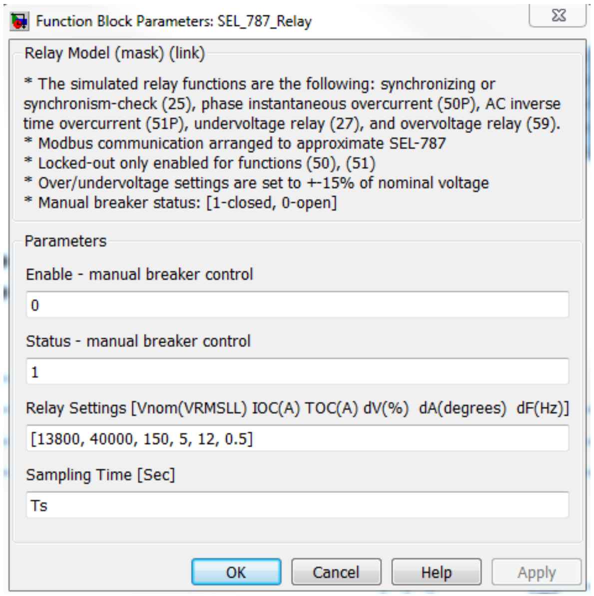


Figure 16.4. Simulink model of the synchronism-check function

16.2 DIALOG BLOCK AND INPUT PARAMETERS



Enable – manual breaker control

If true, enables the manual open/close control of the relay as defined by the status-entry. This parameter does not affect the performance of the relay when controlled by logic or the microgrid controller.

Status – manual breaker control

Defines the status of the relay when manually controlled. This parameter does not affect the performance of the relay when controlled by logic or the microgrid controller.

Relay Settings

Array defining the operation settings of the relay. The input variables are read in the following order: nominal voltage (VRMSLL), instantaneous overcurrent setting (A), ac inverse time overcurrent setting (A), synch-check voltage threshold (%), synch-check angle threshold (degrees), and synch-check frequency threshold (Hz)

Sampling Time

Simulation time step in seconds

16.3 MODEL SCOPE AND LIMITATIONS

Due to the short timeline of the effort, only the basic functions of a relay were implemented. These functions provide protection for overcurrent, protection for undervoltage and overvoltage, and provide synchronism check capabilities required when the two disconnected terminals of the circuit breaker are energized. The model was designed to operate conventionally with one-set of protection settings. Future work will include operation with multiple protection settings (grid-connected and islanded) and capability of allowing the microgrid controller to selected the settings type depending on the state of the system.

16.4 EXAMPLE

This example shows the basic operation of the relay using two simple test setups. The first circuit includes a source, two cables, a load, and a breaker with logic provided by the relay. Results for this case are given in Figure 16.6 (a). The simulation initially reaches the expected steady-state; then, a three-phase short circuit is introduced. Due to the protection settings and the moderate TCC, the resulting trip time was 0.7 seconds. The fault is set to clear at about 0.9 seconds of simulation time. At approximately 1 second, a reclose command is sent to the relay which recloses at 1.06 seconds. The overcurrent protection was exhaustively evaluated and proven to operate properly.

The second diagram shows two sources, a cable and a circuit breaker. This test is used to demonstrate the synch-check capabilities of the model. Results for this case are given in Figure 16.6 (b). Initially the two sources are connected and operating in synchronism. When the circuit breaker is opened, the two sources are driven apart by magnitude, angle and frequency. After few cycles, a reclosed command is issued to the relay which checks for the best moment to close the breaker. A magnification of the voltage at the two breaker terminals and current flow is given in Figure 16.7 which demonstrates successful reclosing without sudden voltage spikes or transients.

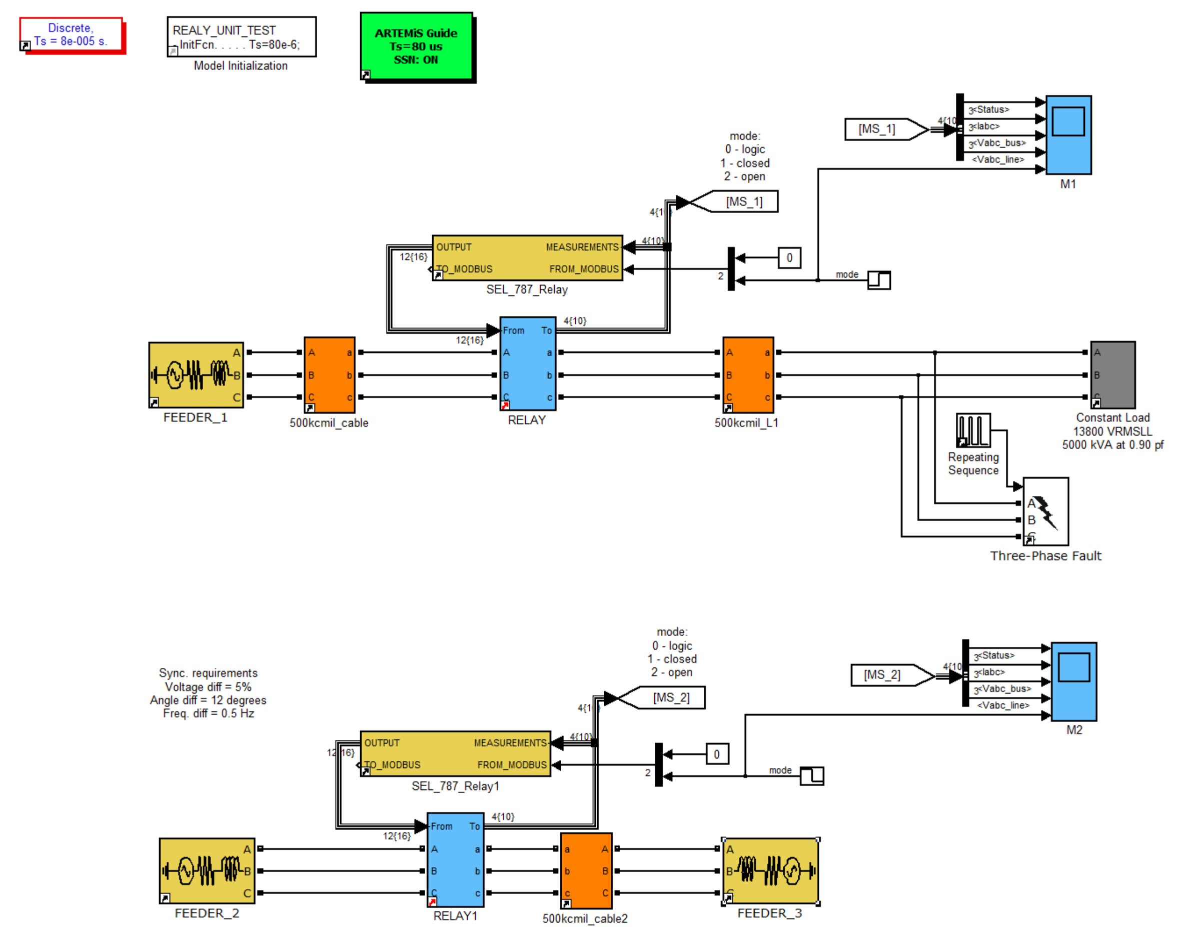
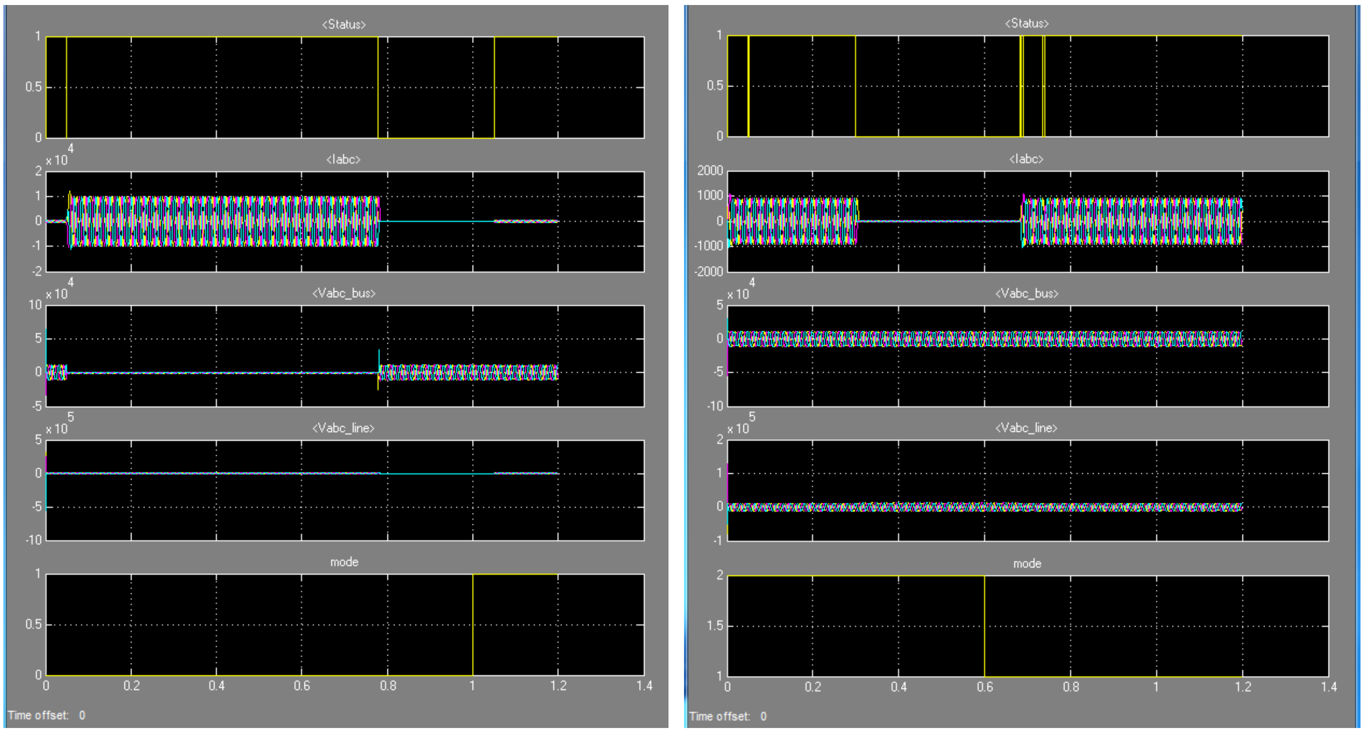


Figure 16.5. Relay Unit Test – Sample diagram



(a) (b)

Figure 16.6. Relay Unit Test – Simulation results

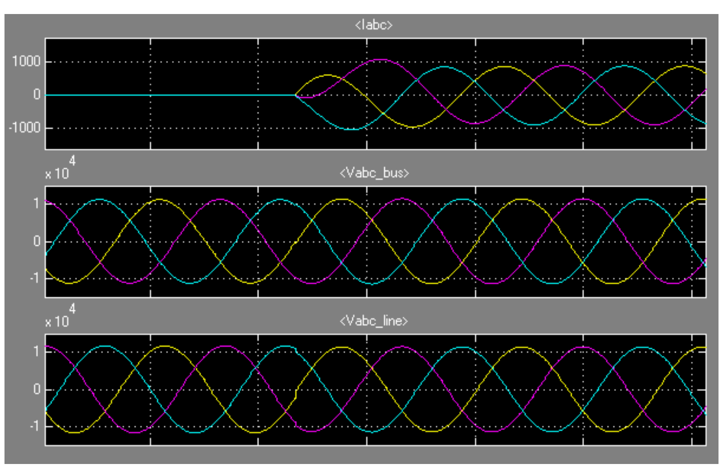


Figure 16.7. Relay Unit Test – Synchronism-check tests

17. WOODWARD WITH MODELED PRIMARY CONTROLLERS AND PRIME MOVER

17.1 LIBRARY

Demonstration / system of elements

17.2 DESCRIPTION

There are three milestone files (v7, v8, and v9) and each model was built off of the previous milestone. There are basic elements of the model that will be highlighted in this document. Each milestone has been tested by opening and running it in Matlab R2011b (32 bit).

17.2.1 Top Level Model:

The highest level of the model has the time step, OPAL RT Artemis solver, and the subsystem's Master and Console. The time step is set to 50 µs as the default, but can be adjusted faster or slower depending on fidelity and simulation resolution needed. The OPAL RT Artemis solver is a different solver than what Matlab defaults too. The Artemis solver has improvements over the basic solver, and there are paper references online that discuss its advantages. The Console subsystem can be related to the user interface when the model is running either in simulation or on the HIL Target. The Master subsystem can be related to the Plant, and occupies one core. If there is a Slave subsystem, then this occupies one core.

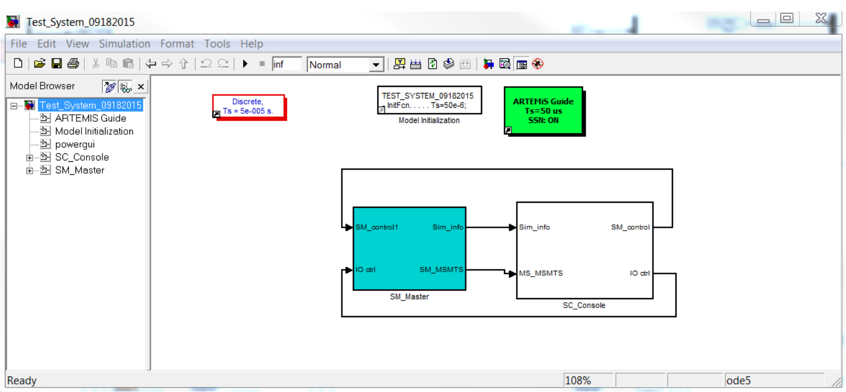


Figure 17.1. Top Level Model that shows the master (plants) and console (user interface and scope signals). The time step is 50µs, the green block is the OPAL RT ARTEMIS Solver. The SM_Master takes up a core on the target.

Example 1: There is a Console subsystem and Master subsystem. This is the minimum needed, the Master occupies a core, therefore only one core is needed / being used. The console runs on the targets internal core.

Example 2: There is a Console subsystem, Master subsystem, and 2 Slave subsystems. There are 3 cores (Master and 2 Slaves) out of the number of "x" available cores.

17.2.2 Master Subsystem:

The mapping of the I/O box to the appropriate component's models is located in this subsystem. This includes digital inputs, digital outputs, analog inputs, and analog outputs, and any signal that would be connected to the physical world. The plant components (Grid, Relays, Load, and Generator) of the modeled system are included here. The generator includes a simulated primary control of governor and automatic voltage regulator, simulated prime mover of rated machine, and the choice of a secondary controller that is physical (i.e. Woodward EasyGen 3500) or simulated (internal model). The relays included are the Generator Circuit Breaker (GCB), Mains Circuit Breaker (MCB), and Load Circuit Breaker (LCB). These breakers operate independent of each other, and depending on the secondary controller configuration may operate via internal or physical external control.

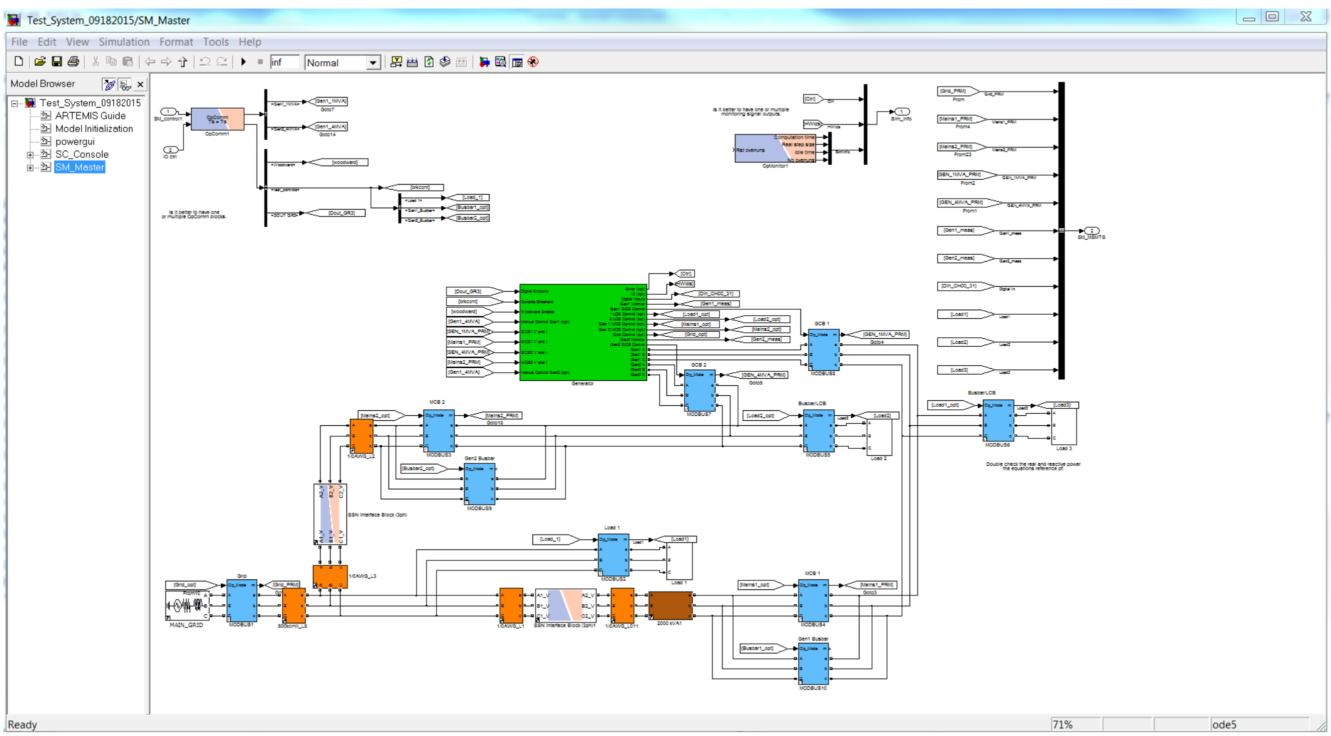


Figure 17.2. This is the model inside the Master subsystem. It includes relays in blue, 3 phase lines in orange, OPAL RT state space nodes (SSN) connectors in white with red and blue, and the generator connection and model in green. The top left bus is the signals from the console and the top right bus is signals sent to the console.

17.2.3 Console Subsystem:

The scoped signals and user interface controls are included here. The scopes have labels to correspond to the point that is being monitored. The digital switches and labeled constant blocks control the type of control (simulated or physical secondary controller, with or without digital I/O, with or without filtering of the analog biases, and with or without breaker control) the model is in.

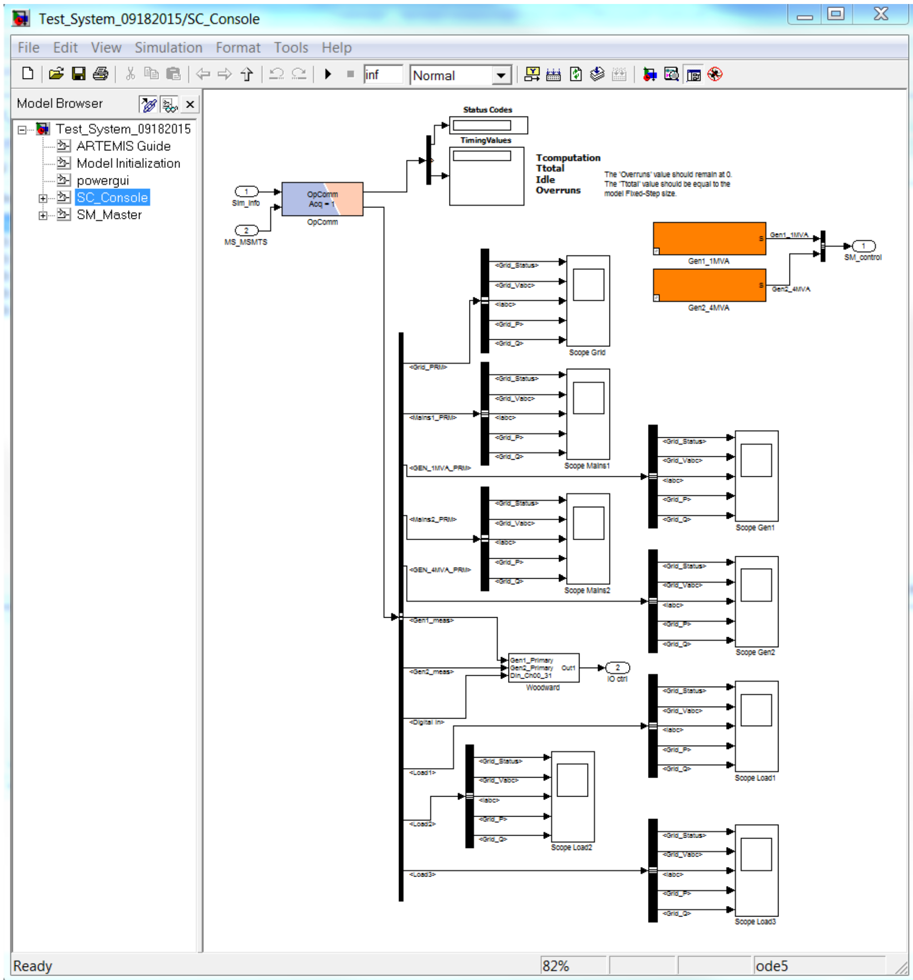


Figure 17.3. This is the model inside the Console subsystem. It includes the simulated secondary controller in orange for the 1 and 4 MVA generators, scopes for all the relays, and Woodward signals for test control and feedback.

17.3 DIALOG BOX AND PARAMETERS:

17.3.1 Console Subsystem:

Q.3.1.1 Woodward Secondary Controller (white colored subsystem)

The controls for simulated vs physical secondary controller, relays, scopes, and physical I/O are included. The constant “control mode” with the line label “Woodward” controls whether the physical device controller (control mode = 1) or the internal secondary controller (control mode = 0) signals are used for the inputs to the primary controller and prime mover. The area of constants that get multiplexed control the relays and what physical signals are passed to the simulated components. This is used to trouble shoot the system or walk through a particular sequence of events. The configuration of the console digital output switches is in the “16Din/16Dout Gr3” block. The scope for the primary controller includes the values (mechanical power (Pm), field voltage (Vf), terminal voltage (Vt), and rotor speed (w)). There is a reference signal and actual signal shown. In the case of Vt and w there is a bias signal shown in addition.

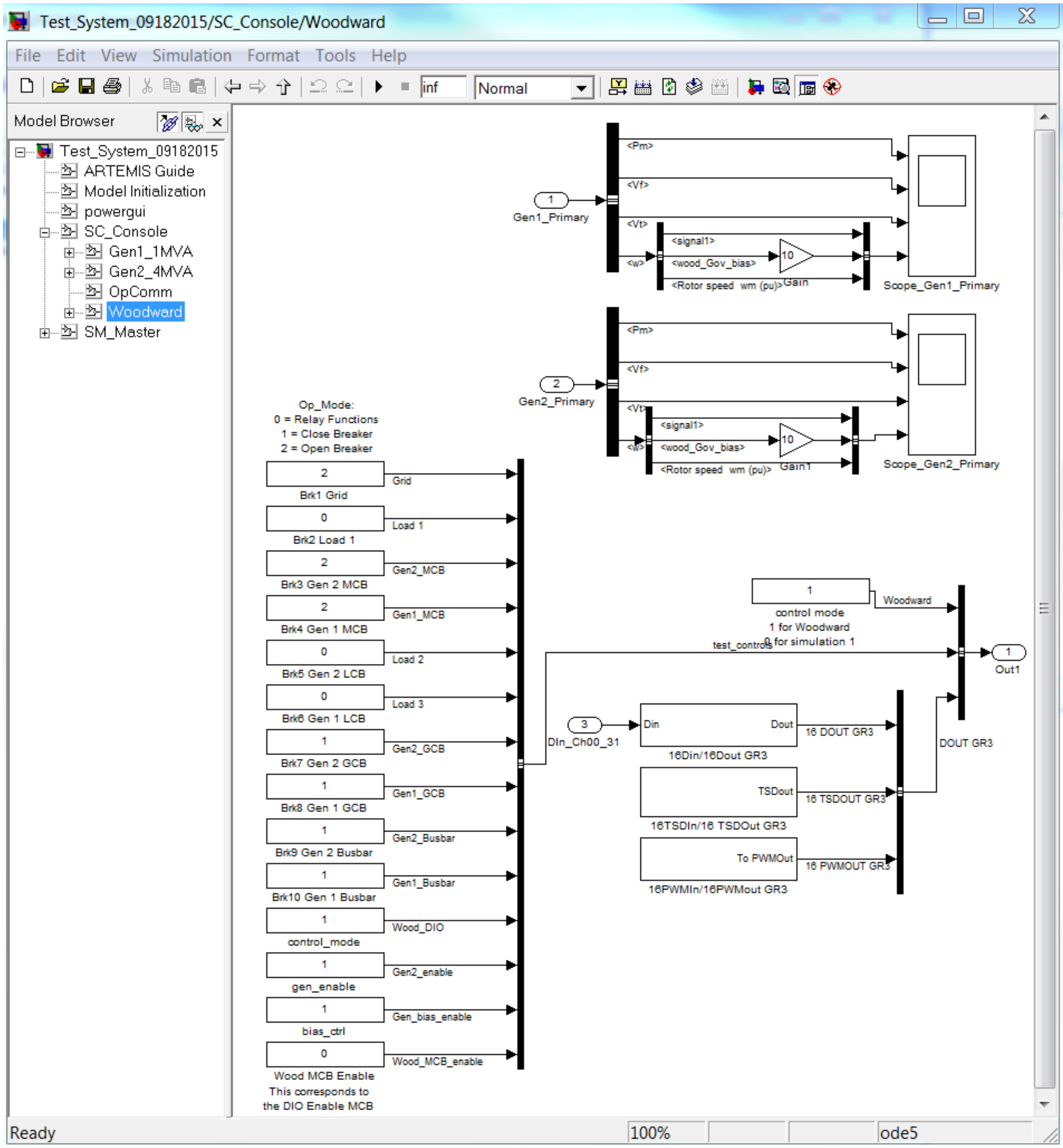


Figure 17.4. This is the console for the Woodward secondary controller. The scopes for the primary controller signals, digital input and output, and control of the modeled relays in the power system are located here.

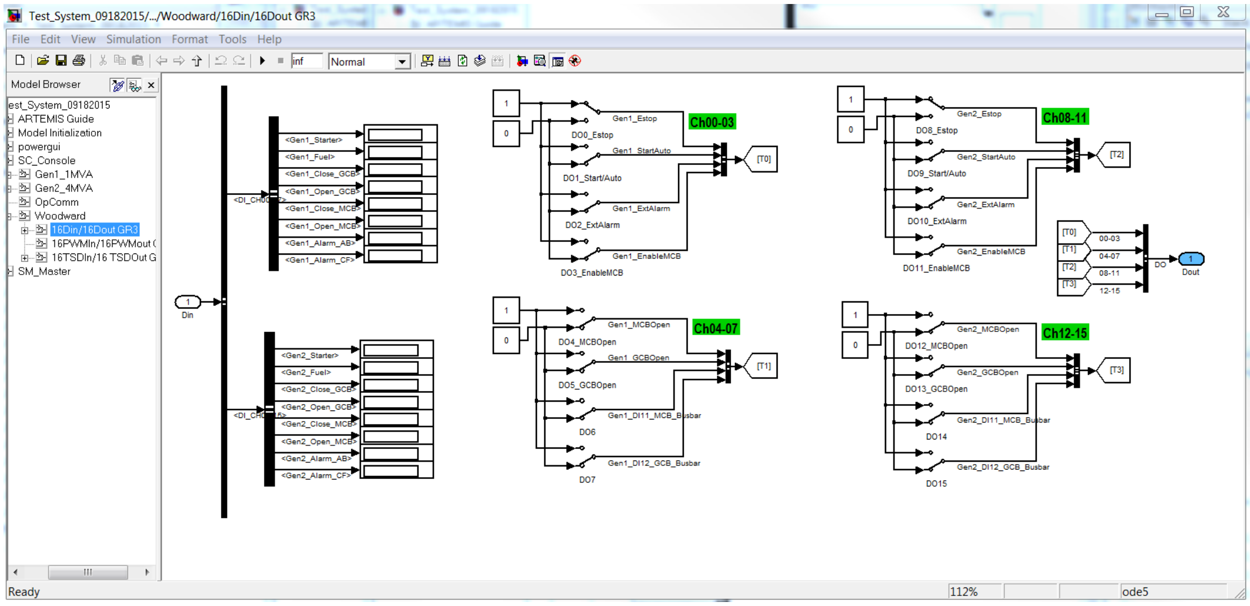


Figure 17.5. This is the testing interface for the digital inputs and outputs of the Woodward controller. It is not needed for the model to run as typically the microgrid controller would talk to the Woodward controller via Modbus communication.

Q.3.1.2 Simulated Secondary Controller (orange colored subsystem)

The real power (P in per unit), reactive power (Q in per unit), voltage (V in per unit), frequency (Hz in per unit), and enable generator (Startup = 1 and Shutdown = 0) are the control variables passed from the Console to the Master Subsystem.

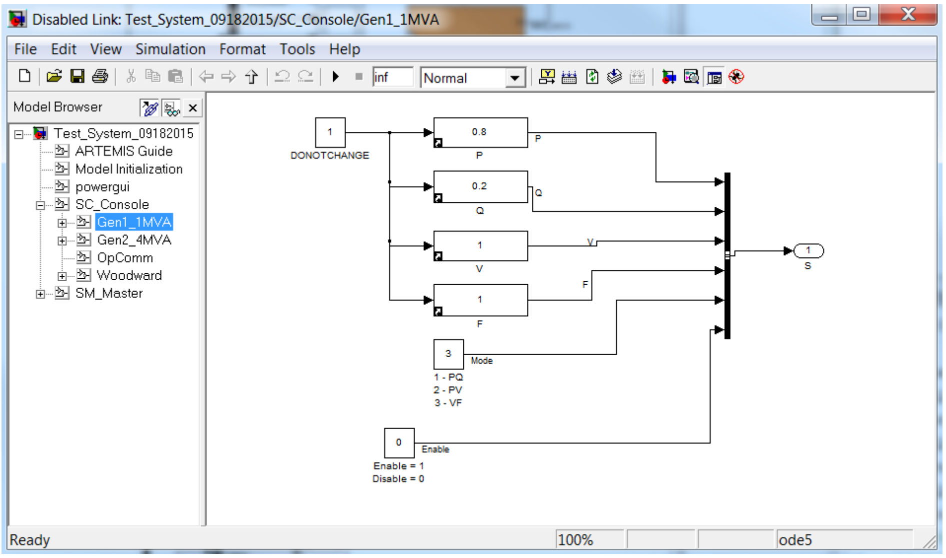


Figure 17.6. This the console model of the simulated generator secondary controller. This models control signals are different than the Woodward controller interface, therefore they are mapped to the appropriate primary controller interface.

17.3.2 Master Subsystem:

Q.3.2.1 Generator Model

This model includes the mapping of the Woodward output and input signals, generator primary and simulated secondary controllers, and any signal routing for control of generator and mains circuit breaker/relay. The blocks in white for the Woodward outputs and inputs will change depending on how your physical inputs and outputs are mapped to the virtual signals. The block in green can be replaced with other secondary, primary, and generator prime mover models.

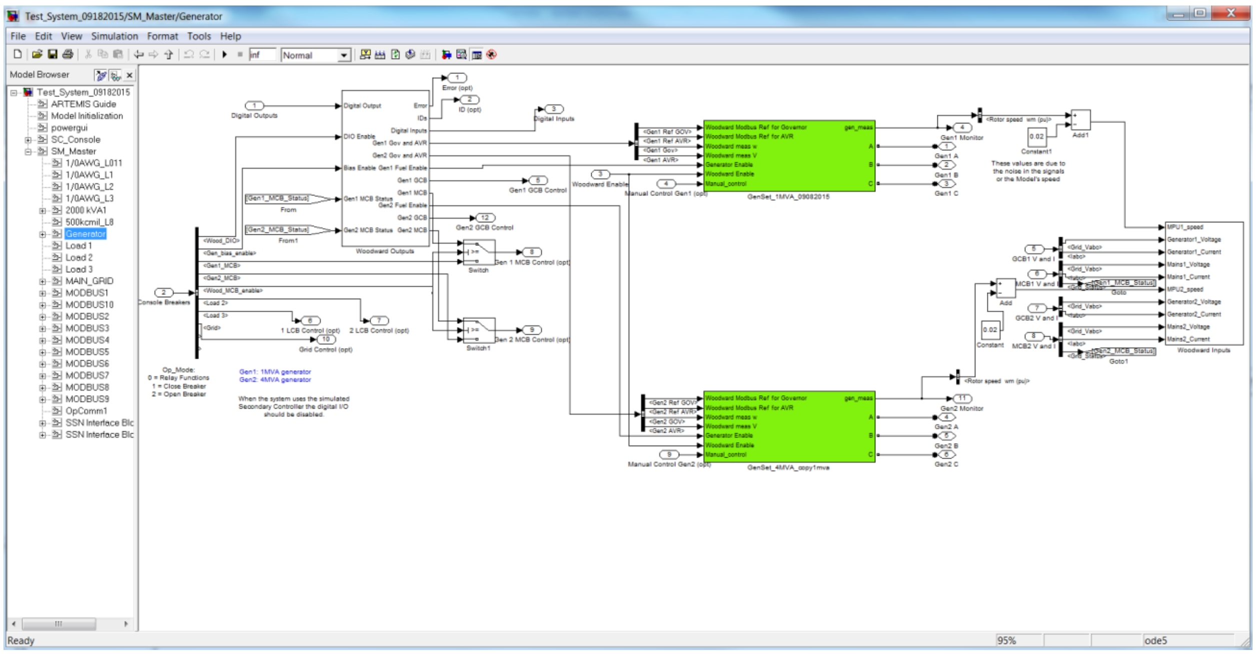


Figure 17.7. Generator interface model that includes the mapping of the Woodward secondary controller and the simulated secondary and primary generator controllers.

Q.3.2.2 Woodward Outputs

This subsystem shows the mapping of the physical Woodward outputs to the virtual signals. There is some logic inside the DIO-Woodward block that is used for the testing inputs in the console. They are not needed for normal operation of the model. The Woodward primary inputs have some signal conditioning to filter out the noise.

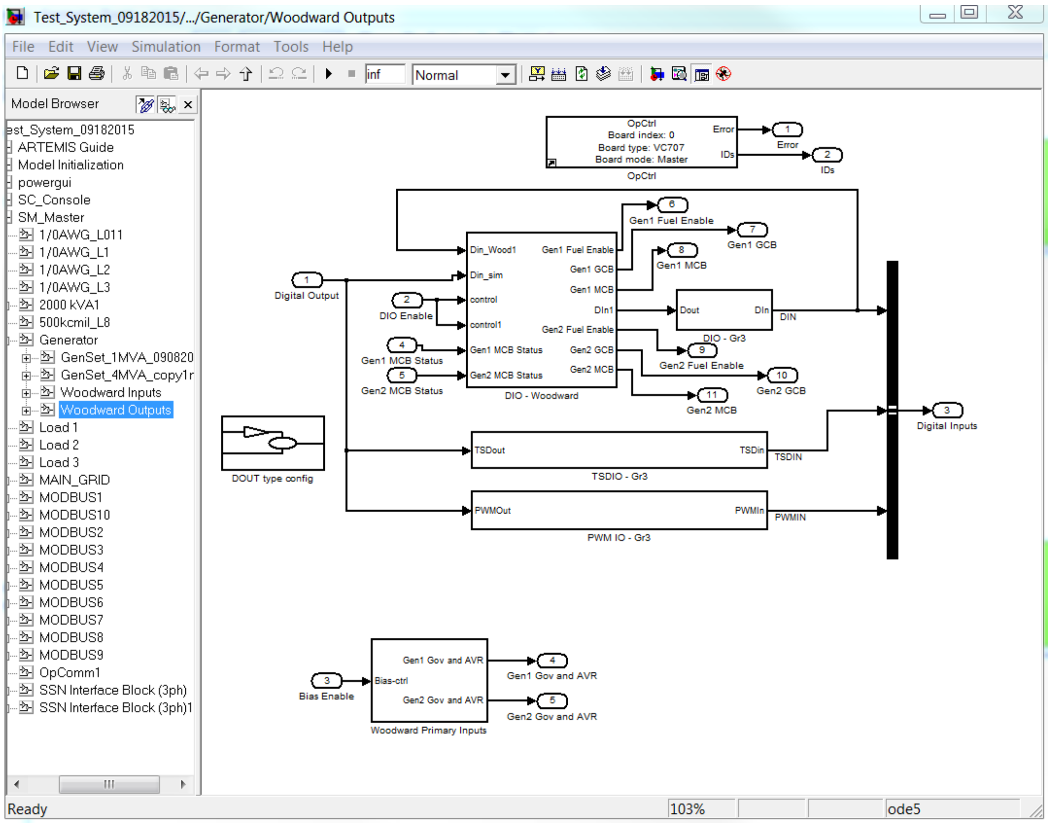


Figure 17.8. This subsystem is setup specific for the Woodward output mapping, testing logic, and signal conditioning.

Q.3.2.3 GenSet_xMVA (green colored subsytem)

This subsystem shows the simulated secondary controller (bottom left), primary controller (middle) that includes governor, automatic voltage regulator, and prime mover, and signal conditioning for numerical solutions (right). The models inside this system can be changed to more or less detailed components.

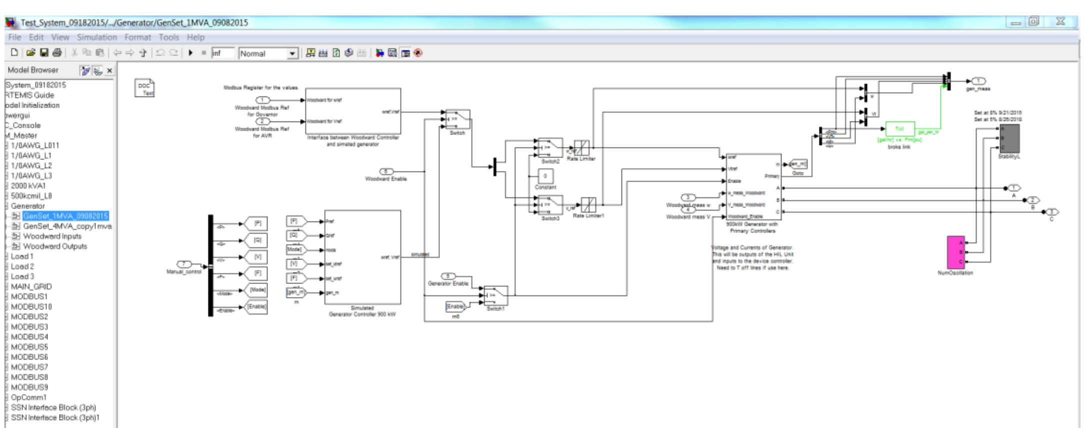


Figure 17.9. 1 MVA generator model of Woodward mapping, simulated secondary controller, and prime mover model.

Q.3.2.4 Woodward Inputs

This subsystem shows the mapping of the virtual signals to the physical Woodward inputs. Similar to the Woodward output subsystem, the mapping of these signals is setup specific.

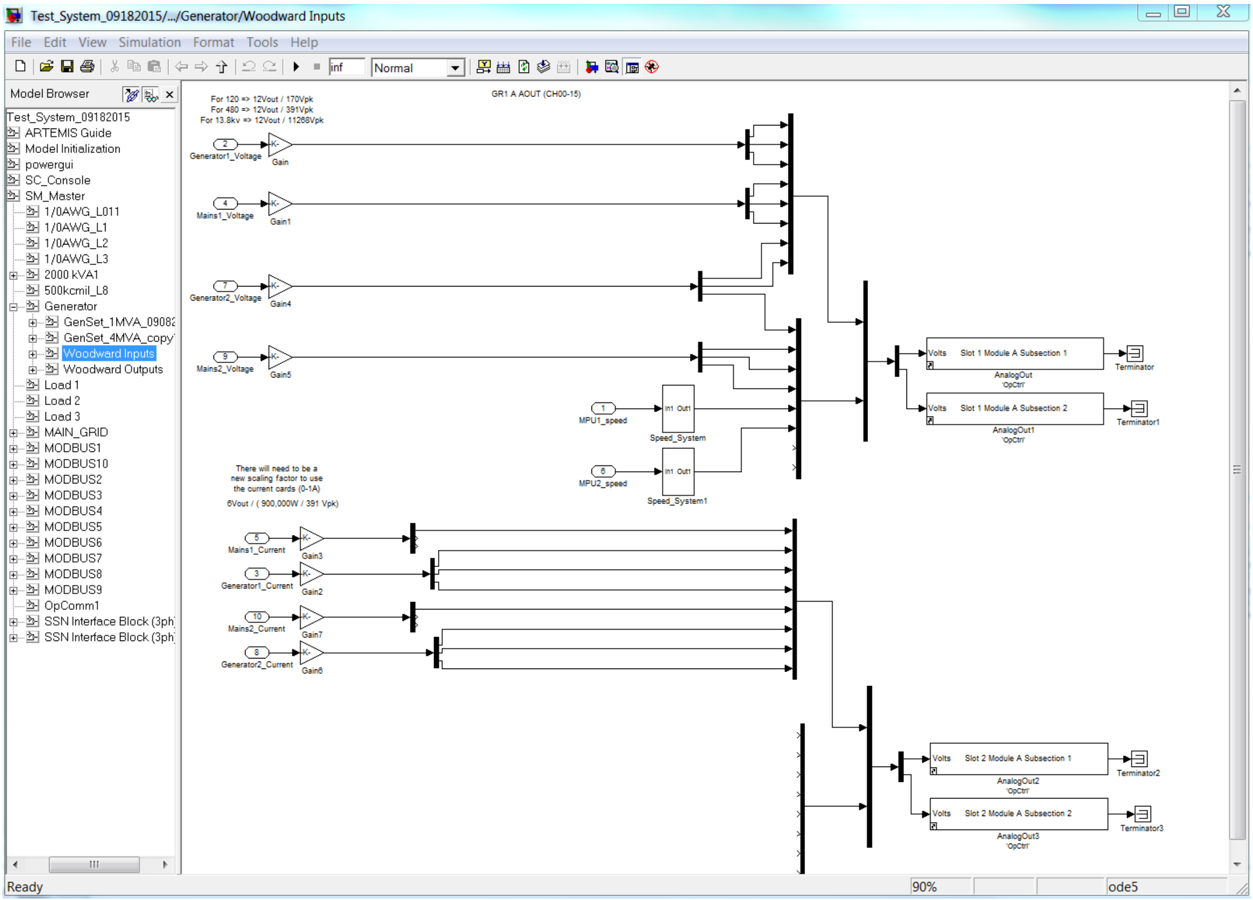


Figure 17.10. This is the mapping of the virtual signals to the Woodward inputs, and is specific to this particular setup.

17.4 MODEL SCOPE AND LIMITATIONS

This modeled system is compatible with integration of a Woodward Easygen 3500 generator controller to the physically mapped input and output parameters in the model. If a different device controller or physical input and output ports are used, then modifications will be needed. The modeled system will function without a physical device controller; therefore the secondary controller would be simulated.

17.5 EXAMPLES:

17.5.1 Milestone V9: 1 and 4 MVA Generators (Model run at the Symposium)

This demo shows grid tied and islanded operation of both the 1 and 4 MVA generators. There are three loads that can be changed in the system. When islanded the 4 MVA was operating in voltage and frequency (V F mode) and the 1 MVA followed in real power and power factor (P pf mode aka P Q mode). In addition, the previous version's capabilities are still functional. Note: The last item to test on the physical device controllers is droop capability.

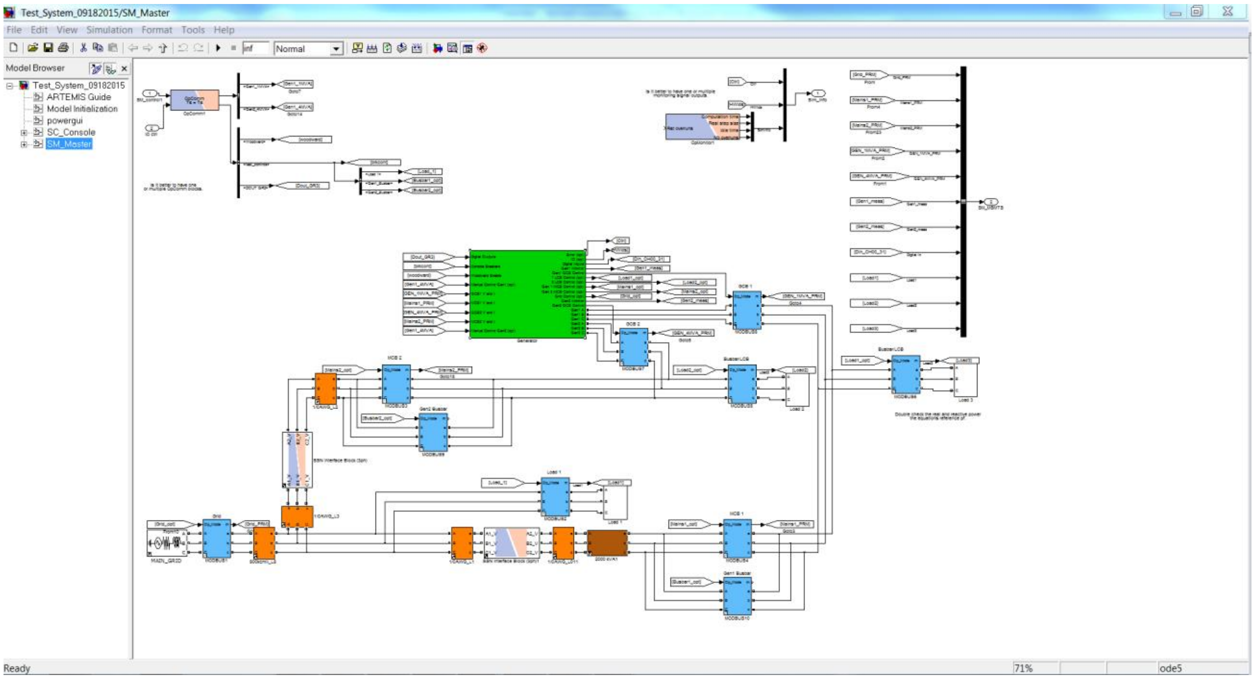


Figure 17.11. Milestone V9 model of Master Subsystem.

17.5.2 Milestone V8: 1 MVA and 4 MVA Generators

This demo added the 1 and 4 MVA generators to the same "Generator" susbsystem (green square block). Each was tested to operate as a backup emergency generator, synchronize the GCB, synchronize the MCB, and perform stable operation when connected to the grid and changes in real power (P) and power factor (pf) were made. Data sheets on the generators' values and ratings were compared to the models, and a low pass filter was added to the bias signals to reduce noise on the +-10 Vdc biases. The relay modules and Modbus blocks were updated using the library. The digital inputs and outputs of the 4 MVA were verified. In addition, the previous version's capabilities are still functional. Note: The Modbus in the relay was removed to another core in the larger model to increase computation speed.

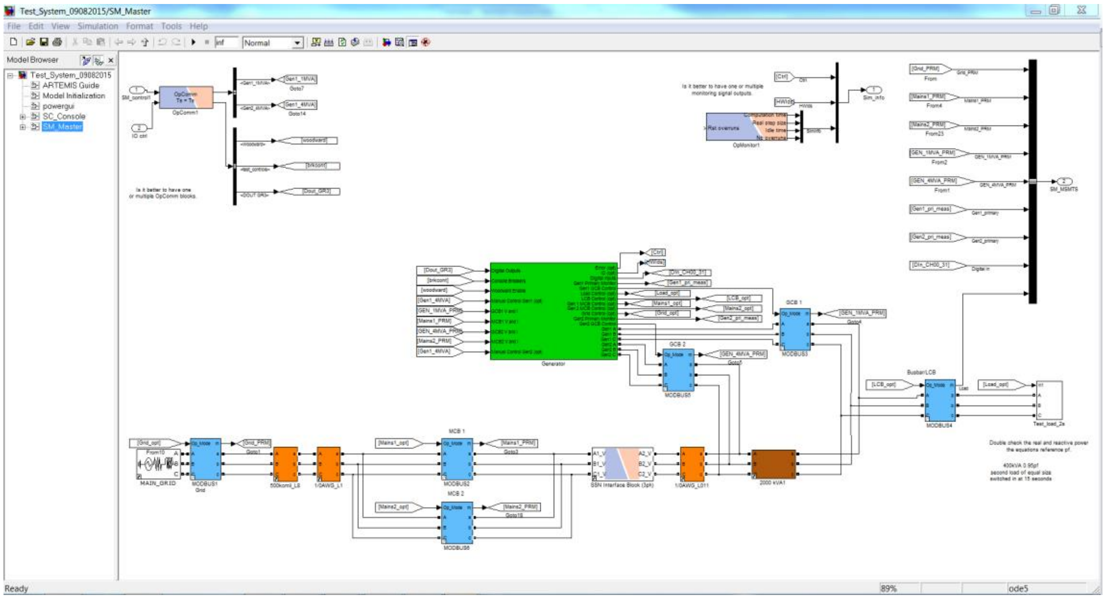


Figure 17.12. Milestone V8 model of Master Subsystem.

17.5.3 Milestone V7: 900 kW Generator

This demo cleaned up the diagram and combined the mapping of the inputs and outputs inside the generator block model (green square block in the Master subsystem). The gains were changed for the voltages and currents because improved circuity components were added to the interface box and calibration of the components provided improved dynamic range of the signal conditioning. The currents for all 3 phases and the mains were configured for the correct outputs. The digital inputs and outputs were verified to work correctly. In addition, the previous version's capabilities are still functional.

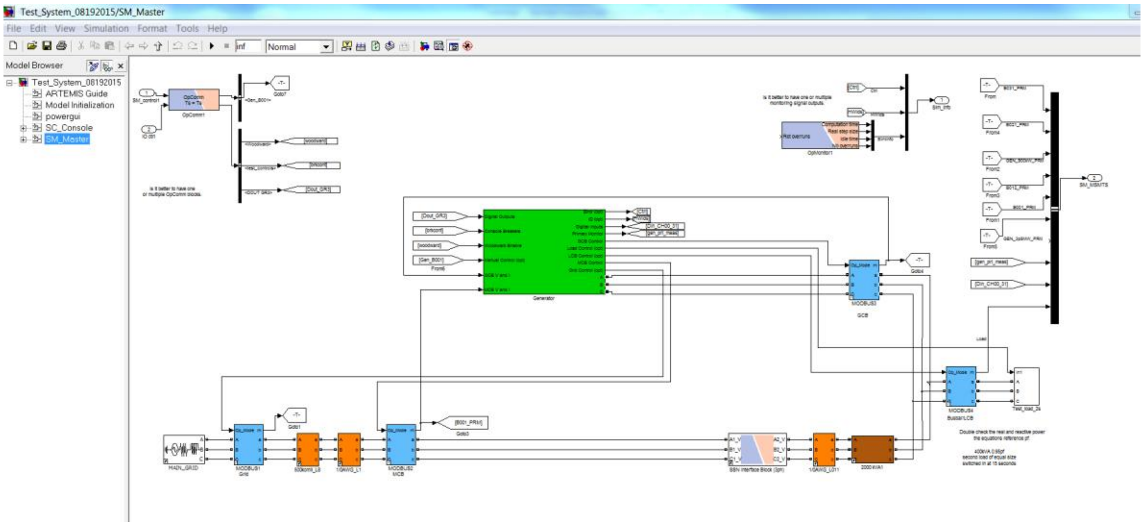


Figure 17.13. Milestone V7 model of Master Subsystem.

17.5.4 Milestone V6: 900 kW Generator

This demo tested the physical device controller to synchronize to the grid and have stable operation when changing the physical controller's power set points. In addition, the previous version's capabilities are still functional.

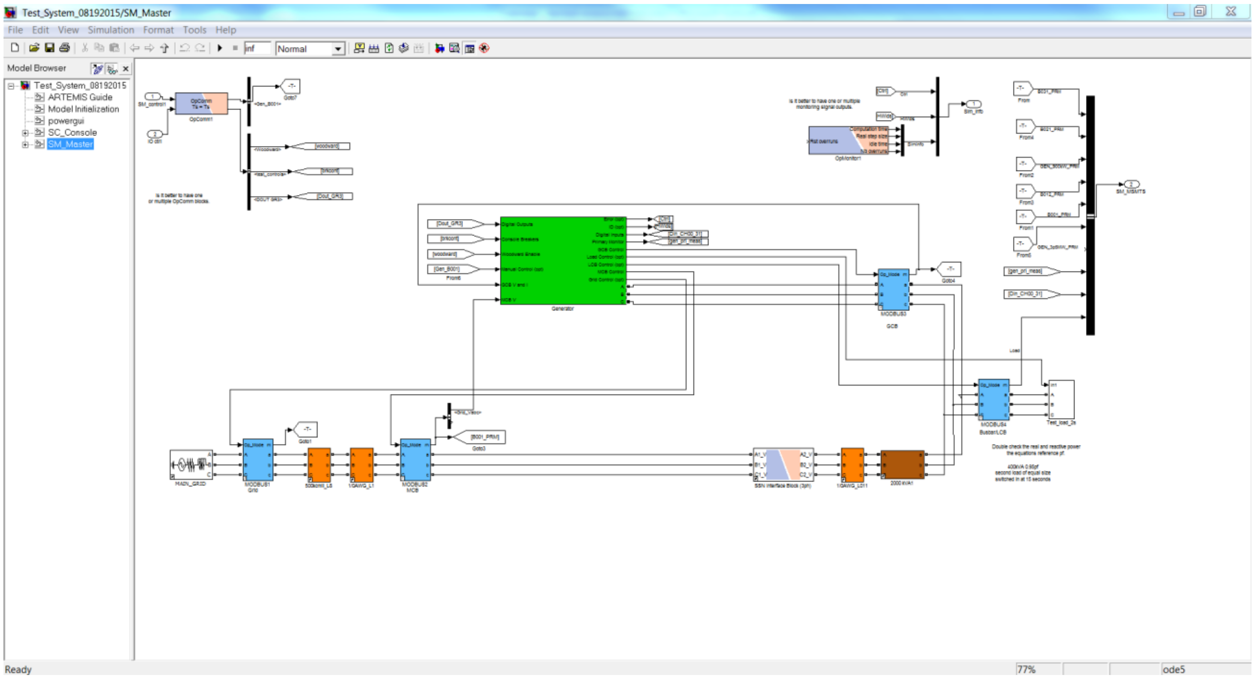


Figure 17.14. Milestone V6 model of Master Subsystem.

17.5.5 Milestone V5: 900 kW Generator

This demo tested the physical device controller to be a backup emergency generator without synchronization to the grid.

18. REFERENCE DOCUMENTS

18.1 PRIMARY DOCUMENTS

[1] R. Salcedo, C. Smith, E. Corbett, J. Nowocin, R. Rekha, E. Limpaecher, and J. LaPenta, "*Development of a Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers*", Technical Report. MIT Lincoln Laboratory, Dec. 2015

18.2 OTHER RELEVANT DOCUMENTS

n/a