Cyber Physical System Modelling of Distribution Power Systems for Dynamic Demand Response

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Abstract. Dynamic demand response (DDR) is a package of control methods to enhance power system security. A CPS modelling and simulation platform for DDR in distribution power systems is presented in this paper. CPS modelling requirements of distribution power systems are analyzed. A coupled CPS modelling platform is built for assessing DDR in the distribution power system, which combines seamlessly modelling tools of physical power networks and cyber communication networks. Simulations results of IEEE 13-node test system demonstrate the effectiveness of the modelling and simulation platform.

1. Introduction
Dynamic demand response (DDR) is a package of control methods to enhance power system security and/or improve operational efficiency through actively modulating power demand, which has gained an increasing attention in the field [1]. The implementation of DDR is of great challenge since the controllable power demand devices are dispersed and very large in number, e.g., hundreds of thousands or even larger for a power system. A key issue to control such large number of devices in a coordinated way is the communication burden [2].

Typical control architectures of DDR can be categorized into centralized, distributed and decentralized ones [1, 2]. For the centralized control, the communication burden is extremely high since each power demand device transfers its working states to the power dispatch center while the dispatch center sends the control commands to the demand devices. The communication burden reduces much for the distributed control considering that data exchanges are limited in the neighborhood of the demand devices. The decentralized control is of the lowest communication burden among all types of control architectures. Nevertheless, an appropriate model for the communication network of the power system is required to depict the information flow of DDR correctly.
A distribution power system plays the role to bridge the transmission power system that is responsible for long-distance and large-capacity power transfer with the electricity end users. Therefore, the interface layer of DDR is in the distribution power system. A cyber-physical system (CPS) model for the distribution power system is necessary to reflect interactions between the information flow and power flow [3]. CPS modelling has gained much more attention in the fields of computer science, control theory, and communication engineering [4, 5].

A CPS modelling and simulation platform for DDR in distribution power systems is presented in this paper. Firstly, CPS modelling requirements of distribution power systems are elaborated. The heterogeneous nature of the ICT architecture of the distribution power system necessitates the CPS model. Secondly, a coupled CPS modelling platform is built for assessing DDR in the distribution power system, which combines seamlessly modelling tools of physical power networks and cyber communication networks. Finally, simulations are conducted on a test system, which demonstrate the effectiveness of the modelling and simulation platform.

2. CPS Modelling Requirements of Distribution Power System

Distribution power systems are undergoing the evolvement from the passive receiving-end power network to the active user-centric power system with multiple types of distributed resources integrated [6]. The conventional data acquisition system for the distribution power system cannot satisfy the information processing requirements of the evolving distribution power systems. Advanced distribution management system (DMS) aims at providing the comprehensive measurement, control, and decision capabilities for the distribution power system [7]. The information and communication (ICT) technology is the core of a DMS.

2.1. ICT Architecture for Distribution Power System

The ICT architecture for a distribution power system is of multiple levels with heterogeneous technologies employed in each level, which is adaptive to the physical structure of the distribution power system. In China, typical voltage levels of a distribution power system include 380 V, 10 kV, 35 kV, and 110 kV. The voltage level of 380 V is the phase to phase voltage grade of residential or commercial users, in which the short-range or medium-range wireless communication technology is a good option to construct a home area network (HAN) or neighborhood area network (NAN). The users are aggregated and connected through 380 V/10 kV transformers to the 10 kV feeder where power line carrier or long-range wireless communication media are available, e.g., WiMAX or cellular networks. The voltage level of 35 kV is suitable for larger industrial users, where a hybrid package of wired or wireless communication technologies can be used. The fiber network is applied to the voltage level of 110 kV and above to ensure the communication quality [8].

The heterogeneous nature of the ICT architecture imposes great challenges to the modelling and management of DMS. It is not viable to assume perfect communication conditions or even neglect the dimension of communication as what the conventional modelling approaches do. The CPS modelling methods are required to depict correctly the impacts of the ICT conditions on the operation of the distribution power system [9].
2.2. CPS Model

The CPS model for the distribution power system should reveal appropriately the coupling mechanism between the physical power network and cyber communication network, which is not simply merging the two parts. Dynamics of the physical power network are usually time-driven whereas it is appropriate to depict the cyber communication network using the event-driven model [10].

Dynamical model of the physical power network can be expressed by using a set of differential equations

$$\frac{dx}{dt} = f(x,u,t)$$

(1)

where $x$ and $u$ are vectors of state variables and input variables, respectively. The above differential equations can be substituted by corresponding difference equations. The occurrence of events in the cyber communication network is stochastic, which is recorded in the list of events along the time axis as shown in figure 1.

![Figure 1. Discrete events in cyber communication network.](image)

A key issue of the CPS model for the distribution power system is the synchronization between the physical power network and the cyber communication network. There are mainly three synchronization approaches including time-stepped, master-slave, and global event-driven approaches [10]. Compared with the other two methods, the global event-driven approach is superior in its performance. The synchronization mechanism of the approach can be explained briefly as follows, which is illustrated in figure 2 [10]. Each time step in the difference equations of the physical power network is treated as a discrete event. Through such conversion, both the physical power network and cyber communication network are event-driven. All events are recorded in the event list in accordance with their occurring time. As shown in figure 2, initially event 1 occurs in the communication network followed by event 2. The jump from event 1 to event 2 is denoted as step 1. The model then traces back to the time instant when event 1 occurs (step 2) and drives dynamics in the power network to the time instant of event 2 (step 3). After the data exchange between the power network and communication network is completed, the model returns to the communication network (step 4) for the subsequent process.

![Figure 2. Synchronization mechanism between physical power network and cyber communication network using global event-driven approach.](image)
3. CPS Modelling for DDR

3.1. Modelling Tools
There are various tools available for modelling and simulation of physical power networks, which include, but are not limited to, PSS/E, PSLF, PowerFactory, Eurostag, and OpenDSS [11]. OpenDSS is a tool more suitable for distribution power systems, which provides versatile modelling functions associated with planning, design, and operation stages of a system. A great advantage of OpenDSS is that it is an open-source tool. Therefore, the modeler can easily add and/or modify components and modules besides the built-in ones. OpenDSS supports a Component Object Model (COM) interface facilitating custom solution modes from an external program, e.g., MATLAB.

The most commonly used tools for modelling and simulation of cyber communication networks are NS-2, NS-3, OPNET, and OMNET++ [10]. NS-2 is preferable considering its several advantages. Firstly, NS-2 is open-source easing further development. Secondly, it supports multiple communication protocols and heterogeneous networks including wired, wireless, and satellite. Thirdly, a good balance can be maintained between modularity and speed since NS-2 is written with C++ and OTcl separately, in which C++ is used for data whereas OTcl is applied to control.

3.2. Coupled CPS Modelling for DDR
A coupled CPS modelling scheme is used in this paper to model appropriately the interactions between the physical power network and the cyber communication network in a distribution power system. OpenDSS and NS-2 are employed respectively in the coupled modelling scheme while MATLAB functions as a bridge between the two tools [12]. The main tasks of MATLAB can be summarized as follows.

Synchronization mechanism: It is through MATLAB to coordinate and synchronize modelling and simulation of the physical power network and the cyber communication network by using OpenDSS and NS-2 respectively.

Data exchange: MATLAB functions as a medium to exchange required data between OpenDSS and NS-2.

DMS emulation: MATLAB emulates DMS in the distribution power system to provide dispatch and control decisions to other entities.

Both of OpenDSS and MATLAB run under the Windows operating system (OS). They communicate with each other via the COM interface. NS-2 does not support the Window OS, for which Cygwin is employed to build the virtual Linux OS. Secure Shell (SSH) protocol and Secure Copy (SCP) protocol are used for data exchanges between NS-2 and MATLAB. The coupled CPS modelling scheme for a distribution power system is illustrated in figure 3 [12].
A coupled CPS modelling platform is built for assessing DDR in the distribution power system. Since controllable power demand devices applied to DDR are dispersed in the system, the impact of the communication environment cannot be neglected. The amount of aggregated DDR in the system is computed by OpenDSS, which is \( \Delta P(t_0) \) and \( \Delta Q(t_0) \) (representing active power and reactive power response, respectively) given the system states as \( X(t_0) \) at time \( t_0 \). If it is in a perfect communication environment, the available provision of DDR will be \( \Delta P(t_0) \) and \( \Delta Q(t_0) \). Nevertheless, the real imperfect communication conditions will cause time delay, bit error and packet loss, which are estimated by NS-2. The symbol \( \Delta t_{ICT} \) represents the time delay weighing data transfer through the communication network and the symbols of \( \alpha \) and \( \beta \) denote metrics for bit error and packet loss. The decision process of DMS will produce time delay denoted as \( \Delta t_{DMS} \), which is mimicked by MATLAB. Consequently, the available provision of DDR will be \( \alpha \Delta P(t_0+\Delta t_{DMS}+\Delta t_{ICT}) \) and \( \beta \Delta Q(t_0+\Delta t_{DMS}+\Delta t_{ICT}) \).

### 4. Simulation Results

#### 4.1. Test System
IEEE 13-node distribution power system is used as the test system [13], which is shown in figure 4. Node 1 is the root node of the distribution power system, which is the connection point to the upstream power system. Controllable power demand devices applied to DDR are air-conditioners, which are assumed to be aggregated at Node 670. The number of air-conditioners is 2000 and the aggregated active power \( \Delta P \) is 1000 kW with reactive power omitted, i.e., \( \Delta Q = 0 \).
4.2. Impact of Communication Conditions on DDR

Communication conditions for the test system can be measured by the data transmission rate of each corresponding communication line. Assuming that there are two DDR vendors providing aggregated DDR at Node 670, which are named as 6701 and 6702, respectively. As shown in figure 5, data transmission rates of communication lines 6701-670, 6702-670, and 670-1 are limited and time variant, which reflects real imperfect conditions of the communication network.

![Figure 5. Data transmission rates of communication lines.](image)

Assuming that the activation time instant of DDR is 5 s, the voltage value of node 670 will increase after that instant with the release of partial load demand, which simulates a typical scenario that stressed operating states of the distribution power system can be relieved via DDR. Nevertheless, imperfect conditions of the communication network will discount the effect of DDR. As illustrated in figure 6, the response of node 670 will be postponed accounting for the time delay in in the communication network.

![Figure 6. Voltage dynamics of node 670 with communication delay.](image)

5. Conclusion

DDR is a set of control approaches to enhance power system security and/or improve operational efficiency through actively modulating load demand. In this paper, a CPS
modelling and simulation platform is built for DDR in distribution power systems. Firstly, CPS modelling requirements of distribution power systems are analyzed. A coupled CPS modelling platform is then constructed for assessing DDR in the distribution power system, which combines modelling tools of physical power networks and cyber communication networks. Simulations results of IEEE 13-node test system demonstrate the effectiveness of the modelling and simulation platform.

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7. References
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