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Specification, implementation, and hardware-in-the-loop real-time simulation of an active distribution grid ☆

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ABSTRACT

This paper presents the IDE4L project reference grid model developed to serve as a benchmark for studies on distribution grid dynamics within the project. The paper demonstrates a MATLAB/Simulink implementation of the reference grid to be used in 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.

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 cannot fulfill the requirements for studies in the IDE4L project [2–4].

This paper develops specifications for an active distribution grid model to be used 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 paper introduces the developed components that are incorporated in the grid model in Section 3 where the grid specifications are explained. Section 4 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 5.

2. Models of components

This section illustrates the developed components for the reference grid model. The components will be used in the next section to be incorporated in the overall grid model.

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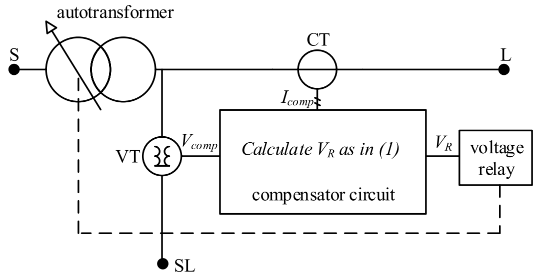

Fig. 1. Conceptual diagram of the developed VR component.

2.1. Single-phase step voltage regulator (VR)

The single-phase VR is implemented based on the model reported in [5]. The model consists of an autotransformer and a step voltage regulating relay that governs a load tap-changing mechanism, as illustrated in Fig. 1. Table 1 lists input parameters of the developed component.

The position of the tap is controlled by the compensator circuit through manipulating the input of the regulating relay as shown in (1):

$$V_R = V_{comp} - (R_c + jX_c)I_{comp} = V_{comp} - (R_{comp} + jX_{comp}) \tag{1}$$

where V_R is the input to the regulating relay, and V_{comp} and I_{comp} are the VT secondary voltage and the CT secondary current, respectively. R_c and X_c represent the per-unit equivalent line impedance from the regulator output to the regulation point. Note that in practice, the compensator settings, R_{comp} and X_{comp}, are expressed in units of volts as R_{comp} and X_{comp} are defined as R_cI_{comp} and X_cI_{comp}, respectively.

The component contains a reversing switch enabling a ±10% regulating range, in 16 steps up and 16 steps down. The regulating relay performs a tap change if:

$$V_R - V_{ref} > BW/2 \text{ during a time } t > T_d. \tag{2}$$

Note that the logic delay can vary from 1 s to hundreds of seconds and is determined by the system operator based on the feeder operating conditions. Having different logic delays results in different system dynamics.

2.2. Static load

In this study, "static loads" are referred to loads that do not contain any motor. Table 2 lists the input parameters of the developed component. The component has been developed in two versions of single-phase and three-phase. It can be chosen to be either constant current, constant impedance or constant power load; however, if the load terminal voltage drops to less than the "Operational minimum voltage", the model changes to a constant impedance load.

Fig. 2 illustrates the conceptual diagram of the developed component. As shown, the load is modeled as a controlled current source whose current is calculated based on V, which is the terminal line-to-ground voltage for single-phase loads or the terminal line-to-ground positive sequence voltage for three-phase loads, and P and Q, which are active and reactive power of the load. P and Q are calculated as:

$$P = P_n\left(\frac{V}{V_n}\right)^{NP} + \underbrace{P_nP_{\sin}\sin(2\pi f_P t)}_{*} + \underbrace{P_nS_{rand}Rand}_{**} \tag{3}$$

$$Q = Q_n\left(\frac{V}{V_n}\right)^{NQ} + \underbrace{Q_nQ_{\sin}\sin(2\pi f_Q t)}_{*} + \underbrace{Q_nS_{rand}Rand}_{**} \tag{4}$$

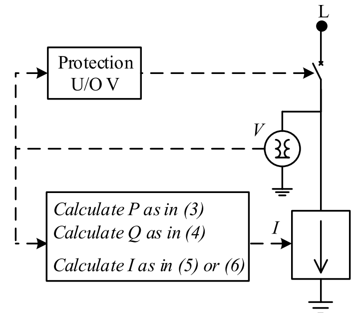

Fig. 2. Conceptual diagram of the developed static load component.

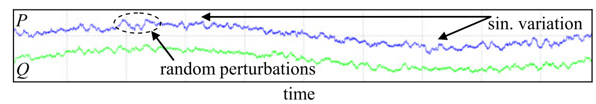

Fig. 3. Static load random perturbations and sinusoidal variation.

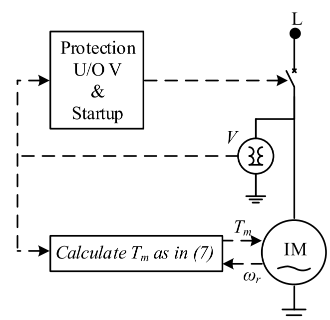

Fig. 4. Conceptual diagram of the developed dynamic load component.

where t is the simulation time. $*$ and $**$ are two additional terms, added to the base power, representing load slow variations and random switchings occurring inside the model (as the model may be an aggregation of small loads), respectively. The impact of these additional terms is depicted in Fig. 3. *Rand* is a function that generates uniformly distributed pseudorandom numbers between 0 and 1. Note that *NP* and *NQ* are both 0 for constant power, 1 for constant current, and 2 for constant impedance loads [6].

The load current, I, is obtained from (5) for single-phase loads and from (6) for three-phase loads.

$$I = (P + jQ)/V^* \tag{5}$$

$$\begin{cases} I_a = (P + jQ)/3/V^* \\ I_b = I_a\, e^{-j2\pi/3} \\ I_c = I_a\, e^{j2\pi/3}. \end{cases} \tag{6}$$

Also, as shown in Fig. 2, an over/under voltage protection scheme is employed for the model which can be adjusted through protection settings. If the load is tripped, it reconnects to the grid provided that the grid voltage remains in the permissible range for at least the "Reconnection time".

2.3. Dynamic load

We refer to "dynamic loads" as loads that have an induction motor. Table 3 lists the input parameters of the developed component. The component has been developed in two versions of single-phase and three-phase. As shown in Fig. 4, the heart of the model is an induction motor whose mechanical load torque is modeled as [7]:

$$T_m = \begin{cases} 0.85 + 0.15\omega_r^4 \text{ p.u.}, & \textit{non-stall condition} \\ 20 \text{ p.u.}, & \textit{stall condition}. \end{cases} \tag{7}$$