**A Cyber–Physical Systems Perspective on Smart Grids**

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**ABSTRACT**

Cyber physical system is a type of system that combines computation, networking, and physical processes in a single system. The CPS technique to system design has been widely applied in numerous sectors, but it is relatively new in the design of power systems. The special characteristics of CPS are projected to considerably improve future smart power networks. Smart grids are electric networks that use modern control, monitoring and communication technologies to ensure a continuous and stable power supply. Smart Grid technology will transform modern industry by offering significant solutions for improving the efficiency of traditional electric grids. It improves generator and distributor operation efficiency and provides prosumers with a variety of options. Smart grids are a hybrid of complicated physical network systems and cyber systems that face a number of technological difficulties. This chapter outlines these issues in the context of cyber–physical systems along with possible contributions of cyber–physical systems to smart grids, as well as the problems that smart grids provide to cyber–physical systems. Finally, the impact of recent advanced technologies on smart grids is discussed.

**KEYWORDS:** Smart Grids, Cyber–Physical Systems, Renewable Energy, Big Data, Cloud Computing, Cyber Security, Distributed Optimization.

**I. INTRODUCTION**

The demand for electricity is continuously increased in recent years due to increase in population which, results in more complex power system. These problems necessitate a considerable upgrade in power system design and operation. Researchers have proposed a cyber-physical systems (CPS) approach to power system design to overcome these problems. The CPS refers to a system that presents close integration between cyber system and physical components. In present days, because of environmental concerns and limited availability of nonrenewable energy sources like coal, gas, and oil, there has been an increase in demand for cleaner energy production and more efficient energy consumption [1].

The Renewable energy (RE) sources including hydro, biomass, solar and wind are available in large quantity, but they are far more difficult to harvest. To make these energy supply more reliable and secure, advanced technologies are required. Throughout the world many governments are giving incentives and using new energy polices to motivate the people to use more renewable energy sources for energy generation using new technologies.

The existing power grid will be reconstructed as a cyber-physical system with smart devices that will communicate data for advanced monitoring and control applications in addition to carrying power. Up gradation of the power system by two-way flows of electricity and information is expected to form smart grids along with intelligent features such as self-healing, adaptive protection and control along with customer involvement [2].

The Smart Grid technology updates the modern industries with powerful solutions that is more efficient, effective, economical, and environmental friendly. The Smart Grid is a digital communications-based energy distribution network. The goal of a smart grid is to smartly integrate the behaviors and action of all stakeholders in the energy supply chain in order to efficiently offer sustainable, profitable, and secure electric energy.

The success of SGs depends on the exact integration and interaction of the power system infrastructure as the physical systems as well as data sensing, processing and control as the cyber systems. The new technology called cyber physical system is used, to address the particular integration and interaction problems in SGs, which maintains efficient interaction between physical systems and cyber systems [3].

Implementing CPS technologies in SGs will improve operational efficiency, responsiveness to prosumers, economic viability, and environmental sustainability. Moreover, the unique properties of SGs will create new challenges for CPS development.

**II. SMART GRIDS**

Smart Grids aren't something that just happened. They emerged from a desire to upgrade the electricity system, make it more environmentally friendly, and enhance power distribution. Utility companies may utilize existing infrastructure and reduce the demand for new power plants and substations since Smart Grids are more autonomous and improve the effectiveness and efficacy of electricity supply. The Smart Grid with the incorporation of modern technologies such as communication and advance computing power is estimated to provide enrichment in efficiency, reliability, and availability [4].Additionally, the Smart Grid provides infrastructure which is integrated with two-way communication and power flows. A Smart Grid uses innovative products and services along with intelligent communication, monitoring, control and self-healing technologies. Smart grid provides properly planned power to a network of smart devices, transformer and machines. To achieve this it uses two way communications. The Smart Grid gives faster and better services for the customers, with a less time delay. The SG structure is shown in Fig. 1, which includes many stakeholders and consumers in the highly complex and large-scale system [5].



**Figure. 1. Smart Grid Structure**

The main function of SGs is to operate and control the entire power system with all smart devices with bidirectional power flows. To achieve greater flexibility, reliability, safety, and security of energy supply and usage through SGs requires better interaction between the power networks, the cyber systems, and consumers. Better support and interaction between physical systems and cyber systems are required [6].

The SG should provide solutions to the some of the technical challenges like intermittency Power generation from of RE sources which affects power quality and introduction of distributed generation at different levels which affects the stability of the system.

Smart Grids' Major Challenges are

* Ensuring adequate transmission capacity to connect energy sources, particularly renewable, thereby improving grid strength.
* Constructing the communications infrastructure that will allow millions of parties to trade and function in the single market.
* Allowing smaller-scale energy supply systems to operate with the larger grid.
* Allowing all consumers to participate actively in the system's operation.
* Use of Advanced energy storage technology in the system.
* Minimize the overall environmental impact of the energy delivery system.

**III. CYBER–PHYSICAL SYSTEMS**

The CPS is made up of a physical system that is tightly connected with cyber systems (control, processing, and communication) and permits the two-way electricity and information flows, for implementation of smart grid technologies. CPS is now paying more attention to many sectors, including agriculture, medicine, energy, the oil and gas industry, and transportation. The CPS is characterized as a heterogeneous multi-dimensional system with an integrated cyber component (control, computation, and communication) that aims for stability, robustness, efficiency, and consistency in physical systems applications [7].

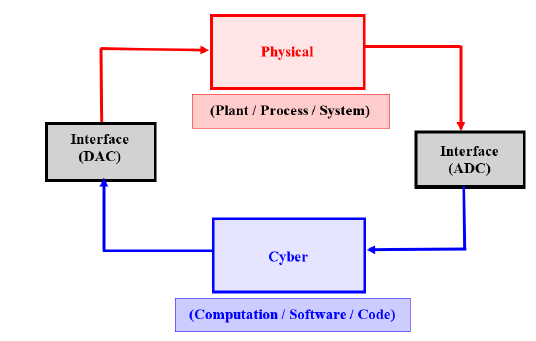
As shown in Fig. 2, the cyber system gathers information from physical system through the sensor and feeds back the control signal to the physical system in order to achieve the common goals. It is required to interface the physical power system with a cyber system in order to ensure the effective and secure operation of the power system. To evaluate, coordinate, and control physical power system actions, CPS depends on embedded computers and networks.

In the construction of CPSs, the strong interaction between cyber and physical components poses big challenges. CPSs consist of computing devices, interfaces, distributed sensors and actuators. In addition, the need for rapid, high-precision communication and coordination between cyber and physical system needs an effective design strategy.

To provide interconnection, cyber-world events and decisions must be conveyed to the physical world and vice versa. As a result, various difficulties must be addressed in order for widespread adoption of cyber-physical systems to become a reality. This highlights the need of studying and comprehending CPSs.The CPS faces some of the major technological challenges while integrating cyber and physical system, one of the challenges is Architecture and design issues. Infrastructure architecture and design are important for enabling seamless integration of control, communication, and processing for efficient design and deployment of CPSs.

Infrastructure architecture and design are important for enabling correct integration of control, communication, and processing for efficient design and deployment of CPSs. In addition, design methodologies and tools are required to support system specifications, compatibility, hybrid and heterogeneous models, as well as modeling and analysis.

Cyber security is an important issue for CPS, with the close integration of cyber systems and physical network, where the processes and methods for computing devices like smart meters, computers, smart phones and computer network are necessary, thus necessitating protection from illegal access and modification. To assure data confidentiality, safety, and availability, along with asset and human protection, new architectures and approaches are required. The, one more challenge that is faced by CPS includes Information science and engineering. Collection of information, processing and control must be given quickly and in real time for correct communication between cyber and physical systems [8].

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**Figure .2. Cyber Physical System**

Starting from generator to distributer many stakeholders, are involved in the interconnected network. The rising complexity and interconnections of components like smart meters, solar panels, and wind turbines, as well as their total numbers, necessitate a reconsideration of how to examine and design the SG's CPS features [9].

We shall explore the developments in SG from a CPS perspective in the following sections.

Today, we're seeing a number of technology trends that could have a big impact on how we design and deploy solutions for cyber-physical infrastructures like the Smart Grid. Because the power grid is a key infrastructure, rapid high-quality data collecting, context assessment, decision-making, and execution must be open, simplified, and consistent. Taking into account of its complication and dynamic interactions, modeling the Smart Grid and evaluating the large amount of information produced by the heterogeneous CPS dominated infrastructure, is a very difficult task.

The progress and problems in a few major broad dimensions will be discussed in the following sections.

**A. Design and Architecture**

Structural designs are concerned with how to build the primary CPS infrastructure and establish design techniques based on CPS principles in order for the CPS to operate smoothly. In the below, section will explain the some of the most important parts of them.

The physical architecture of electricity network systems necessitates a higher level of safety and reliability than general-purpose computer infrastructure. In addition, their physical properties distinguish them from object-oriented software components.

In order to obtain smooth integration of control, communication, and calculation for fast design and operation of CPSs in SGs.There should be CPS architectures that are specifically designed for interfaces between power networks and cyber systems, allowing diversified (dynamic) systems to talk to each other in a timely fashion and work together as a team in uncertain and uncontrollable environments.CPS requires a single standard structure under which Physical systems, communication procedure, computation languages, and software and hardware interfaces are all subject to standards in their own disciplines, can function together.

An integrated modeling approach is required for the CPS to operate effortlessly in SGs, allowing the physical components of the system (power system models) and the cyber system components (communication networks and sensing models) to be united under one structure and an overall control strategy to be developed [10].

**B. Information and Communication Technology**

For efficient and successful interaction between physical and cyber systems, Information andcommunication technologies are essential. When developing SG-tailored communication skills at various levels, such as home area network, community area network, metropolitan area network, and wide area network, two basic aspects of communication, namely space and time, must be considered, referring to the communication distance and time taken for information transportation. This includes determining the tasks and putting in place the appropriate standards for future Smart Grid ICT solutions. The ICT application is required in data exchange between market parties in the electrical supply chain, as well as the secure, cost-effective, and environmentally friendly operation of Smart Grids.

Important components and key aspects are:

* Monitoring, management, control, and dispatching services at all levels up to distribution and customers require a simple, strong, secure, and flexible communications network.
* To achieve consistent database management, common information and data models for all information building blocks must be created at all levels of the power system.
* Better functioning of ICT solutions are necessary to guarantee supply security and effective market interaction.

**C. Modeling and simulation technology**

Modeling of CPS is the basic requirement for the design and analysis. To ensure that, the large-scale network CPSs of SGs can operate smoothly and components can communicate with one another, compatibility, composite and heterogeneous modeling and simulation tools are required to support system and network specifications.

New developments in power consumption reduction and excess capacity savings, such as cost-effective and efficient management of massive electricity storage, multi-dc transmission and major ac/dc mixed-mode power networks, and a extensive range of power electronic equipment applications, necessitate effective operation and control, necessitating a new integrated modeling and simulation atmosphere capable of handling large network for modeling and simulation.

**D. Security risks**

Because of the different communications design of smart grids, designing complex and resilient security measures that can be easily implemented to safeguard communications between different levels of the smart grid infrastructure is extremely difficult. The traditional electrical power grid is in the process of becoming a smart grid. The traditional electrical power grid is combined with information and communication technology (ICT) in a smart grid. Customers and electrical utility suppliers can work together to get better efficiency and availability of the power system by constantly monitoring, controlling, and managing consumer needs [11].

The smart grid system must contain many key security objectives:

* **Adjustable to changes:** Dealing with changes in smart grids isn't easier, but it is difficult. Although smart grids are more complex and involve more people, they struggle to adapt to changes. Change management is therefore a must for healthy smart grids.
* **Two-Way Communication**: Because of the Advanced Metering Infrastructure (AMI), a smart grid has two-way communication. Unlike the electrical grid, AMI enables smart meters to communicate with utility firms located near consumers' homes, making them more accessible to physical attackers. In smart grids, which are having more gadgets than earlier, keeping these devices safe has become more complex.
* **Control Mechanisms:** Smart Grids must have effective access control measures because they have a broad reach and a large number of investors. It's critical to monitor and regulate all possible access to the smart grid's network.
* **Privacy maintenance:** People are concerned about how their personal information will be used. This has becoming a major issue for people as smart grids become widely available. Not only should customer data be encrypted, but anonymization measures should also be suggested to prevent attackers from deriving patterns or encrypted data to disclose private information. This is referred to as "anonymization." As a result, we must ensure that the systems we develop can both secure and collect data safely.
* **Complete Security:** In smart grids, it's beneficial to have a high level of security. It's poor at lower levels. As a result, the level of security that needs to be implemented at each level may differ. In order to accomplish this, many research groups need to develop lightweight solutions. Encryption is also important at all levels of the smart grid to keep data confidential and secure.

**E. Active Distribution Networks**

Transmission networks have always played a balancing and management functions in the electric supply chain, whereas distribution networks are supposed to be inactive. The issue now is to provide many of the services present in transmission grids in distribution networks, such as power flow and constraint monitoring, contingency analysis, and balancing .This is necessary not only because of the growing use of distributed generation, but also because of the rising intelligent building services in both residential and commercial buildings, the need to use local generation to support the local system during times of pressure on the main grid, and the expected widespread adoption of electric transportation vehicles in the future.

The important features of Active distribution systems are:

* In order to facilitate fast decision making and information flow, an active network requires efficient and cohesive visibility of the many devices linked to it.
* To take use of the intelligence that will develop future networks, centralized manual control must be replaced with a distributed control structure that is coordinated and incorporated into existing control procedures.
* It is also important to ensure that all functions and equipment remain compatible during the transition from current to future active distribution grids.
* Communication systems should able to meet the new functions' capacity, reliability, and cost demands

**F. Employment of ‘‘smart’’ technologies such as metering and distribution automation**

Smart Grids provide two-way communication between the meters and the utility through metering. The meters provide more precise billing and give customers more control over their energy consumption. Sensors, power outage alert, and power quality control are all included in smart meters. Smart meters are always linked with distribution automation. Utility companies may collect consumer data more rapidly and provide a system-wide communications network to utility service locations and link devices throughout the grid with advanced metering infrastructure (AMI).

The AMI and distribution automation pave the way for significant grid transformation through monitoring transformers and feeders, outage management, electric vehicle integration, and effective fault isolation. The development of a Substation Automation System, which defines locally control actions to resolve congestion with little renewable energy source restriction, is one technique to achieve distribution automation [12].

**G. Distributed Optimization:**

The success of SGs necessitates a closer combination of global optimization and local control, with global optimization addressing numerous objectives such as lowering energy prices, increasing electricity efficiency, reducing power network losses, and lowering carbon dioxide emissions. Conventional centralized optimization solutions are no longer suitable due to the computational complexity of the continually increasing quantity of equipment, sensors, and facilities deployed and connected to the SG.

Higher level optimization with fewer timing duties should be considered, whereas lower level optimization is done within individual devices, each of which includes a computer to process data locally, and only passes on important information to the upper level. The problem is figuring out how to combine global optimization and local control to produce optimal global coordination. By designing communication protocols and regulations to permit automated convergence to the global optimum, multiagent systems (MASs) can be found effective in dealing with dispersed optimization challenges.

**H. Distributed Intelligence:**

Multiagent systems (MASs) (distributed intelligence) have recently been demonstrated to be a promising method for addressing the large-scale nature of the computing problem in CPS. A software entity called an agent can describe and control a hardware component like a source, a storage unit, or a load. A software entity called an agent can represent and control a hardware component like a source, a storage unit, or a load. It has the ability to communicate and cooperate with others as well as its surroundings in order to assist or compete for local and/or global objective.

An MAS is a distributed intelligent agent network that comprises of a number of agents, each of which has a specific level of intelligence. An application of MAS focused on distributed state estimation, voltage coordinated control, and power flow management was made in, which gives a high level of effectiveness, adaptability, and intelligence. Future SG will necessitate not only micro-operational automation, but also macro-level decision-making that takes into account greater economic and social needs.

**IV. FUTURE RESEARCH CHALLENGES AND OPPORTUNITIES**

**A. Artificial intelligence:**

The innovation in power systems has established advanced metering infrastructure, micro phasor measurement units, and DERs into the grid, which provides huge potential to improve system observability and controllability. Artificial intelligence technologies can describe the power utilization behaviors of consumers, improve situational alertness, and assist system operators to take the right decisions, particularly in serious situations. This has great potential in enhancing system flexibility, which necessitates extra attention [13].

**B.Transportation by Electric Vehicles:**

Economic and environmental considerations modify the existing transportation network by allowing large-scale integration of plug-in electric vehicles (PEV), which can greatly reduce reliance on oil while also reducing carbon emissions. With the usage of EVs, vehicle owner expenses are roughly halved, and EVs have only a modest influence on the network in terms of distribution system losses and voltage regulation. PEV battery banks, wired-wireless charging stations, and large-scale grid interconnection are among the topics covered by electric transportation research.

**C.Sensing and measurement:**

Sensors are major elements of the Smart Grid. These small components act as detecting stations and allow equipment and energy sources to be monitored remotely. Synchrophasors, also known as phasor measurement units (PMUs), are high-speed sensors that allow for synchronized measurements of real-time phasors of voltages and currents. These phasor measurements are utilized to monitor, protect, and manage complex power systems. PMUs are 100 times faster than Supervisory Control and Data Acquisition (SCADA) systems and can accurately capture grid conditions [14].

Digital meters are used in Smart Grids to record usage in real time, give pricing structure, assist in demand response, and automatically connect or remove power. Communication between power facilities and households and businesses is possible through a technology known asAdvanced Metering Infrastructure (AMI). Smart meters are the power measurement technology of the future.

**D.Renewable energy integration:**

While much renewable energy research has been carried to investigate additional clean energy sources, incorporating renewable energy sources into the power network is one of the problems in modernizing the power grid and making the grid smart. Renewable energy sources are inherently unstable and intermittent in nature. Electricity has always gone in one direction, from a power plant to consumers. Electricity must enter the grid from various sites as a result of the increased sources coming from different sources. To integrate wind, solar, and other alternative energy sources into the distribution grid and transport them to their destinations, grid automation, two-way power flow, and contemporary controls are required [15].

New devices in Smart Grid systems must be able to integrate with existing equipment, and coordinated efforts are required to adapt solar photovoltaic and wind energy. There are various computer tools available for studying renewable energy integration into energy systems. In terms of applications, technology, and goals they achieve, these energy solutions are diverse.

**E.Cyber Security:**

Power system communication and information infrastructures are crucial for the development of smart grid solutions. While entire network and computer integration improves power system capability, it also raises vulnerability to cyber-attack threats. Present cyber security solutions may not be suitable or efficient for the security of smart grid cyber-physical systems, necessitating domain-specific techniques and solutions. Privacy, integrity and availability, verification, and vulnerability analysis are some of the open research areas in cyber security for the smart grid.

Other security studies include "Position Dependent Security for Smart Grid Applications, Integrated Smart Grid Systems Security Threat Model, Privacy-preserving smart metering with numerous data users, and Ortho code privacy technique in Smart Grid employing ring communication architecture.

**F.Distributed Energy Resources (DER):**

Utility-independent generation units and energy storage behind the prosumer energy meter are covered in this study topic. The generated energy is mostly used as a negative load on the prosumer premise. Reverse power may be obtained from the prosumer side in some instances, despite the fact that it is not advantageous to distribution system operators (DSO). Improved aggregated DERs would provide autonomous grid topologies with micro grids that could be disconnected from the grid in the event of a utility failure, resulting in a more secure and sustainable system [16].

**G.Network Communications:**

Power companies and customers use a range of public and private communication networks, including wired and wireless, to operate smart grids. Residential meters, transformer meters, feeder meters, and field distribution automation communication such as re-closers, switches, voltage regulators, and capacitor banks are all examples of utility network communication uses. Prosumer network communication aids in the intelligent management of devices, primarily in the Home Area Network (HAN). To operate the grid smartly, wireless machine-to-machine (M2M) communication between smart meters removes the need for human intervention.

**H.Internet of Things**

By exploiting the expanding ubiquity of radio-frequency identification (RFID), wireless, mobile, and sensor devices, the Internet of Things (IoT) has presented a potential opportunity to construct powerful industrial systems and applications. In recent years, a wider range of industrial IoT applications has been created and deployed.

Because of the development of RFID, sensors, smart devices, and "things" on the Internet, the Internet of Things (IoT) is defined as the expansion of Internet services.SG has developed a communications network that connects all future energy-related devices, including transmission and distribution power grid, electrical, water, gas, and heat meters, as well as home and building automation. The IoT computing concepts can be used as a dynamic global network infrastructure with self-configuring abilities based on standard and interoperable information protocols to ensure that the SG functions effectively [17].

**I. Cloud Computing:**

SG facilitates dispersed and renewable energy generation to meet demand in a timely manner through real-time control. Cloud computing is a relatively new paradigm in which computing resources such as computation, storage, and networking are packaged together as computing resources .Efficient management, cost savings, continuous services, risk management, and green computing are all advantages of cloud computing . The main problem is the security and privacy issue, which arises when personal data is given to third-party service suppliers, exposing confidential data to the public. These complicated problems will require attention from a wide range of views, including legal, regulatory, and operational perspectives, all of which will have an impact on SG's architecture and design, data science, and engineering aspects [18].Cloud computing has a number of advantages, including on-demand self-service and resource sharing; yet, the elasticity provided by using a cloud service poses safety and privacy concerns.

**J.Big Data:**

Big data will play a significant role in the fourth industrial revolution from an industry standpoint. The first industrial revolution (from the end of the 18th to the beginning of the 20th centuries) relied on water and steam power, the second (from the beginning of the 20th century to the early 1970s) on mass production based on division of labor and electrical energy, and the third (from the early 1970s to the present) on electronics and information technology for further automation of production. Big data, which will be made available through Cyber-Physical Systems, will be the fuel of the fourth industrial revolution, termed "Industries 4.0" by the German government (CPS).

The idea is to create smart factories that communicate with one another like a social network. This type of smart factory will create intelligent items (smart products) that understand how they were made and collect and send data as they are used; large volumes of data (big data) will be collected and analyzed in real time. As a result, new insights will be developed and used to progress from smart factories to smart process, and then to the level where smart services may be supplied to customers via internet-based services[19].

Data types in SG systems come from a variety of sources, including security cameras, climate forecasting systems, maps, sketches and images, and the internet. They have become increasingly relevant to utilities, since social media and call centre interactions are also sources of critical information for decision-making and planning processes when combined with smart meters and grid generated data. The creation of efficient architecture and design, time-critical information science and engineering knowledge with appropriate semantics, computation tools, and smart algorithms is required for data analytics for those large data concerns connected with SGs [20].

**V. CONCLUSIONS**

Cyber-Physical Systems are at the heart of the Smart Grid’s development. Their ability to act as a bridge between the physical and business worlds makes them vital. However, key questions remain unanswered, and major efforts will be required to comprehend how CPS can operate inside a complex system of systems like the Smart Grid, as well as the influence of their interactions and participation in a network of CPS.

In this paper, the overviews on issues in SGs from a CPS perspective are given and discussion is carried out on the possible contributions CPSs can offer to SGs as well as the difficulties SGs offer to CPSs. The focus is given on the influence of cutting-edge technologies on SGs, including big data, cloud computing, the Internet of Things, and network science. A number of unanswered questions have also been raised, all of which are significant for the future development of SG

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