A CYBER–PHYSICAL SYSTEMS PERSPECTIVE ON SMART GRIDS

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 systems that use modern control, monitor 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 view of cyber–physical systems along with possible contributions of cyber–physical systems to smart grids and the problems that smart grids provide to cyber–physical systems. Lastly, the impacts of recent advanced technologies on smart grids are discussed.

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

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I. INTRODUCTION

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

The Renewable energy (RE) sources including solar, hydro, biomass and wind are available in large quantity, but they are far more difficult to collect. To increase the security and steadiness of this energy supply, 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 in addition to carrying power. It is anticipated that modernizing the electrical system through two-way flows of electricity and information would create "smart grids" that include intelligent characteristics like self-healing, adaptive safety and control, as well as customer interaction [2].

The Smart Grid (SG) technology updates the modern industries with powerful solutions that is more efficient, effective, economical, and environmental friendly. A network for distributing electricity that uses digital communications is known as the Smart Grid. A smart grid's objective is to effectively provide sustainable, profitable and secure electric energy by integrating the actions and behaviors of all parties involved in the energy supply chain.

The successful implementation of SGs depends on the precise integration and interaction of the physical and cyber systems for data sensing, processing, and control. To address the specific integration and interaction issues in SGs, a new technology known as a "cyber physical system" is developed, which maintains an effective interaction among physical systems and cyber systems [3].

The adoption of CPS technology in SGs will increase their operational effectiveness, prosumer responsiveness, financial viability, and environmental sustainability. Moreover, the unique properties of SGs will create new challenge for CPS development.

II. SMART GRIDS

Smart Grids have emerged with a goal to advance the electricity system and make it less harmful to environment. Utility firms may take advantage of existing infrastructure and lessen the need for new power plants and substations as a result of Smart Grids' increased autonomy and enhanced effectiveness in supplying electricity. The Smart Grid is expected to improve in efficiency, reliability, and availability with the addition of modern features like communication and advanced computational capability [4].Additionally, the Smart Grid offers infrastructure that is integrated with electricity flows and two-way communication. A

SG uses recent products and services along with smart communication, control and self-healing technology. Smart grid provides properly planned power to smart devices, transformer and machines. To attain this it uses two way communications. 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 various stakeholders and consumers in very complex and large system [5].

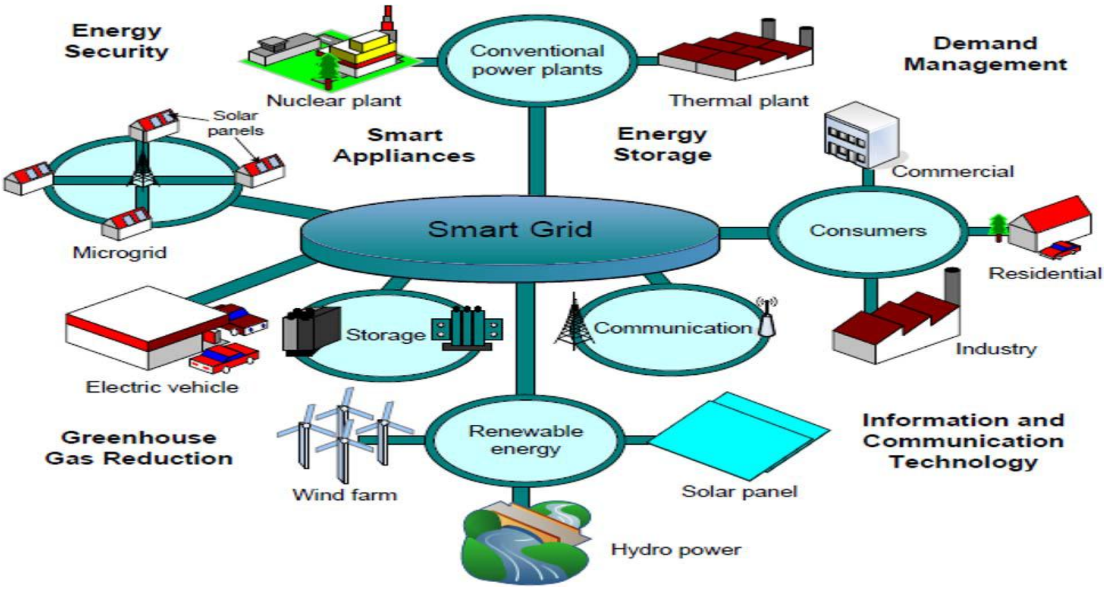

Figure 1: Smart Grid Structure

The main function of SGs is to operate and handle the whole power system with all smart devices with bidirectional power flows. It is necessary for the power networks, cyber systems, and consumers to communicate better in order to achieve more flexibility, dependability and security of power supply and utilization through SGs. There is a need for improved physical system support and cyber system interaction [6].

The SG should present solutions to various 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

1. Ensuring adequate transmission capacity to connect energy sources, particularly renewable, thereby improving grid strength.
2. Constructing the communications path that will permit many parties to trade and function in single market.
3. Allowing smaller-scale energy supply systems to operate with the larger grid.
4. Allowing all consumers to participate actively in the system's operation.
5. Use of Advanced energy storage technology in the system.
6. 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 that aims for stability, healthiness, effectiveness, and consistency in physical systems application [7].

As shown in Fig. 2, the cyber system gathers information from physical system through the sensor and feeds the control signal to the physical system in order to achieve the specific goals. It is required to interface the physical power system with a cyber system in order to guarantee 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. and the construction of CPSs, the strong interaction between cyber and physical components poses big challenges. CPSs consist of computation devices, interfaces, sensors and actuators. In addition, the need for rapid communication and synchronization involving 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 acceptance of CPS 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 structural design issues. Infrastructure planning and design are important for enabling incorporation of control, communication, and processing for efficient plan and use of CPSs.

Cyber security is a significant issue for CPS, with the close addition of cyber systems and physical network, where the methods for computation 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 engineering. Collection of data, processing and control must be given quickly and in real time for correct communication between cyber and physical systems [8].

Starting from generator to distributer many stakeholders, are involved in the interconnected network. The rising complexity and interconnections of various components and 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 subsequent 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 data 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.

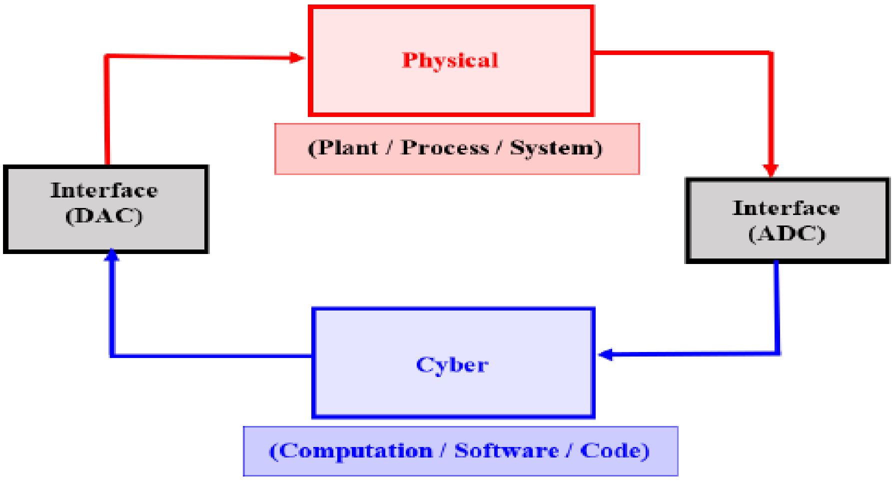

Figure 2: Cyber Physical System

1. **Design and Architecture:** Structural designs are given importance to build the primary CPS infrastructure and establish design techniques depending on CPS principles in order for the CPS to operate smoothl**y.** 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.

   To obtain smooth incorporation of control and calculation for fast design and operation of CPSs in SGs, there must be CPS architectures that are specifically meant for interfaces between power system and cyber systems.CPS need single standard structure in which Physical systems, communication procedure, computation methods, software and hardware are all, can function collectively. An integrated modeling approach is required for the CPS to operate effortlessly in SGs, allowing the physical components of the system and the cyber system components to be united under one structure and a complete control strategy is prepared [10].

2. **Information and Communication Technology (ICT):** For successful communication between physical and cyber systems, Information and communication technologies are essential. In these two basic characteristic of communication, i.e. space and time must be considered, with respect to communication distance and time required for information transport. 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 environmental friendly operation of Smart Grids.

Important components and key aspects are:

- Monitoring, control, and dispatching services at every level up to 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.

3. **Modeling and Simulation Technology:** Modeling of CPS is the basic requirement for the design and analysis. To guarantee that, the large-scale system CPS of SG can work smoothly and apparatus can communicate with one another, compatibility, composite and heterogeneous modeling and simulation tools are required to maintain system and network condition.

   New developments in power consumption reduction and excess capacity savings, such as cost-effective and efficient supervision of massive electricity storage, advancement in transmission network and an extensive range of power electronic device applications, necessitate efficient function and control, necessitating a new incorporated modeling and simulation atmosphere capable of handling large network for modeling and simulation.

4. **Security Risks:** Because of the different communications design of SGs, designing complex and resilient safety measures that will be easily executed to protect interactions at various levels of smart grid is extremely difficult. The conventional electrical grid is being transformed into a smart grid. The conventional electrical system is combined with ICT technology in a smart grid. Customers and electrical utility suppliers can work together to get better effectiveness and accessibility of the power system by constantly observing, controlling, and supervising consumer needs [11].

   The following security goals must be included in the smart grid system:

   - **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 be taken to avoid attackers from deriving pattern or encrypted data to disclose personal 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.

5. **Active Distribution Networks:** Transmission networks are always playing a balancing and management functions in the power system, but distribution networks are supposed to be inactive. The issue now is to convert inactive distribution system into active system. It is necessary not only because of the growing use of distributed generation, but also due to rising smart building services in both residential and commercial buildings, to use locally generated power supply during times of pressure on the central grid, and the expected widespread adoption of electric transportation vehicles in the future.

   The important features of Active distribution systems are:

   - To facilitate fast decision making and data flow, an active network necessitates 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

6. **Employment of advanced technologies:** Smart Grids provide bi-directional communication between the meters and the utility through metering. The meters provide high precise billing and give customers more control over energy consumption. Sensors, power cut alert, and power quality controls are all included in smart meters. Smart meters are always linked with distribution automation. Utility companies may collect consumer data more rapidly and give a system-wide communications network to utility service locations and connect 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, which describes local control measures to resolve problems with little renewable energy source restriction, is one technique to achieve distribution automation [12].

7. **Distributed Optimization:** The achievement of SGs necessitates a closer combination of global optimization and local control, with global optimization addressing numerous goals such as lowering energy prices, increasing electricity efficiency, reducing power network losses, and lowering carbon dioxide emissions. Conventional optimizing solutions are not suitable due to complexity of the continually increasing quantity of apparatus and facilities deployed to the SG.

   Higher level optimization with fewer timing duties should be considered, whereas low level optimization is considered for individual devices, with a computer to process data locally, and just pass on important matter to the higher level. The problem is figuring out how to combine global optimization and local control to produce optimal global coordination. By designing communication procedure and regulations to permit automated convergence to the global optimum, multiagent systems (MASs) can be found effective in dealing with dispersed optimization challenges.

8. **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 difficulty in CPS. A software entity called an agent can specify and manage a hardware element like a source, load and a storage unit. It has the ability to communicate and cooperate with others as well as its surroundings to assist or contend 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. A function of MAS is focused on state estimation, voltage control and power flow control, which gives more effectiveness, adaptability, and intelligence. The upcoming SG will necessitate both micro-operational automation and macro-level decision-making that takes into account greater economic and social needs.

IV. FUTURE RESEARCH CHALLENGES AND OPPORTUNITIES

1. **Artificial Intelligence:** Power system innovation has integrated DERs, phasor measuring units, and improved metering infrastructure into the grid, which has tremendous potential to enhance system visibility and controllability. Artificial intelligence technologies can describe the power utilization behavior of consumers, develop situational alertness, and assist operators to take the accurate decisions, particularly in serious circumstances. It has huge strength in enhancing system flexibility, which necessitates extra attention [13].

2. **Transportation by Electric Vehicles:** Cost and environmental considerations modify the existing transportation network by allowing high level incorporation of plug-in electric vehicles (PEV), which can greatly lessen 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 control on the system in terms of voltage regulation and distribution system losses. Battery banks, smart charging stations, and high grid interconnection are among the topics covered by electric transportation research.

3. **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 controlled remotely. Synchrophasors, also known as phasor measurement units (PMUs),

are high-speed sensors that permit for synchronized measurements of real-time phasors of voltages and currents. These phasor measurements are utilized to monitor, protect, and manage complex power 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 as Advanced Metering Infrastructure (AMI). Smart meters are the power measurement technology of the future.

4. **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 naturally unstable and intermittent in nature. To incorporate wind, solar, and other energy sources into the distribution grid and supply to the consumers, grid automation, two-way power flow, and contemporary controls are required [15].

   Latest devices in Smart Grid systems should be capable to integrate with existing apparatus, and synchronized efforts are essential to adapt solar photovoltaic and wind energy. There are various computer tools available for studying renewable energy integration into energy systems.

5. **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.

6. **Distributed Energy Resources (DER):** The power from DER is generated at the consumer side itself. 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].

7. **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, re-closers, switches, voltage regulators, and capacitor banks are all examples of utility network communication system. 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.

8. **Internet of Things (IoT):** 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. 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].

9. **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.

10. **Big Data:** Big data will play a significant role in the fourth industrial revolution from an industry standpoint. The method is to generate smart factories that communicate with one another like a social network. This type of smart factory will create intelligent items that recognize how they were made and gather and send data as they are used; large volumes of data (big data) will be gathered and analyzed in real time. As a result, new insights will be created and used to progress from smart factories to smart process, and then to the level where smart services may be supplied to consumers via internet-based services[19][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 and also the difficulties SGs offer to CPSs. The focus is given on the influence of cutting-edge technologies on SGs, such as big data, cloud computing, IOT, and network science. A different unanswered questions have also been raised, all of which are significant for the future development of SG.

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