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Research on Cyber-Physical Modeling for Smart Distribution Grid

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Abstract

Smart distribution network will achieve the optimal operation of the distribution network, provide high-quality and reliable power, guarantee the development of modern social economy. The deep integration of cyber system and power physical system is the key to smart distribution network. The emergence of cyber-physical system (CPS) provides a new way to solve this problem, the cyber-physical model for smart distribution grid becomes an urgent problem to be solved. In this paper, the content and method of cyber-physical model for smart distribution grid are analyzed by combining with the coupling of information flow and power flow of smart distribution network from the perspective of cyber-physical model. At last, taking 110 kV typical substation as an example, the coupling mechanism and function of power flow and information flow is studied.

Keywords

Smart Distribution Network, Smart Substation, Cyber-Physical Modeling

1. Introduction

With the improvement of intelligent, digital and informational degree for distribution network and the introduction of concept of micro-grid and distributed generation, smart distribution network has become a new trend in the future development of power grids [1]. Smart distribution network is an extremely large and complex system with a large number of advanced sensing devices and distributed intelligent terminal equipment, such as FTU, TTU and other information equipment, which makes the smart distribution network show typical characteristics of cyber-physical system and form a new cyber physical model for smart distribution grid. A set of scientific, reasonable and comprehensive cyber-physical model for smart distribution grid provides theoretical and technical support for the realization of status assessment, fault diagnosis and prediction, reliability analysis and other fields of smart distribution network.

As the number of sensors and the size of information network in smart distribution network increase constantly, the impact of cyber system on the power grid is more prominent. On August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. An important reason was that the state estimation function was withdrawn; dispatchers lost their ability to perceive the real-time status of the power grid and failed to discover, assess and curb the spread of the fault. In 2001, El Paso Power Company from the United States had an electric power blackout; the cause was also protection malfunction due to abnormal communication delay. The company cut off a 345 kV line eventually [2]. Therefore, it is the most critical and urgent to study the unified modeling of the power physical system and its cyber system.

2. Analysis of Cyber-Physical Model for Smart Distribution Grid

With the advance of smart grid, the available information resources and communication condition have undergone fundamental changes, the system structure is becoming more complex, and the network transmission of information brings challenges to fault identification, rationality and completeness of configuration, the fault type and operation of the power grid. Information flow becomes an indispensable link in the closed-loop chain of power flow. In this context, the coupling of power flow and information flow present the following characteristics: 1) the power flow is more closely coupled with the information flow, so that physical system and cyber system has become deeply integrated. 2) The dynamic process of the distribution network system is more complicated, and the requirement for real-time control is higher.

So, the cyber-physical model is a hot spot of many scholars, scholars have made some achievements according to the heterogeneity of system, time behavior of cyber system, cyber model and so on [3] [4]. However, due to the heterogeneity of physical system and cyber system, the modeling of the physical layer and cyber layer is fragmented, and building a fusion model is very difficult. The method of hybrid system modeling is adopted in reference [5], which embodies the characteristics of cyber-physical system, but it cannot fully reflect the fusion of physical system and cyber system. So far there is no unified modeling method of cyber-physical system. Reference [6] gives a preliminary model framework of the cyber-physical system for power grid, which has some guiding significance for the development of power CPS model. In this section, the method and content of cyber-physical model are described in detail.

2.1. Content of Cyber-Physical Model

In cyber-physical system, the physical system is a continuous system and has a set of mature and complete quantitative analysis method of power modeling and simulation by employing calculus. The cyber system is a discrete system, and has a complete quantitative analysis method of information flow modeling and simulation through the event-driven mechanism of the finite state machine, such as OPNET (Optimized Network Engineering Tools). OPNET is a network simulation technology software package. It can accurately analyze the performance and behavior of complex network and can be inserted into standard or user-specified probe to collect data anywhere in the network model. The simulation data obtained through the probe can be displayed by graphics, data, or a third-party software package. However, the analysis method of power flow does not conform to the model of information flow and vice versa.

So, we propose to establish the coupling model in information flow simulation software to solve the quantitative analysis of cyber-physical model for smart distribution network. The content of cyber-physical model includes three parts:

1) Modeling of physical devices: In cyber-physical system, IED (Intelligent Electronic Device) is the carrier of power system operation. The IED consists of one or more processors. It can receive and transmit data from an external source or control an external source, and can also perform one or more logical contact tasks within the specified range of interfaces [7].

2) Modeling of information flow: At present, the operation function of distribution network system is based on information flow which includes three types: SV (Sampled Value), GOOSE (Generic Object Oriented Substation Event) and MMS (Manufacture Message Specification). The SV is a communication service for real-time transmission of digital sampling information, including voltage and current sampled value [8]. The GOOSE is an object-oriented substation event, mainly used to achieve real-time information interaction between intelligent electronic equipment [9], including switch position information, trip signal, blocking signal, etc. MMS message belongs to the information flow between compartment and station level. The MMS network is the bridge between compartment and station level, including the calling and modification of relay protection setting value [10]. The normal and fault conditions' information flow in power system shows different dynamic characteristics, such as transmission law, which may lead to network fault or network blocking.

3) Modeling of communication protocol: The mode of information transmission has become digital and grown more networked, so power system has formulated a series of communication protocols and standards, these communication protocols and standards establish the communication rules and processes of modern power system, but the simulation platform of cyber system does not have the corresponding protocol model. Therefore, the communication protocol model based on smart distribution network system can accurately and completely describe the dynamic process of the cyber-physical system.

2.2. Method of Cyber-Physical Model for Distribution Network

In the smart distribution network system, the cyber system is a huge system with mass components and complex communication protocol, building a model directly is not only very complex, but also significantly affects the operational efficiency [11]. Therefore, in this research, we abstract the state quantity of physical system and cyber system as "data node", and abstract information processing and information transmission as "information branch", its first and end node are separately input and output data, and the branch characteristic equation is the mapping operator between input and output. For unified modeling, we divide the information module into two major categories in the research: information transmission module and information processing module. These two modules are not independent, but are closely coupled through the exchange of information. In the control system, the data output of some modules will be collected into a total information pool, which will be the data source for other modules. This module is defined as the "information bus" module. The above three modules (information transmission, information processing, information bus) can be modeled as mapping from input to output information. The modeling diagram is shown in **Figure 1**.

3. Example of Cyber-Physical Model for Smart Distribution Grid

In this paper, the equipment model and information flow model of smart distribution network are constructed based on the OPNET simulation platform, which reflect the dynamic operating characteristics of the system. This paper also analyzes the dynamic characteristics of information flow of relay protection IED and switch.

3.1. Model of Smart Substation

1) Modeling of merging unit: For the merging unit, the function module is abstracted into several logical nodes: the data source node generates the SV, its output queue is initialized, and the SV is processed according to the priority

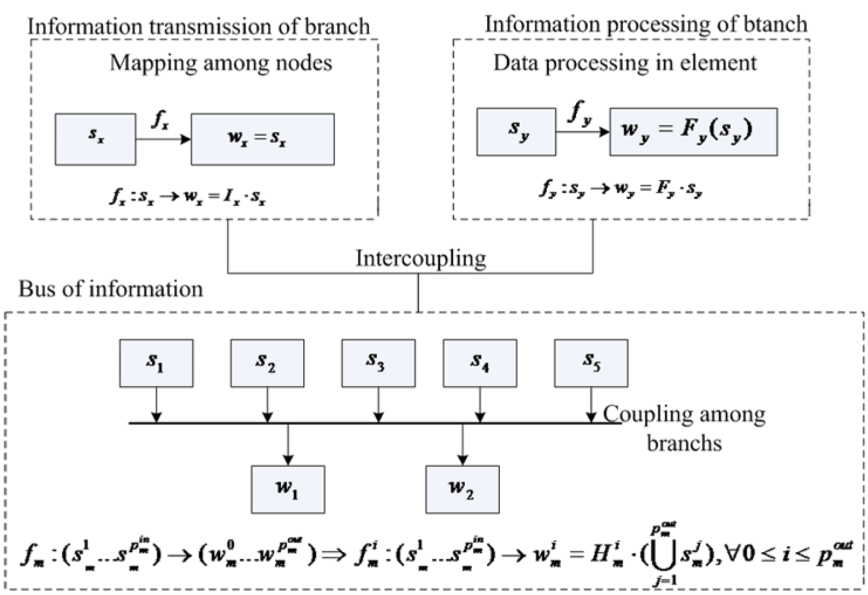

Figure 1. Modeling method of information branch.

level. The interface node completes the mapping of the SV from the application layer to the data link layer. The data link node sends SV to the transmitter, the receiver sends SV to data link node. The data link node completes the mapping of SV from data link layer to application layer. The merging unit model of smart substation is shown in **Figure 2**.

2) Modeling of IED: Taking the relay protective IED as an example, the protective IED is similar to the merging unit in message header, protocol resolution and data transmission, but the application layer is different. The state transition of application layer is shown in **Figure 3**. The application layer of protective IED

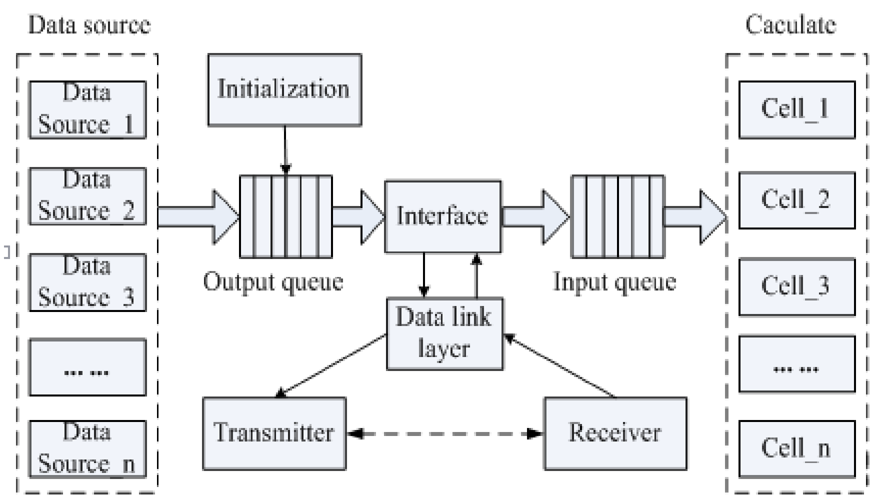

Figure 2. Merging unit model of smart substation.

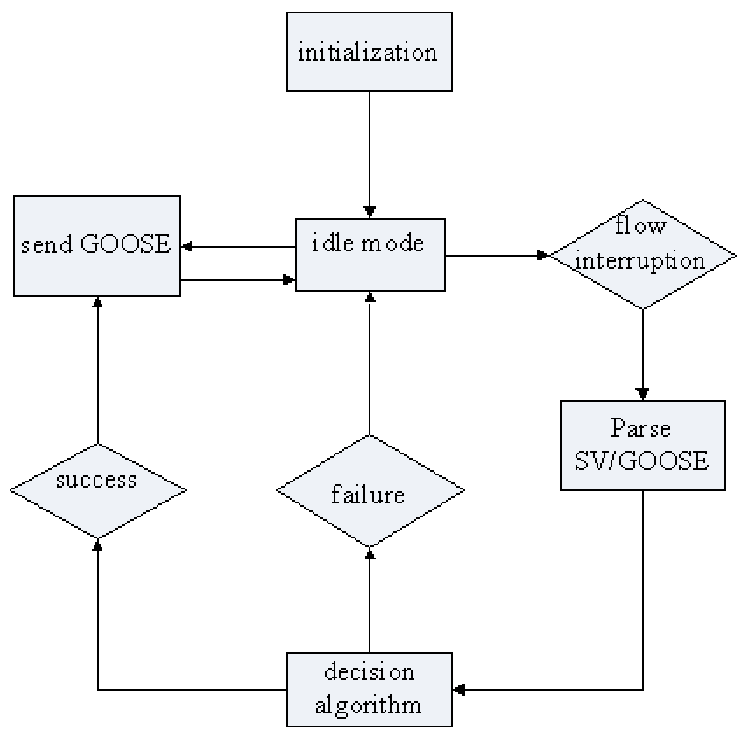

Figure 3. State transition of the application layer.

devices is initialized and then skips to idle state. SV messages are uploaded to the application layer through protocol parsing of physical and data link layer, which generates corresponding flow interruption, the status is transferred to parsing stage of SV, then takes out the relevant fields by protection algorithm from data packet, and the logic decision of protection action by combining the latest COOSE.

3.2. Assessment Method of Line Fault

The vulnerability of power system can be evaluated by N-1 method, which scan all possible line faults and analyze system's each response. In cyber system, information failure may cause the system to generate improper control instructions, thereby affecting physical system.

Therefore, based on its influence on information network, information failure can be divided into two types: topology fault and line fault. There are four kinds of line fault in power system: transmission error, transmission delay, and transmission interrupt and transmission dislocation. Transmission delay is one of the most common faults in the actual site. As the name suggests, the failure causes a delay in the transmission of some data. For the information transmission branch f_x, if the transmission of data s_x occurs the delay of Δt, mapping operator of the branch mapping model increases by Δt.

3.3. Simulation Example

In this paper, the example is based on 110 kV communication network of a practical 110 kV smart substation. Building the exchange model of total net transmission scenario based on OPNET platform, this paper analyzes the action response of relay protection in line fault. The network topology is shown in **Figure 4**.

Referring to the previous section, the simulation mainly makes statistical analysis of the transmission delay of typical objects, such as **Table 1**.

When the line fault occurs, the maximum amplitude of the SV transmission delay reaches 80 s, although the transmission delay of SV is increased by different amplitudes compared with the steady state, but still in the message standard

Table 1. Line fault simulation results of 110 kV smart substation.

Data flow		Delay of SV (μs)	Delay of GOOSE (μs)
Source node	Destination node		
Line merging unit	Line protection	53.37 - 58.965	13.91 - 92.04
Line merging unit	Bus protection	198.3 - 230.695	13.91 - 92.04
GSU merging unit	GSU protection	51.32 - 55.352	13.91 - 92.04
GSU merging unit	Bus protection	256. - 278.936	13.91 - 92.04
Bus merging unit	Bus protection	84.0 - 152.362	13.91 - 92.04
Bus protection	Line smart operation box	/	13.91 - 92.04
Bus protection	GSU smart operation box	/	13.91 - 92.04

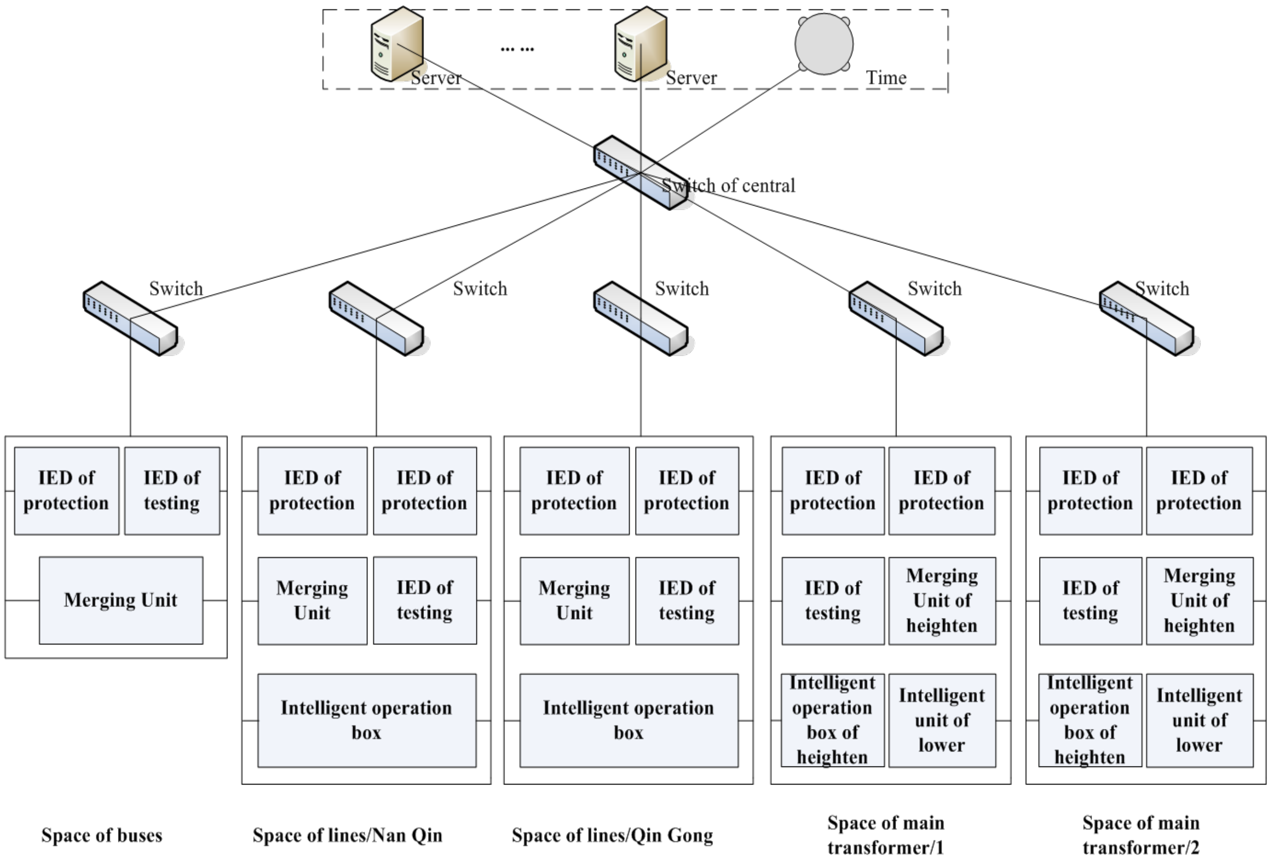

Figure 4. Topology of 110 kV communication network.

transmission delay. This is because the priority of GOOSE is higher than the SV. In the case of total net, the bandwidth is occupied, making the queue delay of SV in the switch increased.

4. Conclusion

The coupling and the interaction of power flow and information flow has become increasingly closely and important. Its emergency opens a new idea for the cyber-physical model for smart distribution grid. The cyber-physical model for smart distribution grid is a new research field; there are a lot of theoretical and technical problems to be solved. Through the analysis of coupling property of information flow and power flow, this paper introduces the content and method of cyber-physical model for smart distribution grid. Taking 110 kV typical substation as an example, we study the coupling mechanism and function of power flow and information flow, which provides guidance for cyber-physical model for smart distribution grid.

Acknowledgements

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References

[1] Zhuang W. and Mu L.H. (2012) Study on Cyber-Physical Relaying Protection System of Intelligent Distribution Network. *Power System Protection and Control*,**40**, 113-118.

[2] Guo, Q.L., Xin, S.J. and Sun, H.B. (2016) Power System Cyber-Physical Modelling and Security Assessment: Motivation and Ideas. *Proceedings of the CSEE*, **36**, 1481-1489.

[3] Yan J.M., Xu J.B. and Ni, M. (2016) Impact of Communication System Interruption on Power System Wide Area Protection and Control System. *Automation of Electric Power Systems*, **40**, 17-24.

[4] Yu, W.J., Xue, Y.S. and Luo, J.B. (2016)An UHV Grid Security and Stability Defense System: Considering The Risk of Power System Communication. *IEEE Transactions on Smart Grid*,**7**, 491-500. https://doi.org/10.1109/TSG.2015.2392100

[5] Susuki, Y., Koo, T.J. and Ebina, H. (2016) A Hybrid System Approach to the Analysis and Design of Power Grid Dynamic Performance. *Proceedings of the IEEE*, **100**, 225-239.

[6] Zhao, J.H., Wen F.S.andXue, Y.S. (2010) Cyber Physical Power Systems: Architecture, Implementation Techniques and Challenges. *Automation of Electric Power Systems*, **34**, 1-7.

[7] Zhang, H.D., Chen, A.L. and Ni, Y.M. (2016) Modeling and Simulation of Relay Protection for Intelligent Substation Based on OPNET. *Electric Power Automation Equipment*, **33**, 144-149.

[8] Zhang, Y.X., Cai, Z.X. and Long, P.P. (2016) Real-time Fault Diagnosing Models And Method for Communication Network in Smart Substation. *Power System Technology*, **40**, 1851-1857.

[9] Duan, J.Q. and Duan,B. (2007) Real-time Processing of GOOSE Message in Substation. *Automation of Electric Power Systems*, **31**, 65-69.

[10] Xiao, Y. (2015) Design of information Flow Scheme for New Smart Substation. *Proceedings of the IEEE*, **35**,1-7.

[11] He R.W., Wang, D., Zhang, Y.X., Cai, Z.J., He, X.W. and Chen, Y.H. (2016) Modeling and Static Calculation Method of the Information Flow on Smart Grid. *Proceedings of the IEEE*, **36**,1527-1535.