REAL TIME SIMULATION OF LARGE DISTRIBUTION NETWORKS WITH DISTRIBUTED ENERGY RESOURCES

Melanie DYCK
RTDS Technologies Inc. - Canada
melanie@rtds.com

Onyinyechi NZIMAKO
RTDS Technologies Inc. - Canada
onzimako@rtds.com

ABSTRACT

The operation of distribution networks with wide-scale, actively managed, Distributed Energy Resources (DERs) has generated a demand for more sophisticated study tools, development aids, and test facilities to analyze technical operational issues related to the bi-directional power flow on distribution networks. This paper discusses the challenges of modeling large distribution networks, characterized by tightly coupled transmission lines, unbalanced phase loads, and power electronic interfaced generating sources, on a real time simulator. The test system used in this work is the IEEE 123 Node Test Feeder and is modeled in the Distribution Mode of the RTDS®. The steady state results are compared against a non-real time simulation tool and the published IEEE data to validate the accuracy of the modeling approach taken. The use of real time simulators for control and power hardware in the loop applications for large distribution networks integrated with distributed energy resources is presented.

INTRODUCTION

Real time Electromagnetic Transient (EMT) simulators have been widely adopted by utilities for analyzing technical issues related to the operation of transmission networks [1]. Similarly, real time EMT simulators can be applied to analyze the technical issues related to the operation of distribution networks integrated with DERs.

The RTDS is an EMT simulator which obtains the solution of the system using the Dommel algorithm [2]. The Dommel algorithm represents power components as a current source in parallel with a conductance using the trapezoidal rule of integration. Real time simulation is achieved by using high-speed parallel processors to share the computation burden as shown in Fig. 1. An Ethernet connection between the work station and a network interface card allows the simulation to be modified in real time by sending user specified command signals to the real time simulator.

The fundamental operation of real time digital simulation is the solution of equation (1) at every given simulation time-step ΔT (typically $\Delta T = 50\mu secs$). Equation (1) is commonly referred to as the network solution, where V and I are the voltage and current vectors respectively and G is the conductance matrix for the network [1].

$$[V] = [I] \cdot [G^{-1}] \qquad (1)$$

For most real time simulations, the elements of the G matrix are not constant throughout the simulation. The G matrix changes when a switch or breaker is operated. In addition, complicated power system components change their conductance elements to account for nonlinearities in their operational behavior [1]. Thus it is highly desirable to solve equation (1) at every simulation time-step.

Due to the limitations in the computational resources, the time available to solve the G^{-1} is limited. This in turn, restricts the number of nodes that can be solved by a network solution in real time. For the size of the network to be scalable, it must be possible to use more than one network solution in a simulation [1].

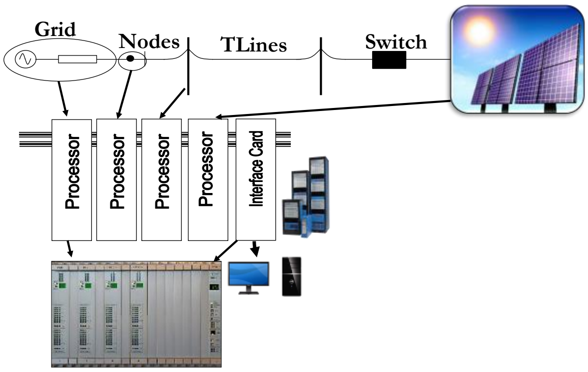

Fig. 1: RTDS simulation with parallel processors.

MODELING LARGE TRANSMISSION VS LARGE DISTRIBUTION SYSTEMS

Large simulation cases that represent major transmission (230 kV and above) typically include long transmission lines that carry the power from generating stations to substations located closer to the load centers. An overhead line longer than 15km typically has a travel time ($\tau = \sqrt{LC}$) greater than 50µsecs and can be used to decouple the simulation case into multiple network solutions. The decoupled networks can be solved independently on parallel processors to achieve real time simulation [3].

Transmission lines whose travel time is less than the simulation time-step are represented using a coupled PI-section model, or for very short lines using uncoupled passive components. Lines represented using a PI-Section or set of passive components have an impedance directly connected between the sending and receiving ends of the line and therefore it is not possible to use such a line to divide the network into separate subsystems.

Distribution systems are structured somewhat differently from major transmission systems. Distribution systems commonly consist of a number of radial feeders that begin on a substation bus. The feeders are not usually interconnected to form a mesh. Each feeder may contain a large number of nodes and many short line or cable segments. In most distribution systems there are no line or cable segments long enough to permit traveling wave models for decoupling the system into multiple network solutions.

For large distribution networks with short lines and cables, the number of nodes will quickly exceed the explicit number of nodes that can be handled by a single network solution. Lengthening line or cable segments, or using other means to introduce a subsystem split leads to an unacceptably large capacitance being added to the distribution system model. The introduction of artificial subsystem splitting devices in the distribution system model may result in bus voltages becoming unusually high [3].

DISTRIBUTION MODE OF THE RTDS

A new operating mode of the RTDS hardware and software RSCAD® has been developed to permit the modeling of distribution systems in real time. Distribution systems may have many hundreds of nodes and yet can be modeled on a single RTDS rack in real time at an increased time-step in the 100-200μs range. With a larger time-step it is possible to represent a much larger number of explicit nodes and handle more power system components per auxiliary processing element [3].

As a system gets larger, the conductance matrix increases in size. The radial nature of distribution systems results in a conductance matrix with more sparsity than a mesh connected system. A matrix with more sparsity takes less calculation time to invert than a matrix of the same size with more density. Therefore a radial system can be made larger without a significant increase to the time-step.

Distribution systems may include a large number of connected nodes, but the number of components connected to a node is typically limited. Often no more than two line segments and a shunt component are connected to a node. In many cases a distribution system includes series connected branches that represent line or cable segments of the same configuration where there is no shunt between the series segments. Those segments can be combined, and the intermediate nodes eliminated, with no loss of precision. Power system components comprising the distribution system are often limited to overhead line and cable segments, and shunt loads. Substation equipment at the head end is usually limited to a transformer and a system equivalent (source model) to represent the sub-transmission system. Short lines or cables can be represented using a PI-section or even a simple branch consisting of a series R-L and shunt capacitive components. These fairly simple component models take small amounts of computational resources, and therefore a large number of these components can be included in a single subsystem and will still perform as expected at a larger time-step of 100-200μs.

In this paper, the IEEE 123 Node Test Feeder, seen in Fig. 2, is modeled in the Distribution Mode of the RTDS. The system was modeled twice in RTDS Distribution Mode, initially with more detail, and then with some simplifications in order to reduce the number of auxiliary processors required. The results were compared against the IEEE123 Node Test Feeder documented results and a non-real time simulation tool CYME’s CYMDIST software to validate the accuracy of the modeling approaches taken. Both cases have a total of 288 nodes. A node is defined as a single phase connection between two components in the power system.

Initially the system was modeled in detail with unbalanced and coupled PI sections. The maximum bus voltage error of RTDS compared to IEEE and to CYME was observed to be below 0.1%. The detailed simulation case requires 6 processor cards and has a time-step of 103μs.

The IEEE123 Node Test Feeder was then modeled by representing the short lines and cables as simple R-L branches and shunt capacitive elements to reduce the number of auxiliary processors required. The complex calculations of the unbalanced and coupled PI-section models were simplified by using passive R, L and C components. The passive component calculations are performed on the network solution processor, which reduces the amount of power system processors needed for this case. As a result of these simplifications the maximum bus voltage error increased to just over 1.5%. The reduced case requires 2 processor cards, and has a time-step of 87μs.

Table 1 compares the power of the detailed IEEE 123 test feeder (RTDS1) and the simplified simulation case (RTDS2) against the results obtained from the CYME. The power error is observed to be less than 0.1% for the full case and less than 0.5% for the simplified case.

Table 1: Full (RTDS1) and reduced (RTDS2) IEEE123 test system results with CYME – No DGs.

	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2
	P (kW)	P (kW)	P (kW)	Q (kvar)	Q (kvar)	Q (kvar)	S (kVA)	S (kVA)	S (kVA)	PF (%)	PF (%)	PF (%)
Total Gen.	3621.0	3621.1	3621.5	1321.3	1322.2	1315.2	3854.5	3855.0	3852.9	93.9	93.9	94.0

Table 2: Full (RTDS1) and reduced (RTDS2) IEEE123 test system results with CYME – With DGs.

	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2	CYME	RTDS 1	RTDS 2
	P (kW)	P (kW)	P (kW)	Q (kvar)	Q (kvar)	Q (kvar)	S (kVA)	S (kVA)	S (kVA)	PF (%)	PF (%)	PF (%)
Sources	3265.3	3265.9	3266.2	1267.7	1269.7	1263.2	3502.7	3504.0	3501.9	93.2	93.2	93.3
DGs	345.0	345.0	345.0	12.8	12.8	12.8	345.2	345.2	345.2	99.9	99.9	99.9
Total Gen.	3610.3	3610.9	3610.9	1280.5	1282.6	1276.3	3830.6	3831.9	3830.1	94.3	94.2	94.3

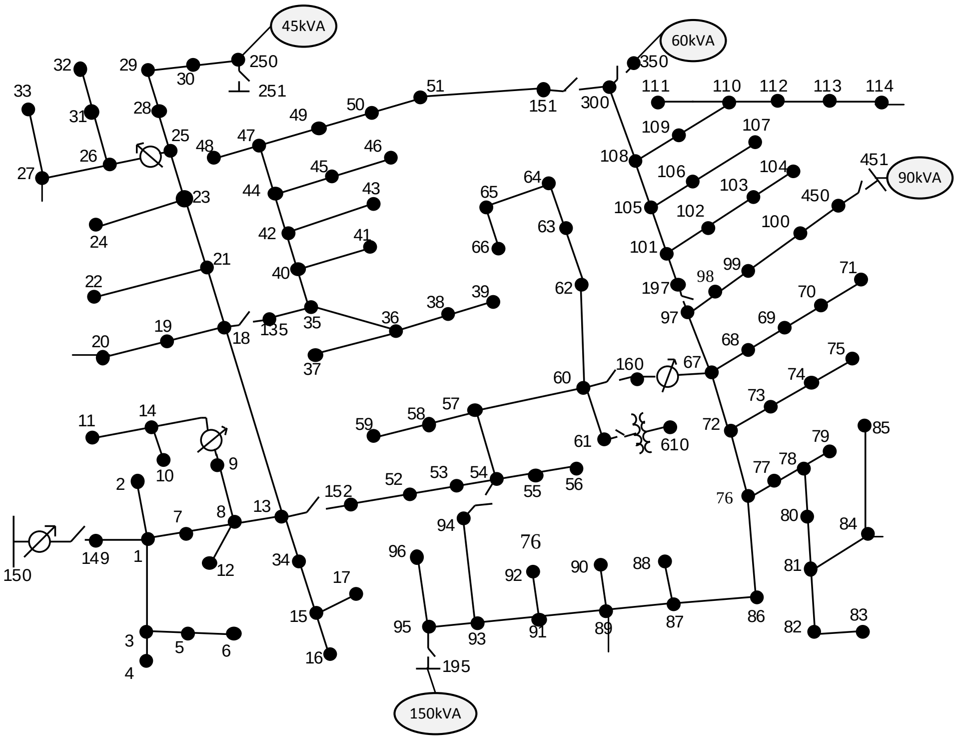

Fig. 2: IEEE123 Node Test Feeder with DERs.

MODELING DISTRIBUTED ENERGY RESOURCES

Power electronic based distributed energy resources such as wind, PV, and energy storage are increasingly being integrated in distribution grid systems. Small simulation time-steps (< 4µsecs) are required to accurately model the power converter high switching frequency transients.

Achieving real time simulation of power converter topologies at small time-steps requires dedicated computational resources which increase with the number of power converter based interfaced sources in the simulation.

In the RTDS Distribution Mode, the time-step is increased to allow for modeling large power systems. The increased distribution mode time-step is too large to simulate the high switching frequency transients of converter models. Dynamic models that represent the control dynamics and terminal AC and DC voltage-current relationships with sufficient accuracy and reduced computational resources are required for distribution applications.

Fig. 3 shows a dynamic average model that allows interfacing of DC sources such as PV without switched converter models. The AC voltage is obtained from a reference sinusoidal control signals ($m_{i=a,b,c}$) and the DC bus voltage [4]. Control methods such as decoupled current control are typically used to obtain the control signals. The DC current is obtained using the power balance between the AC and DC circuits.

Fig. 4 shows a reduced dynamic model that uses a controlled AC current source to provide the real and reactive power injections to the grid. The AC side filter found in converter topologies is neglected as the current injections are the grid currents. The DC side dynamics could also be neglected by assuming a large and constant DC source. The injected currents are obtained from the control of the given real and reactive power set points. The reactive power injected can be set from a voltage or power factor control. This reduced dynamic model is sufficient for applications where the focus is on the grid response to P and Q power flows from a large number of distributed energy resources.

The dynamic models shown in Fig. 3 and Fig. 4 use controlled voltage and current sources to represent the averaged dynamics of the power converters. The models neglect the high switching frequency transients allowing simulations at higher simulation time-steps and reduced computational requirements.

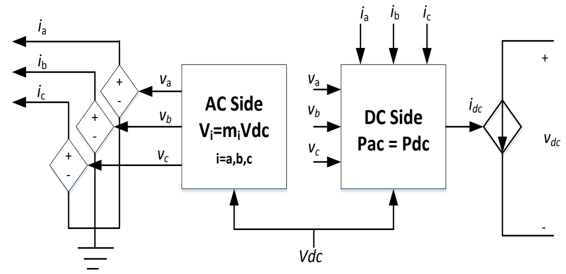

Fig. 3: Average model with DC-AC V-I relationship.

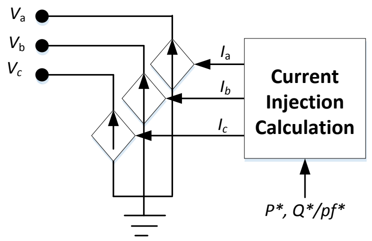

Fig. 4: Average model for AC power injection.

As shown in Fig. 2, distributed energy resources rated at 45kVA, 60kVA, 90kVA, 150kVA were placed on buses 250, 350, 451 and 195 respectively in the CYME case as well as the full and reduced RTDS cases. Each source was operating at unity power factor except the source on bus 451 operated at a power factor of 0.99.

Table 2 compares the power of the detailed IEEE 123 test feeder (RTDS1) and the simplified simulation case (RTDS2) against the results obtained from the CYME simulation case. The power error is observed to be less than 0.2% for the full case and less than 0.4% for the simplified case.

HARDWARE IN THE LOOP APPLICATIONS FOR DISTRIBUTION SYSTEMS

The increasing integration of renewables and distributed energy resources on distribution systems has generated a demand for detailed study tools and sophisticated hardware in the loop (HIL) test facilities to evaluate the operation of their associated control and power devices. The HIL capability of real time simulators (RTS) provides a realistic environment to perform large number of contingency tests to validate the device operation before it is connected to the grid.

HIL simulations can be divided into two classes, namely Control and Power HIL.

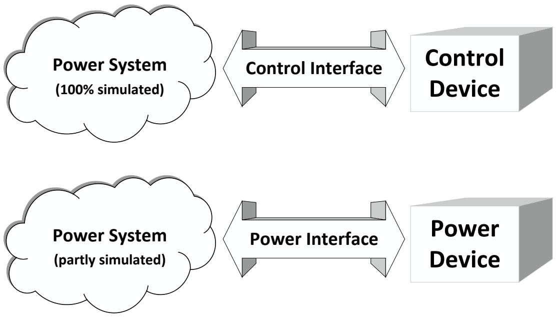

Fig. 5: Control and Power Hardware in the Loop.

In CHIL applications, all the power system and power components (transformers, converters, electric machines) are modeled entirely in the real time simulator. The control device under test can include relays, generator controls, power electronic controls etc. No power is exchanged over the interface and the interface to the control hardware is made using low level voltage and current signals and/or source-only power amplifiers.

The demand for reliable and efficient operation of the distribution network with wide-scale integration of DERs has driven the use of information and communication technologies (ICT) enabled control devices. Several ICT based devices support industry standard protocols such as distributed network protocol (DNP) for supervisory control and data acquisition (SCADA); IEC 61850 for substation automation and protection, IEEE C37.118 for phasor measurement units with GPS time synchronization [3]. Real time simulators with the capability to support these industry standard protocols enable testing of ICT enabled devices in CHIL applications [3].

For CHIL applications, the challenge in simulating the power system entirely in the RTDS is the difficulty in obtaining the exact system parameters as well as the topology and controls for power devices such as power converters, transformers and electric machines.

PHIL applications involve the connection of physical power system components, such as power converters, electric machines and transformers, with the real time simulator. Unlike CHIL simulations, the stability and accuracy of the power interface should be carefully considered to avoid instabilities as the power device exchanges power with the real time simulator at high voltage levels [5,6]. Fig. 6 shows a PHIL test with a PV inverter and the RTDS [7].

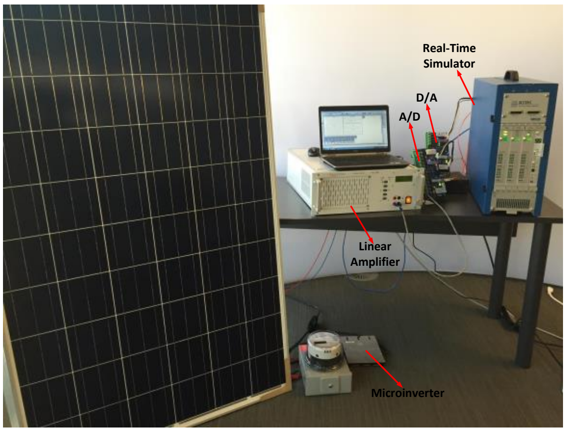

Fig. 6: PHIL testing of a PV inverter.

Voltage and current sensors send the response of the power device to the real time simulator and vice-versa through analog-digital converters. The inverter was interfaced to the real time simulator using a 1kVA linear voltage amplifier with overload and short circuit protection. Fig. 7 shows the inverter current response to a line to ground fault. The response shows the point at which the inverter disconnects from the grid. PHIL simulation enabled the operation of the unknown (black box) PV converter and control topology to be tested with the grid modeled on the real time simulator.

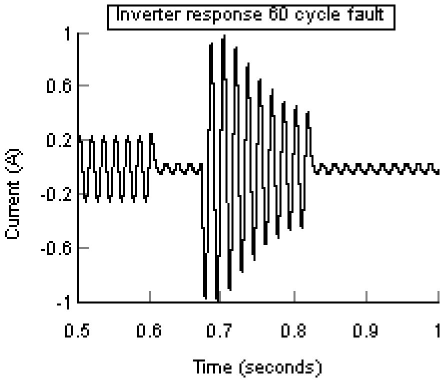

Fig. 7: Inverter fault response in PHIL test.

CONCLUSION

The paper discussed the modeling and simulation of large distribution systems with distributed energy resources on a real time simulator. The results compared against a non-real time simulation tool and the published IEEE data to validate the accuracy of the modeling approach taken. Applications of the real time simulator for Control and Power hardware in the loop simulations was discussed.

REFERENCES

[1] P. Forsyth, O. Nzimako, C. Peters and M. Moustafa, 2015, "Challenges of modeling electrical distribution networks in real-time," *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, Vienna, 2015, pp. 556-559.

[2] H.W. Dommel, 1969, “Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks” IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, no. 4, pp. 388-399.

[3] R.Technologies, 2016, RTDS Manuals and Documentation, www.rtds.com, Winnipeg.

[4] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*, New Jersey: Wiley-IEEE Press, 2010, p. 204.

[5] W. Ren, M. Steurer and T. L. Baldwin, 2008, "Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms," in *IEEE Transactions on Industry Applications*, vol. 44, no. 4, pp. 1286-1294

[6] O.Nzimako and R. Wierckx, 2015, "Stability and accuracy evaluation of a power hardware in the loop (PHIL) interface with a photovoltaic micro-inverter", *Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE*, Yokohama.

[7] PHIL Simulation with a PV Inverter using the RTDS Simulator. www.rtds.com