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# Cyber–physical interactions in power systems: A review of models, methods, and applications

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ABSTRACT

Owing to the advanced metering infrastructure and communication networks, modern power systems have gradually evolved into multidimensional heterogeneous cyber–physical power systems (CPPSs) with continuous coupling interactions between cyber systems and power systems. The rapid development of the cyber infrastructure is leading to a new era of high-level intelligence revolution; however, currently, CPPSs face newly emerging problems such as stability, vulnerability, reliability, and security. Exploring and resolving the nature of these problems while formulating corresponding solutions will depend on the modeling methods and investigation of interaction mechanisms in CPPSs. Accordingly, this study aims to systematically summarize the interaction models and corresponding solution methods in the current CPPS research. First, the interactive features of CPPSs are discussed, and their modeling mechanisms are elaborately reviewed and summarized from the viewpoints of graphic, mechanism, probability, and simulation. In particular, the applicability and characteristics of these models pertinent to specific research issues are discussed technically. Next, the crucial problem-solving strategies are analyzed and concluded comprehensively. Finally, the cutting-edge CPPS research in China is discussed, and the potential research directions in this field are highlighted.

## 1. Introduction

Exploiting the large-scale sensing measurement systems and more complicated information communication networks, power systems can optimize their operations continually to ensure a safe, stable, and reliable power supply. With the continuous development of power systems, the scale of cyber networks has increased enormously, accompanied by emergence of a large number of intelligent electronic devices (IEDs) deployed in power systems. Meanwhile, the promotion of energy internet (EI) enables increasing external information to influence the control and decision of power systems directly or indirectly through various business channels. In this situation, modern power systems are no longer power infrastructure networks in the conventional sense. Instead, they have gradually evolved into multidimensional heterogeneous complex cyber–physical power systems (CPPSs) coupled by the interaction between cyber networks and power systems.

The powerful functions of cyber systems in CPPSs provide significant technical support for the observability and controllability of power systems. However, the strong coupling of cyber–physical systems makes the performance of cyber systems significantly affect the operating characteristics of physical power systems. Incorporating electrical power infrastructure, information communication technology and computational intelligence, the CPPSs covers all the key domains in power systems including electricity generation, electric power transmission, electric power transformation, electric power distribution, electric power consumption and electricity selling, as shown in Fig. 1. Meanwhile, there are three tiers of CPPS structure considering the information transfer, namely component tier, communication tier and function tier. These aforementioned tiers are abstracted to tier 1, tier 2 and tier 3 respectively as shown in Fig. 1. The tier 1 mainly consists of primary equipment (i.e. generator, transformer, transmission line, circuit breaker, etc.), secondary equipment (i.e. protection relay, sensor, actuator, etc.), and electric appliances, which are all interconnected in a specific topology. The secondary sensor devices would gather the operational information from primary equipment and transmit this information to local controllers, such as local feeder automation controller. This controller may send certain control instruction to actuators that would affect primary equipment for the purpose of optimization or protection. This process forms the first level of interaction in CPPSs. For example, the local feeder automation system, located in the electric power distribution domain shown in Fig. 1, utilizes remoter terminal units to monitor the distribution lines and isolate fault areas that may minimize outage duration. In Ref. [1], authors have investigated how time delay of transmitting measurement data of generators affect the

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**Nomenclature**

| | |
|---|---|
| AGC | Automatic generation control |
| AM | Analytical model |
| AMI | Advanced metering infrastructure |
| CN | Complex network |
| CPN | Colored Petri net |
| CPPS | Cyber–physical power system |
| CT | Communication terminal |
| DA | Distribution automation |
| DER | Distributed energy resource |
| DMS | Distribution management system |
| DR | Demand response |
| DST | Dynamic system theory |
| EI | Energy internet |
| EMS | Energy management system |
| EV | Electric vehicle |
| FDI | False data injection |
| FSM | Finite state machine |
| GM | Game-theoretic model |
| GT | Graph theory |
| HS | Hybrid system |
| IED | Intelligent electronic device |
| LP | Linear programming |
| LQR | linear quadratic regulator |
| MAS | Multi-agent system |
| MC | Markov chain |
| MCS | Monte Carlo simulation |
| MDP | Markov decision process |
| NA | Network attack |
| OM | Other model |
| PDF | Probability density function |
| PMU | Phasor measurement unit |
| PN | Petri net |
| P-Table | Probability table |
| SA | Substation automation |
| SCADA | Supervisory control and data acquisition |
| SCD | State chart diagram |
| SCPN | Stochastic colored Petri net |
| SE | State estimation |
| SMP | Semi-Markov process |
| SPN | Stochastic Petri net |
| UM | Uncertainty model |
| VSS | Variable structure system |
| ZOH | Zero order hold |

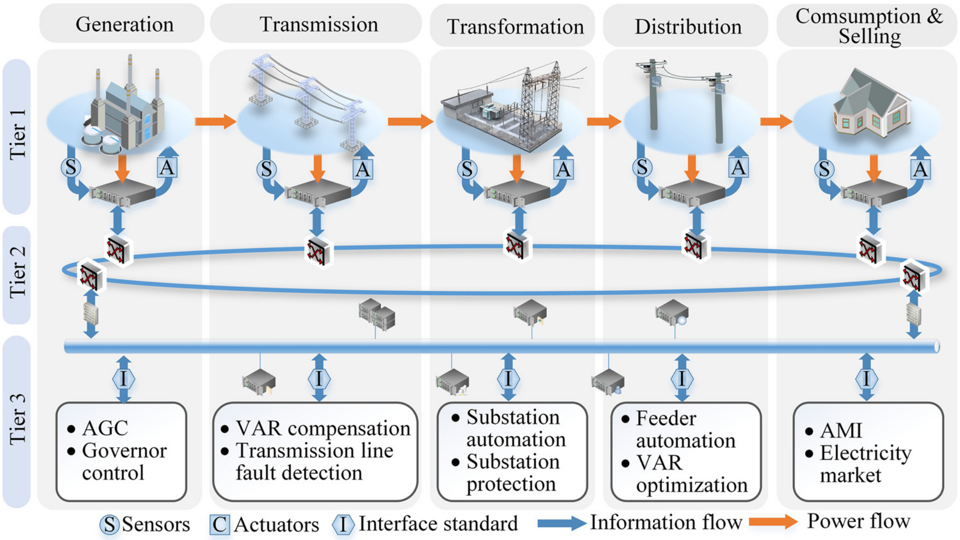

**Fig. 1.** Structure of CPPSs.

stability of CPPSs. The cascading failure mechanism between cyber system and physical system in the transmission domain is analyzed in Ref. [2]. In Refs. [3,4], the impacts of IED failures and merging unit failures within the substation from the transformation domain on the reliability of composite CPPSs are analyzed.

In the meantime, the acquired information in tier 1 would be transmitted to dispatch master station (or control center) through the communication network in tier 2. Communication architecture that keeps coordination among all components of power systems has always played a crucial role in CPPSs. The commutation technologies (i.e. IEEE 802 series, power line communication, mobile communications, etc.), network traffic, routing mechanism, communication topology would affect communication efficiency and effectiveness, and have further impacts on power systems. This can be considered as the second level of interaction in CPPSs. The authors in Ref. [5] have presented how communication latency jeopardizes the stability of CPPSs in transmission domain. In Ref. [6], the impacts of network traffic between distributed phasor data concentrators on the convergence and accuracy properties of wide-area oscillation monitoring method are investigated.

Finally, all the operational information would be stored and processed in the control center in tier 3. The tier 3 can realize various advanced functions and operational decision-making. There can be multiple stations, and accordingly these stations are interconnected through different topologies. The main elements of master station are web server, communication server, application server, database and human machine interface. Allowing for easier information exchange and interoperability of advanced functions, the information models of each function are integrated into the information bus through the international interface standards. Thus, the calculation and analysis of these functions through the elements of master station can be considered as the third level of interaction in CPPSs. Taking the feeder automation function for example, the integrated feeder automation strategy would implement the optimal instructions that could minimize outage duration and number of switching operations simultaneously. Accordingly, these instructions would be sent to the circuit breakers in tier 1. Obviously, the errors in information modelling, interface for