

HIL Simulation of a Distribution System Reference Model

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SUMMARY

This paper presents the IDE4L project reference grid model developed to perform real-time hardware-in-the-loop simulations. The simulations will be carried out to study distribution grid dynamics and to evaluate the techniques developed in IDE4L project for TSO/DSO interactions. Performance of the grid model is shown through sample real-time simulation results and a hardware-in-the-loop setup for PMU-based grid monitoring applications.

KEYWORDS

distribution network, dynamic performance, real-time, hardware-in-the-loop, PMU, OPAL-RT

1. INTRODUCTION

Funded by the European Commission's FP7 program (7th FRAMEWORK Program for Research and Technological Development), the IDE4L (Ideal Grid for All) project has recently started to define, develop and demonstrate distribution grid automation system, IT platform and applications for active distribution grid management [1]. The project is composed of several work packages to cover different aspects of active grid management. As part of work package 6 of the project, tighter integration of the operation of transmission grids (HV) with distribution grids (MV and LV) through exchange of key dynamic information between TSOs and DSOs will be investigated. The key information exchange will be performed by coupling the use of PMU data from HV, MV, and LV grids, coherently. To demonstrate such tight interaction and also to evaluate the quality and relative merits of the developed techniques, there is a need to develop a reference distribution grid model that includes a distribution grid (MV and LV) and also parts of the transmission grid (HV). The model will be then coupled together with PMUs, external controllers, and a co-simulation of communication networks to carry out real-time hardware-in-the-loop simulation studies.

The proposed test grids in the literature often operate at single voltage levels and also lack components such as distributed generators and protection systems, so they can't fulfill the requirements for studies in the IDE4L project [2-4].

This paper demonstrates a reference active distribution grid model that has been developed for this purpose. The model is implemented in MATLAB/Simulink and modified for its use with the OPAL-RT real-time simulator. The grid topology is based on Roy Billinton Transmission Test System and IEEE standard test feeders, including HV, MV and LV voltage levels. In the next section, the grid specifications are explained. Section 3 elaborates on real-time simulation of the grid model and illustrates a hardware-in-the-loop setup prepared for grid monitoring applications via PMU measurements. Conclusions and future work are listed in Section 4.

2. THE REFERENCE DISTRIBUTION GRID MODEL

Fig. 1 depicts MATLAB implementation of the reference distribution grid model. As the figure shows, the grid model includes four different sections: HV (220 kV), MV (36 kV), LV (6.6 kV), and residential LV (0.4 kV). Although the HV section is not considered to be part of the modeled distribution grid, it's included in the model to incorporate the dynamics of the HV grid.

The HV section consists of an EPS model (composed of a sixth-order model of synchronous generator together with steam turbine and governor, excitation system, and PSS models) and a 5-bus network adopted from the Roy Billinton Transmission Test System (RBTS) [5]. Since the model will be used in a European project, the system voltage is reduced from the original 230 kV to 220 kV to comply with the European voltage levels [6]. As shown in the figure, a 50 MW wind farm generation (developed by OPAL-RT [7]) is added to this section.

The MV section topology is based on the IEEE 34 bus test feeder [2]. The system voltage is increased from the original 24.9 kV to 36 kV, a European voltage level. As the figure shows, three constant power loads (total of 110 kVA) are replaced by dynamic load models (composed of induction machine model) to incorporate motor loads dynamics. Also, two 1.5 MW wind farm model is added to the middle and to the end of the feeder. Since the original test feeder lacks any protection system, a circuit breaker supervised by an overcurrent protection block and a three-phase recloser are added to the beginning and to the middle of the MV feeder, respectively.

The LV and residential LV sections are built based upon the IEEE 37 bus test feeder [2]. Similar to the HV and MV sections, the voltage levels have been changed to comply with European voltage levels: for LV, from 4.8 kV to 6.6 kV, and for residential LV, from 0.48 kV to 0.4 kV. As the figure shows, two constant power loads (total of 150 kVA) are replaced by dynamic load models. Also, two PV farm models (total of 1.05 MW), three residential PV system models (total of 0.77 MW), two CES (Community Energy Storage) models (total of 325 Ah), and two sets of single-phase recloser are

added to this section [8, 9]. Note that the relatively high generation of residential PV models is because these models represent aggregation of residential PV systems.

Finally, note that, as a result of having several components connected to the grid model, it is quite difficult to initialize the grid model in an equilibrium operating point. So, two auxiliary ideal voltage sources, called AVS in Fig. 1, are used at the simulation startup to help the grid model to reach to a stable operating point. The AVS components are then disconnected after the first 10 seconds of simulation.

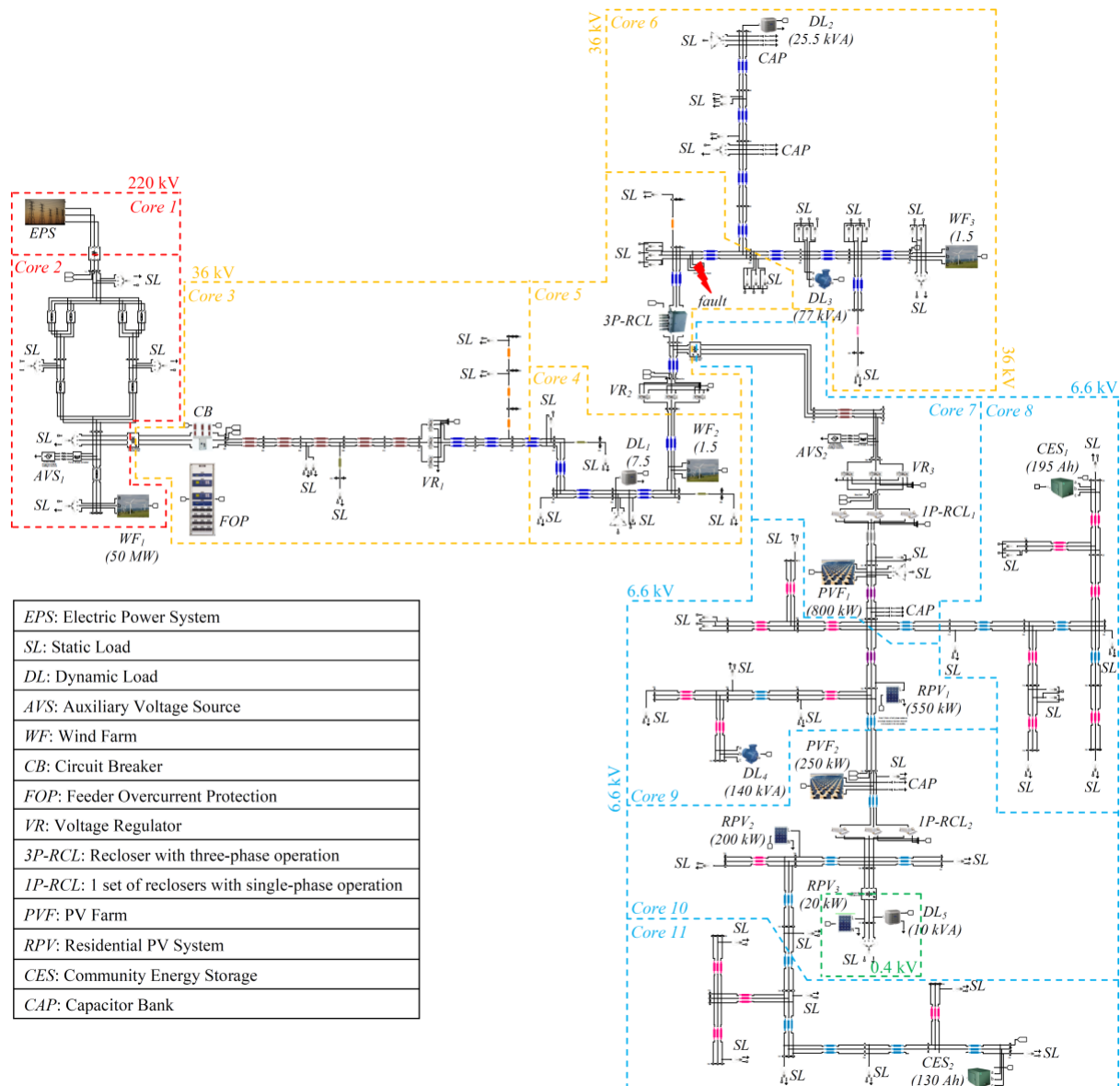


Fig. 1. MATLAB Simulink implementation of the reference distribution grid model.

3. HARDWARE-IN-THE-LOOP REAL-TIME SIMULATION

This section elaborates on real-time simulation of the grid model, developed in the previous section, and illustrates a hardware-in-the-loop setup prepared for grid monitoring applications via PMU measurements. Note that algorithms, to be developed during the IDE4L project, for exchange of key dynamic information between TSOs and DSOs will be added to this setup for evaluation and demonstration purposes.

3.1 Model Setup for Real-Time Simulation

Due to high computational burden of the grid model, parallel distributed computing capability embedded in OPAL-RT's simulator has been utilized to comply with real-time simulation constraints. Hence, as shown in Fig. 1, the grid model is distributed into total of 11 cores of the OPAL-RT simulator (HV section into 2 cores, MV section into 4 cores, and LV and residential LV sections into 5 cores).

3.2 Sample Real-Time Simulation Results

Fig. 2 shows sample real-time simulation results for a test scenario where all dynamic loads (total of 260 kVA) are switched on at $t = 30$ s and a 6-cycle three-phase fault occurs on the MV feeder (shown in Fig. 1) at $t = 50$ s.

As indicated in Subplot 1 of the figure, the random perturbation and sinusoidal variation embedded in static load models are reflected in the measured frequency. After the fault occurrence at $t = 50$ s, the three-phase MV recloser detects and isolates the fault within 2 cycles. The fault clears during the first open interval of the recloser. As shown on Subplot 4 of the figure, due to insufficient voltage support after the fault, a sequence of disconnection and reconnection of loads and distributed generation occurs before the grid returns to its normal operation. It's worth noting that, as highlighted in Subplot 4, such sequence of events in an active distribution grid like the modeled reference distribution grid can result in noticeable unexpected variation of power flow, in this case 2 MW (≈ 0.66 p.u.) and 4 MVAR (≈ 1.33 p.u.) change in the power flowing from the HV section to the MV section. Such sudden demand variations imply the need for tighter operation and coordination of the transmission and distribution grids' operators.

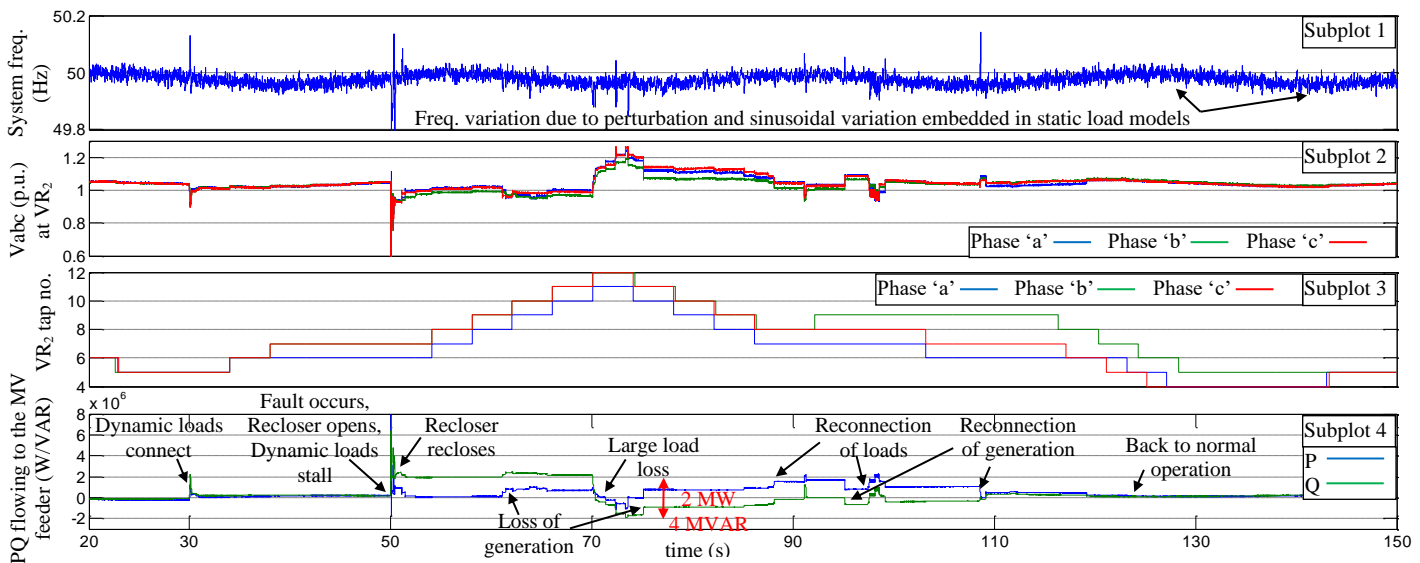


Fig. 2. Sample real-time simulation results.

3.3 Hardware-in-the-Loop Setup

Fig. 3 shows the hardware-in-the-loop setup for grid monitoring via PMU measurements. As shown, four measurement locations at different voltage levels have been specified on the grid model. The measured voltages are fed to PMUs through the analogue output ports of the OPAL-RT simulator. As indicated in the figure, two PMUs used in this setup are Compact Reconfigurable IO systems (CRIO) from National Instruments Corporation, programmed with LabVIEW graphical programming tools to perform phasor calculations [10]. The other two PMUs are SEL-421 from Schweitzer Engineering Laboratories, being fed through a voltage amplifier. This is because the rated voltage of SEL-421

input is 300 V, making it suitable for commercial applications; hence, it's much higher than the rated voltage of the simulator analogue output which is 16V.

The PMU data are then sent to a PDC which streams the data over TCP/IP to a workstation computer holding Statnett's Synchrophasor Development Kit (S³DK) [11], which provides a real-time data mediator that parses the PDC data stream and makes it available to the user in the LabVIEW environment. Utilizing functions provided by the S³DK, an interface was developed using LabVIEW. The LabVIEW interface displays the time-stamped frequency and voltage data on a diagram and the voltage phasors on a phasor pane. There are also lamp signals, functioning as alarms, that change color if the measured frequency goes beyond the permissible range.

This is the basic platform that will be used to develop PMU-based monitoring applications for TSO/DSO interaction through dynamic information exchange.

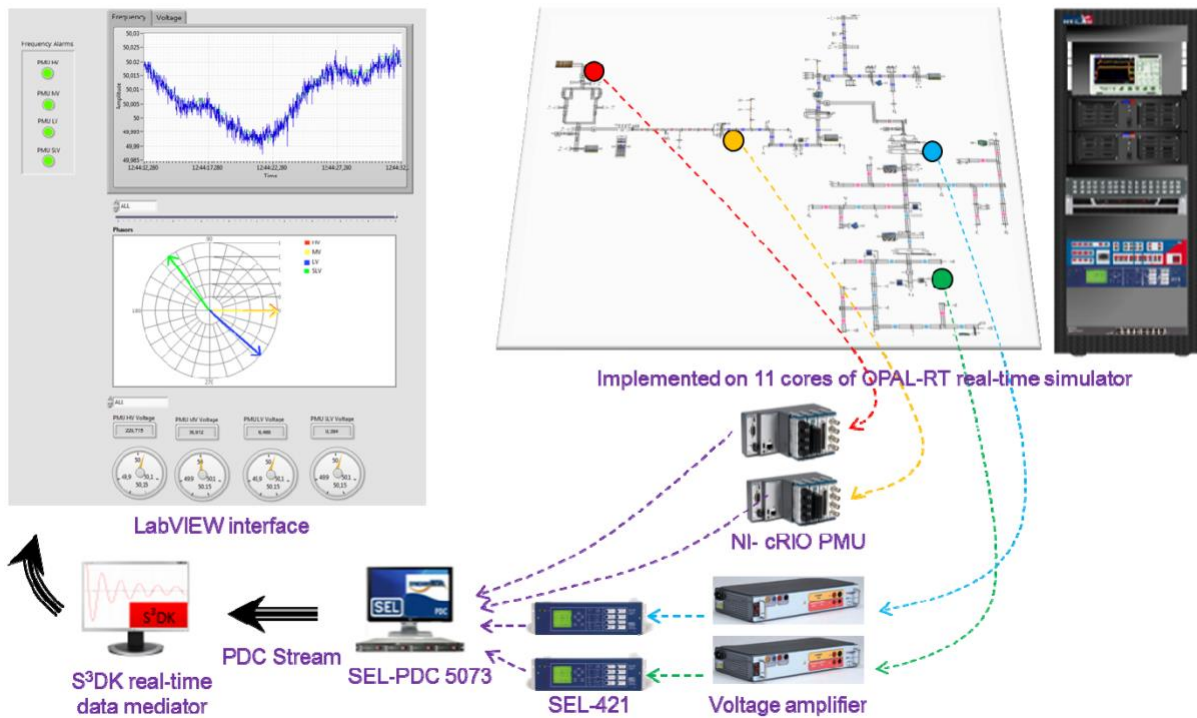


Fig. 3. Hardware-in-the-loop setup and LabVIEW interface prepared for monitoring the reference distribution grid model via PMU measurements.

4. CONCLUSION

This paper presented a reference distribution grid model, specified, implemented and simulated to serve as a benchmark for dynamic performance studies on active distribution grids. The model was simulated in real-time using the OPAL-RT simulator and was utilized in a hardware-in-the-loop setup to develop grid monitoring applications that exploit PMU measurements.

As future work, algorithms, to be developed during the IDE4L project, for exchange of key dynamic information between TSOs and DSOs will be added to this setup for evaluation and demonstration purposes.

5. ACKNOWLEDGEMENT

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