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SURVEY

Intelligent Computing in Electrical Utility Industry 4.0: Concept, Key Technologies, Applications and Future Directions

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ABSTRACT Industry 4.0 (I-4.0) is referred to as 'fourth industrial revolution' towards incorporation of artificial intelligence and digitalization of industrial systems. It is meticulously associated with the development and advancement of evolving technologies such as: Internet of Things, Cyber-Physical System, Information and Communications Technology, Enterprise Architecture, and Enterprise Integration. Power systems of today face several challenges that need to be addressed and application of these technologies can make the modern power systems become more effective, reliable, secure, and cost-effective. Therefore, a widespread analysis of I-4.0 is performed in this paper and a summary of the outcomes, future scope, and real-world application of I-4.0 on the electrical utility industry (EUI) is reported by reviewing the existing literature. This report will be helpful to the investigators interested in the area of I-4.0 and for application in EUI.

INDEX TERMS Digitalization, electrical utility industry, Industry 4.0, smart grid, the Internet of Things, communication infrastructure, cyber physical system.

NOMENCLATURE

AI	Artificial Intelligence.
AM	Asset Management.
AMI	Advanced Metering Infrastructure.
BAN	Building Area Network.
CC	Cloud Computing.
CPPS	Cyber-Physical Power System.
CPS	Cyber Physical System.
DL	Deep Learning.
DMC	Data Matrix Codes.
DoS	Denial of Service.
EUI	Electrical Utility Industry.
EV2G	Electric Vehicle to Grid
FAN	Field Area Network.
FDI	False Data Injection.
GCI	Grid Communication Infrastructure.
HAN	Home Area Network.
HEM	Home Energy Management.
IAN	Industrial Area Network.
ICT	Information and Communication Technologies.
IDS	Intrusion Detection System.
IED	Intelligent Electronics Devices.
IoT	Internet of Things.

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IoS	Internet of Service.
IoP	Internet of People.
IoE	Internet of Everything (IoE).
ML	Machine Learning.
M2M	Machine-to-Machine.
MDM	Meter Data Management.
NAN	Neighborhood Area Network.
OTM	Overhead Transmission Line Monitoring.
PCA	Principal Component Analysis.
PMU	Phasor Measuring Units.
PHEV	Plug-in Hybrid Electric Vehicles.
PEV	Plug-in Electric Vehicles.
RES	Renewable Energy Sources.
RFID	Radio Frequency Identification.
SA	Substation Automation.
SM	Smart Meter.
SVM	Support Vector Machine.
SCADA	Supervisory Control and Data Acquisition.
WASA	Wide-Area Situational Awareness.
WAN	Wide Area Network.
WSN	Wireless Sensor Networks.

I. INTRODUCTION

Electrical industry has no relation with the first industrial revolution (Industry-1.0 or I-1.0). However, the second industrial revolution (I-2.0) was initiated in the 19th century after the developments in the domain of electricity. The third industrial revolution (I-3.0) started in the 1970's via limited automation using memory-programmable controls and computers. Recently, the fourth industrial revolution (Industry-4.0 or I-4.0) is taking place. I-4.0 is generally characterized by the application of Information and Communication Technologies (ICTs), Internet of Things (IoT) and Cyber-Physical Systems (CPS) to the industry. Several key components of I-4.0 are shown in Fig. 1.

Proper integration of the traditional electric power system with advanced information, communication, protection and control technologies is one of the important developments in making the modern power systems smarter. These technologies help in providing effective solution to the challenges of automation, monitoring, optimizing, and managing each component of the power system [1], [2], [3]. The environmental concerns about generating electricity using fossil fuels and global warming have motivated the Electrical Utility Industry (EUI) towards renewable energy sources (RES).

The main purpose of incorporating new technologies is to achieve cost-effective performance of power systems with good efficiency, high reliability, better flexibility, improved resiliency, and high security in the presence of demand response, demand-side management, plug-in hybrid electric vehicles (PHEVs), RES, and plug-in electric vehicles (PEVs) [4], [5]. In this regard, intelligent electronic devices (IEDs) such as smart sensors, smart meters, digital relays, circuit breakers, reclosers, and phasor measuring units (PMUs) are becoming the basic modules of a modern power system, and necessitate a communication infrastructure to transmit/interchange data, information, and collective actions securely in an automated environment [6].

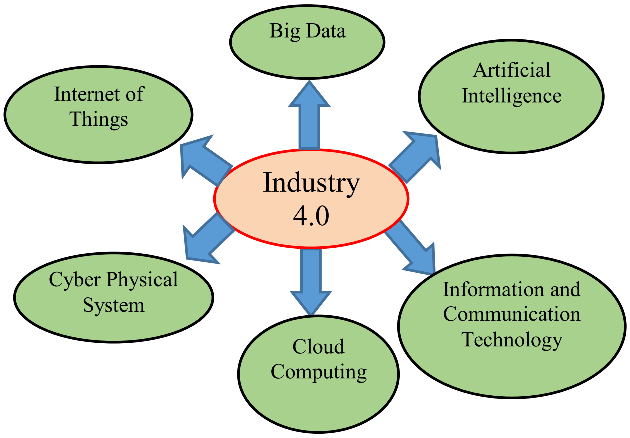

FIGURE 1. Several key components of I-4.0.

The Grid Communication Infrastructure (GCI) can be described as the nervous system of the modern power system and plays a vital role in EUI-4.0. The main function of GCI is to support: (a) RES's integration with the main grid, (b) smart metering, (c) demand response, (d) PHEVs, (e) demand side management, (f) advanced control & automation, and (g) consumer side energy management. Therefore, in the general sense, the architecture of the evolving power system can be represented through the integration of the electric power system and the GCI [7]. The architecture of GCI can be described in three levels, such as short-range, medium-range, and long-range networks [7], [8]. Each of these three levels is a heterogeneous mixture of wired and wireless equipment having unique standards appropriate for specific applications and meant for particular needs like bandwidth, handling area, data transmissions speed, flexibility, mobility, frequency range, latency, economic, reliability, and security [9], [10]. The fourth industrial revolution is triggered by the development of ICTs. Advanced ICTs, the key component of GCI, establish a medium of communication for the power system community and perform an important job in dealing with different aspects of the GCI efficiently.

The IoT technology is another key component of I-4.0. In the EUI-4.0, the major role of IoT is to handle all connected objects/devices concerning monitoring, analyzing, and controlling the whole power system network, and ensure a smooth functionality at generation, transmission, and distribution levels, and also consumer side [11].

Cyber-Security and CPS are two additional major components of EUI-4.0. The present power grid is likely to be reorganized as a CPS comprising intelligent policies not only to transmit energy but also to transfer information for the monitoring and control of progressive EUI [12]. Protecting important information/data from physical and cyber security attacks is a critical challenge for the grid. Therefore, end-to-end secure communication system is important to ensure reliable operation of the modern grid. Cyber-attack in power systems usually affects the technical and economical values along with energy concerns and reputation [13].

Criteria for including suitable articles from the available literatures:

- To address the key components of I-4.0 and its application to EUI.
- To address the architectures of I-4.0 in the research domain of electrical engineering
- To address the major impact and open research issues related to each key component of I-4.0.

Criteria for excluding other articles from the survey:

- Articles not closely related to EUI or I-4.0 and applied to other domains for example: agricultural industry, aquaculture, traffic management, transportation industry, home automation, healthcare industry, computer vision, and medical domain.
- Articles published in books, Ph.D. and Master dissertations, meta-analysis, and other types of literature reviews.
- Abstracts or full manuscripts which require subscription charges are not accessible.

FIGURE 2. **Inclusion and exclusion criteria of the considered systematic review process.**

EUI-4.0 turns out to be highly complicated and knowledge-intensive through the addition of new advanced technologies like IoT, Internet of Service (IoS), and CPS. Thus, the data referred to EUI becomes heterogeneous (digital or analog) and large in volume. The necessity of big-data management, data mining tools, data recognition algorithms, and storage has increased accordingly. The Cloud Computing (CC) architecture can be also used for accessing data subject to security and safety issues [14]. The Machine Learning (ML) and Deep Learning (DL) techniques-based data-mining tools integrated with CC facilities are coming as a new area of future research scope [15].

The main goal of this review is to expand the perspectives of electric power systems in the context of I-4.0 application by reporting various challenges and requirements. Although several studies on the concept of I-4.0 are available in the literature, a systematic and extensive review of the electrical power system in the context of I-4.0 is hard to find in the existing literature. Therefore, the proposed review is intended to present a comprehensive literature survey on EUI-4.0 that highlights the current status, future scope, and major findings. In this regard, a systematic review process has been followed, where around 5125 articles, mostly related to I-4.0 and its components, were collected. After applying suitable including and excluding criteria (Fig. 2) on this database, 220 closely related articles on the review domain are selected and reviewed based on different perspectives.

The major contributions of the article are:

- It provides an overall concept of I-4.0, key technologies and their implementation challenges for academia and research community.
- The role and transition of electrical utility system in the fourth industrial revolution is investigated.
- The major objective and application of each key technology associated with the architecture of I-4.0 towards EUI-4.0 are comprehensively analyzed.
- Several open research issues associated with EUI-4.0 and future research directions, which may be helpful to the electrical researcher/utility engineer, are presented

The remaining paper is organized as follows: A bibliometric literature review is given in Section II; Concept of industry-4.0 and EUI-4.0 are presented in Section III, and key technologies of EUI-4.0 are described in Section IV. Several future directions of EUI-4.0 are highlighted in Section V, and finally, some concluding statements are given in Section VI.

II. A BIBLIOMETRIC LITERATURE REVIEW

A brief study on the available state-of-the-art review articles related to I-4.0 and its application domain is provided in this section. As SCOPUS is one of the most widely used bibliometric databases, this database has been used for an in-depth analysis in the present study.

I-4.0 is gaining increasing attention each passing year, Fig. 3 (a). A pictorial proof of the preceding statement is provided in Fig. 3 by showing the number of publications (NoPs) in the past 10 years. With only one publication reported in the year 2012, an exponential growth in NoPs per year has been observed since then. The NoPs reported in the year 2020 was 1498. The above analysis has been carried out by searching the word "Industry 4.0 (I-4.0)" in the search engine of the Scopus database. As I-4.0 belongs to different sectors of different industries, the discipline-wise popularity was analyzed and is given in Fig. 3 (b). The highest NoPs is reported for the discipline of 'Engineering' (NoP = 3128) and 'Computer Science' (NoP = 2287) got the next place. The NoPs reported in the discipline 'Energy' was 316. After searching the keywords integrated to electric industry 4.0 such as 'electrical', 'power', 'Smart Grid or smartgrid, 'Microgrid or micro grid', 'renewable energy', 'transmission system', 'distribution system', 'photovoltaic', 'PV' and 'wind', only a few articles are found to be reported in the database. However, several other articles are also available in the literature that explains the key components and concept of EUI-4.0, but is reported in an unintended manner.

Based on the above analysis with a bibliometric study on I-4.0, the electrical power, and energy-based investigators may get motivated to think beyond the box, as the research scope and the application field of I-4.0 is still in the early stage.

III. CONCEPT OF I-4.0 AND EUI-4.0

The main concept behind I-4.0 is based on the expansion and transformation of the I-3.0 concept. In I-3.0, the computer and

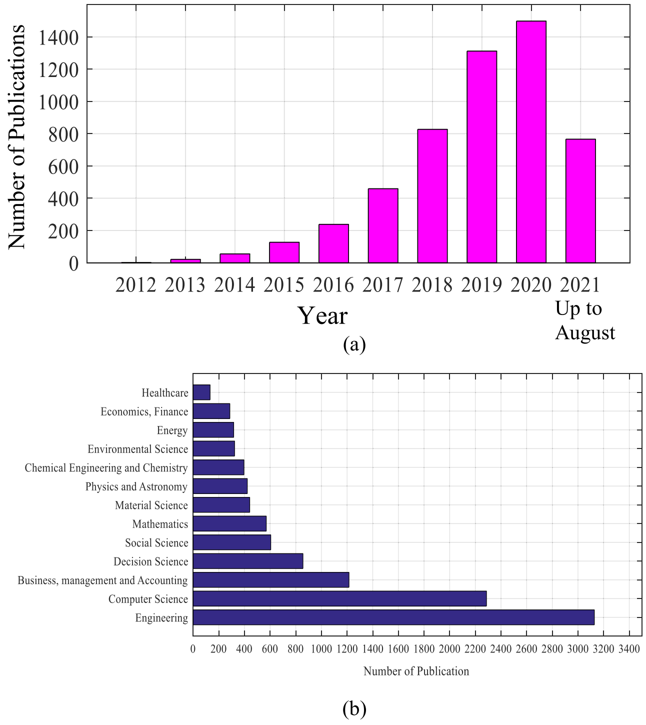

FIGURE 3. Status and popularity of research domain on I-4.0 (a) NoP vs Year (b) Research domain vs NoP.

programmable memory-based limited control and automation of industry was started. Although, in the era of I-3.0 the manufacturing industry has achieved a new height of automation, the development of supercomputing and its related positive energy and negative threat, forced the industrial environment for another revolution. In this revolution, several new advanced technologies are also integrated with the current system to make it more automatic, safe, reliable, adaptive, and flexible. As the final aim of the present work to portray the concept of EUI-4.0, the origin of I-4.0 and its connection with utility system are described first.

A. CONCEPT OF INDUSTRY 4.0 ON GENERAL PERSPECTIVES

The concept of I-4.0 has been reported widely in the past few years. Several articles related to I-4.0 with a bibliometric study have been reviewed in [15] and [16]. The concept of I-4.0 is explained in Consortium II, Fact Sheet [17] by a definition: ‘‘It is an integration of multifaceted physical machines and tools through interactive sensors and software with an intention to predict, control and plan for improved industrial growth and social outcome.’’ Similarly, I-4.0 is defined as ‘‘an improved value-chain organization and management across the lifecycle of the product.’’ In [18], I-4.0 has been reported as ‘‘a collective term for technologies and concepts of value chain organization’’ in [19]. It allows interconnection, digitalization, data integration, secure connection, interoperability, flexible adaptation, and intelligent self-organizing, in the conventional industry [20], [21].

The following four design principles for I-4.0 have been suggested in [19] and [22]: connections, information transparency, technical assistance, and decentralized decisions. The principle based on connection states that the information exchange between machines, sensors, and people be through a proper connection/communication platform, for example, IoT, Internet of People (IoP), and Internet of Everything (IoE). The operating principles of IoT, IoP and IoE require machine-to-machine, machine-to-human, and human-to-human joint collaboration to achieve a common goal without compromising the necessary standards and securities. The principle is based on information transparency and also highlights the ability of the information system in a collaborative environment of the physical and virtual world through various interconnected devices/sensors. In this regard, a virtual copy of the physical system is created through sensors and IoE platform. With the intention to build transparency, the result of data analytics must be embedded in support systems that are available to all IoE contributors [23].

The technical assistant facility toward I-4.0 helps in urgent decentralized decision making through aggregating the visual information that is collected comprehensively and precisely within a short-time span. By the way, it is helpful toward increasing the ability of CPS and acts as a supporting system to the field workers handling different unpleasant and unsafe tasks. The amalgamation of unified and dispersed decision-makers allows the utilization of both native and global information to improve policymaking and grow global efficiency [24]. The IoE applicants execute their responsibilities independently. Besides exceptions, interventions, or contradictory goals, jobs are deputized to an upper level. From the technical viewpoint, decentralized decision-making is generally supported by CPSs and smart factories of I-4.0. Hence, the technical assistance and decentralized decision are two important principles along with connections and information transparency for designing I-4.0.

B. CONCEPT AND PERSPECTIVES OF ELECTRICAL UTILITY INDUSTRY 4.0

It is mentioned above that with new developments, electricity began to be used after the second industrial revolution started. The application of Information Technology (IT) and Artificial Intelligence (AI) in the production sector through automatic control of electrical devices and the grid was seen in the era of I-3.0. Now, in addition to IT and AI, few more advanced techniques such as CPS, IoT, IoE, big-data, Cloud Computing, IoS, communication infrastructures, cyber-security, etc. are being integrated with electrical network or grids for different applications such as Substation Automation (SA), transmission/distribution line monitoring, outage management, wide-area situational awareness (WASA), demand response, Advanced Metering Infrastructure (AMI), home energy management (HEM), PHEV, distributed energy resource (DER), power storage system, Blockchains and Asset management (AM) [25]. In this regard, several major objectives toward energy issues can be addressed such as energy saving, green manufacturing, managing energy peak loads, reduction of energy cost, protection from energy break down, improved energy balance in the factory, etc., [26].

IV. KEY TECHNOLOGIES OF EUI-4.0

A. APPLICATION OF AI AND ML IN I-4.0 (AII-4.0)

The present industrial development seems to be more biased towards the application and growing research in AI and ML, as it enables a plethora of new opportunities in the automatic industrialized manufacturing process. The application of AI and ML uses a vast amount of data/information generated from the CPS and IoT-based technological paradigms, for decision making in industrial manufacturing and controlling processes. Generally, data has a certain life-cycle (for example, data sources, collections, storage, pre/post-processing, conceptions, visualizations, transmissions, and applications) [27], but, the noisy data/information are mostly handled in succeeding steps as filtering noise is an essential and challenging task. Also, the dynamic operating condition of industrial machines is a challenging situation to handle for the AI/ML-based faults recognition, predictions, and prevention techniques. Generally, the ML techniques are classified as supervised (key term: labeled data, direct feedback, predict outcome), unsupervised (key term: no labels, no feedback, find hidden structure), and reinforcement (key term: decision process, reward system, learn series of actions) types. Different types of ML techniques are applied for electrical domain application [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53].

The details of different ML technique applied in various articles are provided in Table 1. In the modern power system environment, these techniques are used for the following major applications: power system transmission line fault detection and classification [54], power quality analysis [55], [56], microgrid protection [57], renewable energy forecasting [58], demand-side management [59], and many more. For a smarter grid application, Deep learning is one of the most emerging fields of AI which is highly appreciated and attracted by the researcher [60].

TABLE 1. Several family members of ML techniques.

ML Family	Concern Techniques	Electrical Domain Application
Bayesian models	Bayesian networks, Naïve Bayes	[28,29]
Canonical variable analysis	Canonical variable analysis	[30,31]
Clustering	C-Means, density peak clustering, hierarchical clustering, k-means	[32,33]
Ensemble learning	Bagging, gradient boosting, machine learner fusion-regression, random forests, stacking	[34-36]
FURIA	Fuzzy Unordered Rule Induction Algorithm (FURIA)	[37]
k-NN	K-nearest neighbors (k-NN), neighborhood component feature selection	[38,39]
Neural network (NN)	Artificial neural agent, autoencoders, convolutional neural network (CNN), deep belief networks, extreme learning, machine, long short-term memory (LSTM), multi-layer perceptron, self-organizing maps, stacked denoising autoencoders	[29]
Principal component analysis	Principal component analysis	[40-42]
Q-learning	Q-learning	[43,44]
Regression	Gaussian process regression, linear regression, logistic regression, polynomial regression, radial basis function approximation	[45]
R-learning	R-learning	[46]
Sarsa	Sarsa	[47]
Supervised locally linear embedding	Supervised locally linear embedding	[48]
Support vector machines	Support vector machines (SVM)	[49-51]
Decision trees	Decision trees	[52-53]

B. ROLE OF IoT IN THE ERA OF I-4.0

The IoT technology is a key component of I-4.0. In the traditional power-grid infrastructure, IoT has become one of the key-enabling technologies that pave the way for further advancements in power systems in view of I-4.0. In the EUI-4.0, the major role of IoT is to handle all connected objects/devices concerning monitoring, analyzing, and controlling the whole power system network, and ensure a smooth functionality at generation, transmission, and distribution levels, and also consumer side. Therefore, in the I-4.0 revolution, IoT is regarded as the strongest and important candidate among key technologies. The major uses of IoT technologies in the EUI system can be described as in Fig. 4 [61]. It is generally depleted in the distribution and consumption power sector. The importance of IoT in power systems can be recognized during the failure in transformers or malfunction in any of the electrical apparatus. It can send an instant notification to the automation and control center. This technology is also helpful in reducing power consumption and also improves the power quality by continuous and uninterrupted monitoring of the power system network.

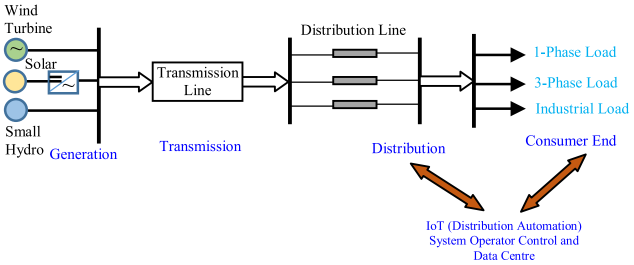

FIGURE 4. Major application area of IoT in power system.

The major role of IoT can be categorized as follows: (i) via internet connectivity, a smart connection can be made between each system element. (ii) besides internet facilities, a cluster of auxiliary equipment is essential to recognize the sensitivity of the connected devices such as radio-frequency-identifications (RFIDs), machine-to-machine (M2M) communication tools, sensors, and actuators. (iii) ensemble of requests and facilities leveraging such technologies to built-up fresh trade and market opportunity [62].

Use of the three networks, such as Home Area Network (HAN), Wide Area Network (WAN) and Neighborhood Area Network (NAN) are not required in modernizing the power systems technology owing to the IoT-based transformation. This transformation is generally based on a common Internet Protocol (IP). This single IP address based digital network compliments all the sub-sections in any industry according to the application without any hurdle. In this regard, the IoT-based communication acts as a cost-effective solution with respect to the different communication networks.

By this process, IoT is recommended as a significant element of the future power systems with facilities to meet all necessary needs. Application areas of IoT in power systems have been classified in [61] as (i) energy delivery and pick demand (ii) residential, commercial and industrial, and (iii) utilities and consumers. The first application area has the following sub-areas: Smart Metering analysis, advanced control strategy for transmission/distribution systems, and real-time monitoring of power generation. Similarly, the second one has been divided into Home Energy Management (HEM), Charging of PHEV, and demand response modeling. The last area is sub-classified as SM (Smart Meter)/ computerized meter reading (electric water, gas, and heat), AM and micro-generation. In the study described in [62] it has been reported that 60 billion IoT-enabled SMs have been already deployed by many computing agencies [63].

Different major components of an IoT-enabled power system are shown in Fig. 5. Here, the examples of sensors and actuators include SMs, Intelligent-converters for solar and energy storage applications, sub-station feeders, and grid monitoring control systems. The gateway is a public link used by both commercial customers and suppliers in distinct networks. During the monitoring operation of the system, data collection is done from the sensor, information is received from the IPs, and several temporary decisions are performed followed by the final data exchange process. The M2M interface through cloud-server has been considered as an added key research field in order to supervise the assembled data/information held. Appropriate data streaming with verification is completed in an unremitting manner. Big data is the next important component that handles series of data. Even the amorphous data is reorganized appropriately. The application of IoT technology in power systems shows a number of benefits in terms of efficient grid monitoring. This helps to reduce the economic loss and unnecessary consumption of energy. Security and privacy issues of IoT can be structured by the following five major entities: (i) reliability of data; (ii) authenticity; (iii) privacy of consumers with proper communication with utility; (iv) data secrecy; and (v) control access of the recognized data.

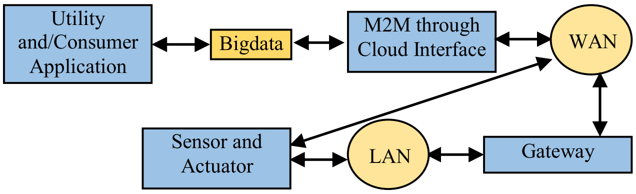

FIGURE 5. Different modules of IoT built with modern power systems [61].

1) MAJOR IoT APPLICATION STUDIES IN POWER SYSTEMS

Several applications of IoT technology in the power systems environment have already been reported [61], [64]. A few of them are mentioned in Table 2. The importance of IoT in future power systems is emphasized in [65] and ''in what way the IoT technology helps to improve the practical data transfer capability of different power-grid components?'' is explained. Here, the focus is on the application of IoT in the T&D system for online monitoring. The applicability of IoT in transmission line monitoring, studied in [65], shows that it helps to prevent blackouts, reduces power loss, and improves the power transmission line reliability. A novel architecture of Last- metered Smart Grid (SG) through proper implementation is proposed in [66]. Here, the necessity of IoT platform in power system infrastructure is justified through a demonstration using IoT servers embedded with Zigbee based SMs with flexible user interface. Moreover, an intelligible integration of power-grid beside domestic application built-in with SMs considering a similar infrastructure is also discussed. A novel approach for contingency management by means of smart-loads, realized by a developed prototype of IoT, is proposed in [67]. The framework includes a system operator, load serving entities, and the end-user with Smart-Home Management Systems (SHMS) that inevitably control flexible loads. The issues and challenges in the IoT-enabled grid architecture are comprehensively studied in [68]. The authors have defined the main security services concerning to the smart grid security. However, security issue of one of the key elements of smart grid such as AMI has not been discussed in detail.

The IoT-based SHMS with demand response and load scheduling is done in [69]. This IoT-based SHMS helps in the prospect of economical consumption of per-day electricity of the clients through proper coordination with the utility system. Again, in the perspective of utility profit, an appropriate demand response modeling method [69] is proposed. The security and privacy issue of IoT-based SHMS in terms of quality, reliability, and safety measures of the mechanism is studied in [70]. Based on a study of the security concerns and challenges of the IoT-based grid, several key safety measures that should be taken into consideration while dealing with system security are defined in [68].

The application of IoT in smart building management in terms of energy optimization and energy scheduling between production and utilization of electric energy is studied in [71].

Application of IoT in load demand forecasting problems in power system environment is shown in [72]. A method based

TABLE 2. Summary of IoT application domain in EUI-I4.0.

Ref.	Application Area
[65]	T&D line monitoring, prevention from blackouts, reduction of power loss, and improve the power transmission line reliability
[66]	IoT in SMs for residential applications
[67]	Contingency management by means of smart-loads and smart-home management
[68]	Security issue and challenges of IoT based Smart Grid
[69]	Residential Demand Response system and Load scheduling
[70]	IoT based smart home management to increase the quality, reliability and security of the devices.
[71]	IoT based smart-building in order to reduce energy cost and improved surveillance system
[72]	IoT based load forecasting
[73]	IoT based Smart Grid in the form of CPS
[74], [75]	Sensing and measurement features in SMs
[76]	Simulation of IoT enabled Smart Grid aimed at large-scale distribution of data transmission.
[77]	Handling privacy and security of the SMs data through IoT based applications
[78]	IoT based useful integration of non-conventional energy sources and energy storage system
[79]	IoT-based power systems for automatic monitoring of power system
[80]	Design of smart-power system and smart monitoring of SMART GRID
[81]	Demand Response application
[82]	Routing for medium voltage and low voltage Smart Grid
[83]	Design of WiFi-based WSNs for Smart Grid

on IoT and DL system that extracts features automatically from past collected data and provides an accurate prediction of load demands is proposed.

The security issue of IoT-based electric grid in the form of CPS modeling is addressed in [73]. Here, the aids available in a forward-thinking manner, highlighting the prevention of every single customer's data/info attack, are explained. A vision towards IoT-based hardware support to handle the sensing and measuring task of the smart power meter is presented in [74]. Several articles with the theme of IoT-enabled power system via SMs are reviewed in [75]. The simulation strategy of IoT-enabled grid, aimed at large-scale data transmission and distribution, is investigated in [76]. It is also mentioned here that for an effective and reliable operation of IoT-based modern grid, a continuous improvement in the design of SMs with accurate data analytics capability is required.

A decision-support system framework utilizing ML algorithms that operates inside the IoT environment is presented in [77]. This decision-support system including electrical SMs enhances the IoT ecosystem to the next level where smart-metering, data privacy and security is an important matter for controlling IoT-based appliances. The uses of Bluetooth under IoT platform has not been discussed in this work for potential quality monitoring. Novel privacy-preserving protocols used for data integration in IoT-enabled AMI, ensuring high security and reliability are proposed in [78]. The capability of IoT-based power systems in the monitoring of generation, distribution, and consumer side is described in [79]. The output information later helps to handle the financial trading and forecasting the future electricity price.

An IoT-based energy management scheme through GCI is presented in [80]. The GCI comprises heterogeneous and hierarchical communication networks such as HAN, NAN, and WAN. A solution for all these three GCIs, using prototype development and testing, is also presented. In addition, an application of this technology in smart-farming to yield better output is also described. A study related to demand resource application in the world, more specifically in Turkey, is presented in [81]. It is suggested that considering IoT applications, the demand side electric power consumption can be controlled more easily. In this regard, the demand resource will offer different perspectives on electrical energy generation and consumption and the function of electric power system. An IoT-based improved architecture for effective monitoring and controlling of low and medium-voltage transmission lines is proposed in [82]. In this regard, an IPv6 compatible routing protocol using clustering for IoT-based grid is designed. Application of Wifi-based wireless sensor networks in IoTs and electric grid is studied in [83]. Here, different application areas of grid, like smart power generation, smart transmission, substation, and intelligent energy use, are discussed.

C. ROLE OF CPS IN ELECTRIC GRID IN THE ERA OF I-4.0

CPS is an advanced engineering system that integrates the physical system through several advanced computing, communication, and control technologies. This is, so as to achieve stability, reliability, and upgradeability, and interact with physical systems of several application domains, for example transport, health care, power and energy [84]. Out of these, the power system is considered as a conventional application domain of CPS tools in the EUI [85]. The physical system dynamics of the grid are generally controlled with the assistance of CPS by connected sensors and controllers via a communication link (see Fig. 6).

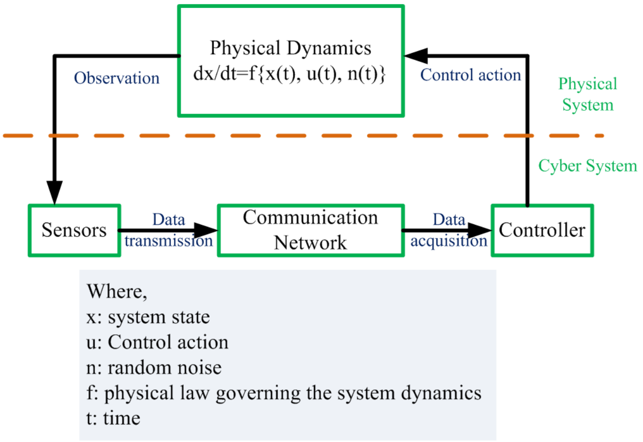

FIGURE 6. Architecture of CPS [89].

Subsequently, the real-time data measurement, its analysis, decision making, and feedback control of the grid could be done in order to increase the efficiency of power consumption, ensure the safety of the grid and reduce the cost of electricity. Similar benefits are highlighted in [86] and [87] through integrating the complex physical system and cyber system. Therefore, analysis on CPS offers a widespread interdisciplinary structure for analyzing and fabricating these real-time systems. With the CPS, for instance, a wide area monitoring system (WAMS) and a set of controllers integrated with the grid could build the 'conventional' AC-transmission system to 'Flexible' one. Similarly, in a microgrid, several RESs can be allied to the utility grid through power electronic converters controlled by using local signals (voltage/current/frequency) at point of common coupling (PCC) side, which entails a communication network in support of the measurement feedback [86]. Moreover, from the protection viewpoint, the protective elements such as relays also necessitate communication-based network control. These theories clearly indicate the importance of communication infrastructure in the CPS framework. Any malfunction of communication network can cause serious damage to the system dynamics [87], [88].

The four key elements of CPS are Physical Dynamics, Sensors, Controllers and Communication Network (Fig. 6) [89].

(*a*) *Physical Dynamics:* In the abbreviation 'CPS', the 'P' indicates the physical dynamics. In the power system environment, variation of frequency in the grid can be considered as an example of physical dynamics. It varies with respect to time. The evolution law is governed by the physical system itself and the control activities.

(*b*) *Sensors:* they are used to sense the physical dynamics. For example, in modern power systems, a sensor could be a PMU that senses the electricity dynamics and calculates the resultant frequencies and phases. The CPS may have multiple sensors connected to it.

(*c*) *Controllers:* Controllers collect the data from the sensors and perform the control actions through necessary computation. For example, a frequency controller can figure out the position of the governor valve of the turbine and activate it, corresponding to the collected frequency data of the utility grid. At times, the calculation and actuation of the control actions may be performed independently, and that may demand advanced communication systems.

(*d*) *Communication Networks:* As mentioned above, the importance of a communication network could be felt in the absence of a direct link between the sensor and the controller. This communication infrastructure may be wired or wireless. At present, Supervisory Control and Data Acquisition (SCADA) is the most used application to supervise the utility-grid in off-line mode. Several wireless sensor networks (WSNs) associated with CPS are also used for real-time and consistent supervisory action undertaken by the grid in dispersed manner for unlike provisions [90], [91]. By analyzing the change in required parameters, command signals are fed to the control center for needed action. Similarly, RFID or Data Matrix Codes (DMCs) technologies can also be integrated with CPS for identifying several objects in grid owing to its smart-sensing capabilities. Once the objects are identified, they can connect and interrelate with one another in real-time via a particular form of interconnectivity.

Different grid-CPS testbeds have been established and reported in [25]. This report was accomplished by analyzing the grid-CPS testbeds based on four major classifications such as grid domain, research goals, test platforms, and GCI. Several other investigations highlight the sensor data exchange standard in CPS domains [6]. These standards are comprehensively presented in Table 3.

TABLE 3. **Sensor data exchange standard in CPS domains.**

Standard	Description	Ref.
CBRN, EDXL, IRIG, TEDS, Transducer ML and Sensor ML based on ISO/IEC	Insist on the real-time data/information access from the system or otherwise known as AIDC (Automatic Identification and Data Capture).	[92], [93]
IEC/ISO 19762:2016	Describe about the AITs (Automatic Identification Techniques) in term of meanings and terms.	[94]
ISO/IEC 15459 series	Refers to common rules, groups, individual product and product packages, identification for registration procedures, individual returnable transport items and specific transport entities.	[95]
ISO/IEC 18000, ISO/IEC 15963–2009 series	Refers to several exclusive frequency scales and numbering schemes for the documentation of RFID (Radio frequency identification) tags. It also allows employers to select suitable RFID means based on their requirements.	[96], [97]
ISO 10374:1991, ISO/TS 10891:2009, ISO 18185 and ISO 6346:1995 series	Defines the communication, coding and freight containers electronic seals for RFID applications. It is also used to approve the RFID tag in a variety of Smart Grid applications.	[98]
ISO 17366:2013, ISO 17365:2013, ISO 17367:2013, ISO 17363:2013 and ISO 17364:2013	Defines the information hierarchy and technical features for RFID applications in the supply chain management.	[99], [100],
IEC/ISO 29179:2012, IEC/ISO 29176:2011, IEC/ISO 29178:2012, IEC/ISO 29173-1:2012, IEC/ISO TR29172:2011, IEC/ISO 29143:2011 and IEC/ISO 29175:2012	Define for the mobility and data capturing flexibility provision of AIDC/RFID.	[101], [102], [103], [104], [105], [106], [107]
IEC/ISO 29182	Pacifies SNRA necessities for evolving smart WSNs.	[108]
ISO/IEC/IEEE 21451, IEC/ISO/IEEE 21450:2010, IEC/ISO 30128:2014, IEC/ISO 20005:2013 and ISO/IEC 30101:2014	Helps users to create intelligent WSNs.	[109], [110], [111], [112], [113]

The presented or tabulated standards with their collective information help to form a highly reliable and smart sensor setup for several applications. Therefore, the CPS integrated with innovative control systems is likely to supervise the grid in the future in a dispersed, independent, and real-time manner. It allows instantaneous data/information trade among customers and utility directing high-quality electricity generation and distribution (EGD) with cost minimization [78]. However, integrating several multifaceted and varied subsystems in the grid in term of CPS is expensive and requires extra domain-specific approaches to deal with in addition, several other challenges may also arise during implementations of the CPS in time and space for several grid applications, such as collaboration among dissimilar systems, modeling and system integration, confirmation and analysis of different CPSs.

1) MAJOR CPS APPLICATIONS STUDIES

Several articles published in the literature shows the importance of this field toward ongoing and future scope of CPS in power systems. A few of the recent studies are enumerated below.

CPS security for electrical utility systems is presented in [114]. Cyber vulnerabilities and solutions in the context of power system control applications, such as generation control and security (for example, automatic voltage regulator (VAR), governor control and automatic generation control (AGC)), transmission control and security (for example, state estimation, VAR compensation, and wide-area monitoring and control), distribution control and security (for example, load shedding and AMI and demand Side management), have been analyzed. IoT-enabled CPS architecture in the context of power systems is reviewed in [115] and [116]. Similarly, a detailed survey on modeling, simulation, and analysis for cyber security application is given in [117].

A framework and security requirements of grid-CPS were presented in [118]. Cyber physical security for present evolving grid initiatives was surveyed in [119]. Several past cyber-attacks and defense system-based research on cyber-physical power systems (CPPS) are reviewed in [120] and several grid restoration techniques to improve CPS Resiliency are reviewed in [121]. Challenges and opportunities of Cyber-Physical Security in the modern grid were studied in [122], and several cyber-physical attacks and defense systems in the grid were reviewed in [123]. In addition to this, the opportunities and challenges in a grid-cyber physical security environment are also highlighted. A widespread analysis of grid security against CPS attacks on its distinct functional components is presented in [124] and [125].

A co-simulation framework that validates the perceptive of cyber-data transmission and dynamic performance of physical systems, and summarizes the communications among them in power system applications is presented in [126]. The efficiency of the stated CPS was confirmed in the following case-studies: (i) hierarchical control of Electric Vehicle (EV) charging in microgrids. (ii) IEC-61850 protocol emulation for protection of active RES. (iii) Resiliency improvement in contrast to false data injection attacks. A new Hybrid Attack Model that syndicates probabilistic learning attacker dynamic defender model, and a Markov chain model to simulate the planning and execution phases of a wicked data injection attack in an electrical utility grid is introduced in [127]. A new multi-QoS information flows control algorithm based on time-sensitive networking and distributed agent technology for CPS applications in the power system environment is proposed in [128]. The experimental result shows that the stated approach can reckon the fast-forward path with multi-agents and ensure transmitting quality. However, in few cases the bandwidth occupation ratio has been reported to be dangerously high. Therefore in future prospective, the data aggregation procedure should be sincerely analyzed to efficiently protect bandwidth and upgrade the results.

A microgrid is a CPS with combined power and communication networks. The secondary control of microgrid with periodical communications limits the power system efficiency and resiliency. A dispersed event-triggered subordinate control structure in an islanded microgrid with its CPS implementation is proposed in [129]. The stated control structure works with the condensed frequency of communication system which depends on the microgrid operating state change ''events'' (for example, load deviations and communication breakdowns).

A more accurate vulnerability assessment method for CPPS is proposed in [130]. Vulnerability of CPPS through fault propagation under cyber-attacks is studied in [131]. In this regard, a fault propagation model generally in view of the impact of interruptions on some nodes of the cyber-network on the electric physical systems, is proposed. A data-centric scheme for CPS heterogeneity in the grid is proposed in [84]. A Support Vector Machine and Principal Component Analysis based approach to classifying the real and false faulty conditions in the transmission line of CPS-based electrical grid is proposed in [132] and an Intrusion Detection System to sense lethal attacks with a focus on two grid security issues (integrity and availability) is proposed in [133].

Against integrity issues with price manipulation attacks, initially a cumulative sum method to detect these attacks, even with small price changes, is proposed. Secondly, against availability issues with Denial of Service (DoS) attacks, an effective technique has been developed to monitor and sense any misbehaving node.

A good analysis with the aim of facilitating reliability standard in the grid is presented in [134]. In this regard, an analytical reliability model that captures the effect of impairments originating from physical and cyber components, as well as the effect of cyber-physical interdependencies among these components, has been designed.

PHEVs are one of the economical choices of current smart transportation structures and are used to balance demand and supply through provisionally storing the electrical energy in their batteries. A novel context-aware coated design for demand-side management using vehicular-CPS with cloud provision is proposed in [135].

TABLE 4. Notable features of GCI [2].

Network	Application	Data-rate	Coverage Area	Technology	Power system levels
Short-range	Advanced metering, demand response, DER, home and building Automation	<100kbps	<100m	Zig-Bee, WiFi, Z-wave, PLC, Bluetooth, Ethernet	Consumer and end user (Meters)
Medium-range	Smart metering, demand response, electric transportation	(0.1-10) Mbps	<10km	Zig-Bee, WiFi, PLC, WiMax, cellular, DSL, coaxial cable	Distribution network (Sensor, Switchgear, transformer)
Long-range	Wide area control, monitoring and protection	(10-100) Gbps	<100km	Optical, cellular, WiMax, satellite communication	Generation and transmission network (PMUs, protection system and compensators)

False data injection (FDI) attacks are vital security hazards to grid-CPS which result in devastating cost to the whole power system. A parallel rule-based majority voting system to detect FDI inserted by negotiated PMU is used in [136]. Additionally, an advanced standing system with an adaptive reputation updating to assess the total running status of PMUs, by which FDI attacks can be detected, has also been designed.

D. REQUIREMENT AND ROLE OF ICT AND INFRASTRUCTURE ON EUI-4.0

ICT is one of the key components of I-4.0 infrastructure including the electric grid. The main objective of ICT is to provide a reliable, and rapid communication infrastructure that allows automatic information trade amongst the massive volume of scattered CPSs inside Grid-I-4.0. This real-time information trade between utility and consumers will lead to effective and reliable monitoring, control, and management of the electrical grid [9]. The grid-communication technologies infrastructure has been separated into two major groups i.e., private and public, in [25]. The primary goal of both GCIs is to provide smart self-awareness and improved reliability.

Again, the GCI can be characterized into 3-hierarchical levels considering the exposure area, data-rate, and functionality:

- Short-range networks (for example, HAN, building and industrial area networks)
- Medium-range networks (NANs and field area networks),
- Long-range networks (WAN) [2].

A brief comparison between these levels considering remarkable characteristics of GCI is presented in Table 4 [2].

HANs are essential at the consumers and end-users' level to facilitate communications infrastructure for the application of services related to energy utilization. Similarly, NANs provide communication services for distribution systems. WAN is the communication support unit. A number of scattered small-scale communication networks are connected to each other.

Again, the technologies used in GCI can be classified into wired and wireless categories [2]. Nominal features of several recent GCI technologies with respect to this classification are reviewed in Table 5. In this GCI, the following are some major communication requirements [137]:

- Bandwidth/Spectrum: It signifies the range of frequency operated for data transmission.
- Coverage area: It signifies the available physical area possible for communication.
- Data rate: It signifies the quantity of data transported inside a definite time period or speed of data transferred.
- Latency: it signifies the time required to transfer data between two sources.
- Reliability: It signifies the standard representing the availability of data capability.
- Security: It indicates the ability of the GCI to deal with physical and cyber-security attacks to provide satisfactory data exchange condition.

Based on the applications of GCI, the system is designed to meet some pre-requisite values related to these technological features.

1) APPLICATION FIELD OF GCI

A grid is comprised of several different units such as generation, transmission, distribution, and end-users. There is good communication between these elements of the grid through networking technologies so as to achieve several application goals [72]. The key applications of GCI are reported as AMI services, Advanced Metering, Demand Side Management (DSM), DERs, microgrid distribution grid management and automation (DGMA), demand response (DR), Electric Vehicle to Grid (EV2G), SCADA, Overhead transmission line monitoring (OTM), SA, Electric Transportation (ET), Meter Data Management (MDM), Home Energy Management (HEM), Distribution Automation (DA), Outage Management (OM), program/configuration update (FCU), firmware update (FU) and WASA. In this regard, the communication requirements of different grid applications are presented in Table 6. A detailed application of communication infrastructures in these application domains is comprehensively presented in [139] and [142].

E. ROLE OF CLOUD COMPUTING IN EUI-4.0

Cloud computing can be defined as a service over the network for resource allocation and uses. In this regard, the architecture of CC is divided into the following three types: infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Data as a Service (DaaS) [141], [142]. In the electrical utility grid scenario, CC plays a very important role owing to the requirement of a distributed data center as a replacement of a communication network management system (For example, managing millions of SMs in a secure, reliable, and

TABLE 5. Technical features of GCI [2], [25], [140].

Technology	Data rate	Bandwidth /Spectrum	Coverage area
	Wired		
DSL	**256kbps-10Gbps**	240kHz-1.5MHz	300m-7km
ADSL	1-8Mbps		<5km
ADSL2	12Mbps		<7km
ADSL2+	24Mbps		<7km
VDSL	15-100Mbps		<1.5km
VDSL2	<200Mbps		300m-1.5km
Fibre Optic	100Mbps-40Gbps		
PON	155Mbps-2.5Gbps		<60km
AON (*IEEE 802.3ah*)	100Mbps		<10km
BPON (*ITU-TG.983*)	155-622Mbps		<10-60km
GPON (*ITU-TG.984*)	155Mbps-2.44Gbps		<20km
EPON (*IEEE802.3ah*)	1Gbps		<100km
SONET/DSH	10Gbps		<100km
WDM	40Gbps		
PLC	2-45Mbps	1-30MHz	
NB-PLC	1-500kbps		<2km
BB-PLC (Home Plug)	1-200Mbps		<200m
	Wireless		
Cellular Communication			100km
2G-GSM	<14.4kbps	900-1800MHz	1-10km
2.5G-GPRS	<170kbps	900-1800MHz	1-10km
3G-UMTS	384kbps-7.2Mbps	380MHz-2.5GHz	5-75km
EDGE			
3.5G	14Mbps		
4G-LTE	50(UL), 100(DL) Mbps	700,850,900, 1800,2100,2300,2600 MHz	3-12km
5G	20Gbps	<6, 24-86 GHz	
Cognitive Radio (WRAN)	18-24Mbps	54-862 MHz	10-100km
Microwave Communication	155 Mbps	2-40GHz	60km
Satellite Communication		1-40GHz	100-6000km
LEO	2.4 knps-100Mbps		
MEO			
GEO	<1 Mbps		
Wi-Fi (WLGN)	2-600 Mbps	2.4, 5 GHz	20m-1km
WiMax	< 75 Mbps	2.5-3.5GHz	10-50 km
WPAN			
Zigbee	250 kbps	2.4GHz, 868-915 MHz	<100m
Zigbee pro	250 kbps		<1600m
Bluetooth	721 kbps	2.4GHz	<100m
Dash7	200 kbps	433 MHz	2km
Z-wave	40kbps		<100m
6LoWAPN		2.4GHz	10-100m
LPWAN			
LoRaWAN	0.3-50kbps	430,433,868, 915 MHz	2-15km
SIGFOX	600 bps	868,902MHz	<50km

scalable way). In each passing day, there is a sharp curve of the development rate of Smart Grid can be observed, which necessitates bi-directional communication capability support and information processing in real-time.

This development leads to the generation and collection of a massive volume of analog/digital data, that necessitates a big-data management system for storage, organization, maintenance, cleansing, mining, and high-performance computing so as to improve the electric grid service infrastructure. In this perspective, the concept of CC helps in providing high-performance data storage, handling resources, and services at a low cost for numerous grid applications. Therefore, the cloud is recognized as an important platform with a highly secure and stable link in-between network and application layers, for efficient use of the grid resources and services. Because of CC, grid end users are able to access the services and resources through the internet from a remote location [143].

1) OPPORTUNITIES AND CHALLENGES FACED BY CLOUD COMPUTING IN ELECTRIC GRID

The application of CC in the electric grid perspective is very beneficial; however, there are a few difficulties that may be faced by the EUI toward complete implementation. In spite of these hitches, grid application necessitates real-time computing and improved data storage capability, which can be fulfilled by the cloud. In this regard, electric network architecture has several opportunities and challenges for CC technologies [144]. A few of them are discussed as below. To improve the electric grid capabilities, CC adds several attractive features like improved efficacy, lower cost, better strength, central data storage, advanced security, and scalability [145].

Clouds provide a suitable and less costly platform through the internet to share and exchange information between numerous devices connected in the diversified DERs based architecture. Therefore, it offers a low-cost computing platform respecting older models. Some earlier grid applications were abandoned owing to the scalability problem for grid modules installed on larger scales. Could computing technologies have solved this scalability issue by installing storage facilities geographically and mounting them vertically/horizontally [146]. Due to this, the need of physical data storage devices has become unnecessary. Additionally, the robustness of the system is also improved; for example, if power outages/failures occur in an area, an alternative/replicated service will be instantaneously activated.

TABLE 6. Requirement of the GCI applications area [2], [25], [139], [140], [141].

Application	Data Rate	Data Size	Latency	R	S
AMI	10-100kbps/node 500kbps for backhaul	100B-several MBs	2-15s	EG	H
AM	56kbps	25B	2000ms	VG	H
DR	14-100kbps/node	100B	500ms -several min.	EG	H
DA	9.6-100kbps	25-1000B	20-200ms	EG	H
DER	96-56kbps	25-1000B	20ms-15s	EG	H
MG	96-56kbps	25-1000B	20ms-15s	EG	H
DGMA	9.6-100kbps	25-1000B	100ms-2s	EG	H
ET	9.6-56kbps	100-255B	2s-5min	EG	RH
HEM	9.6-56kbps	10-100B	300-2000ms	EG	H
MDM	56kbps	25-200B	2000ms	VG	H
OM	56kbps	25B	2000ms	VG	H
OTM	9.6-56kbps	25B	15-200ms	EG	H
SA	9.6-100kbps	25B	15-200ms	EG	H
WASA	600-1500kbps	>25B	20-200ms	EG	H
EV2G	9.6–56 kbp/s	>25B	2 s–5 min	EG	H
FCU	25–50 kbp/s	>100B	5min–7 days	G	H
FU	400 kbp/s–2000 kbp/s	>100B	2min–7 days	G	H

R: Reliability: S: Security;
VG: Very Good (>98%)
EG: Extremely Good (99%-99.99%);
G: Good (>98%)
H: High
RH: relatively High ()

Security and privacy of data in clouds are one of the greatest concerns for the electric grid. It is generally achieved through an automatic management system for cloud services that offer simpler and improved protection against cyber-attacks [147]. In electric grid-CPSs, the communication link between the physical electrical infrastructure and cyber-infrastructure is somewhat blurred and, as a result, the control system of grid application has been critically exposed to cyber-attacks. In this regard, the power system application needs to be operated under some specific standards to evade these cyber-attacks. On the other hand, there is no specific standard available for privacy concerns. Generally, the cloud environment is used by the electrical utility systems to enhance data safety and privacy for grid applications. For instance, consumers' information (e.g., power usage data) gathered from SMs is encoded with each customer's own pass-key before communicating to the operators in real-time in power system networks [148]. Moreover, the data size and time constraints vary corresponding to the specific application and CC ensures safe and reliable control access of data and communication with utilities.

For different applications, the cloud platforms are also different (either shared or restricted). In this regard, the cloud platform is divided into three basic categories: public-, private-and hybrid-cloud [149]. The public-clouds ensure their essential services to their clients through streaming on the same hardware. Here, a cloud fabric is applied to split the data of various organizations. Although public-clouds appear well-organized, they are less-reliable and vulnerable owing to the possibility of attacks. Thus, public cloud type is not appropriate for electric grid applications. In contrast, the private-cloud provides better security for power systems applications. Visualizations and storing facilities are offered by means of cloud fabric to supervise the access of data. Hence, in power system applications for supervising and communicating client data, private-cloud is used.

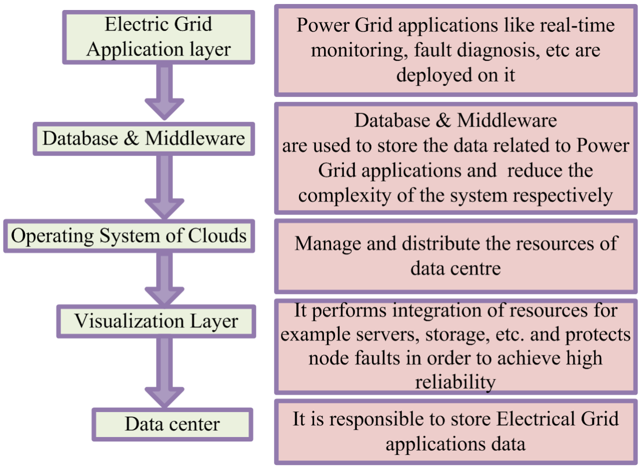

FIGURE 7. Electric grid application layers in CC environment [144].

However, the need for a risk-free environment in the access of data, information management, data protection, and transfers are the foremost issues for private clouds. It can overcome these issues through the provision of safety controls at the operating system levels. Data-security in the electric grid networks should be assured owing to the cloud's confirmation and encryption policies. In this regard, the electric utilities utilize private-cloud infrastructure having five basic layers as presented in Fig. 7 [144]. As the hybrid-clouds comprise the advantage of both public and private clouds, they can also be preferred for power system applications. During stable workloads, work with private-clouds considering the reliability, but in peak workloads, shift the operation to public-clouds in order to improve performance. Thus, on few occasions, hybrid-clouds are preferred for electric grid application so as to meet the consumer requests, such as higher performance or higher security [150], [151].

The US Department of Energy [152] and the National Institute of Standards and Technology [153], [154] have published the results of their studies regarding data access and privacy in electric grid applications. Reference [152] is focused on the issues such as data safety, customer access, and privacy policies. Similarly, the privacy concerns of electric grid consumers, in regard to individual data, personal privacy, behavioural confidentiality, and personal communications confidentiality, are studied in [153]. In addition, the secureness of the electrical grid technologies that unfavourably distress the operation of the grid, are cited in [154].

An advanced grid security system that includes a public key infrastructure technology and few reliable computing features, providing the utmost level of safety for the grid is proposed in [155].

An Integrated Security System (ISS) for the security of the power systems against cyber-attacks is proposed in [156]. ISS comprises of three basic working modules: (i) manager module; (ii) switch & agent module; (iii) assess unit. These units help to improve the security of the grid control systems and legacy control apparatus by ensuring the SCADA system.

A privacy-preserving protocol using steady multi-party computation (SMC) for real-time demand management is proposed in [157]. The privacy-preserving protocol architecture sustains the SM necessities like the safety of the consumer data, load management, supporting a viable billing system, and eliminating the necessity of third-party requests for security.

2) CC SERVICE-BASED ELECTRIC GRID APPLICATIONS

Presently, CC is used to strengthen all three of the EUI basic subsystems: power generation, power transmission and distribution, and power utilization, and has become an important element for grid applications. Many power system projects based on CC have been implemented in recent years, such as Globus [158], EGI-InSPIRE (Integrated Sustainable Pan-Europe an Infrastructure for Researchers in Europe) [159], Information Power Grid from NASA [160], Open Nebula [161] and TClouds [162]. In addition, several other studies citing the application of CC in power systems are presented below.

A system architecture model in the CC platform to realize the grid demand response optimization and generation scheduling is proposed in [163]. The model was the outcome of the Los Angeles Smart Grid Demonstration Project and was further implemented in that city in real-time [164]. The model is used to perform the demand response tasks by retrieving the real-time SMs data, identifying anomalies in a short period of time, updating demand forecast in line with most recent information, and providing targeted replies as soon as peak load occurs.

A CC application in SM framework is presented in [164]. In this framework, all the grid services that execute a progressive metering application are located in the SM cloud applications. All these services are industrialized, maintained, and modernized by the utilities within this cloud. An SM gets into these services by means of a public interface and regulates the system's machines relating to the responses received from the cloud.

A smart CC-based energy management system (EMS) is suggested in [165]. This CC-based EMS is built with three important layers such as consumer, EMS middleware, and physical resources. The EMS middleware and physical resources are positioned within the CC platforms. This CC based EMS provides several benefits, such as easy management of local renewable energy, providing dynamic load demand management, continuity of power supply, energy balance during its processing and storage, increased energy efficiency by clustering resources effectively, increased energy efficiency by decreasing several operations (e.g., monitoring, processing, and communication) of machine-to-machine devices, and it also provides user-friendly EMS.

Application suitability of CC in the grid-CPS structure is explored in [166] and a multi-agent technology to control each node of the grid in cloud architecture is proposed.

The application of CC in grid condition monitoring in order to increase reliability and security is explored in [167]. In this regard, application of Hadoop and HBase tools to increase power system productivity through operating idle servers is suggested.

A model for optimizing the cost of electricity using dynamic power-supply, internet data centers (IDC), and corrected marginal cost (CMC) algorithm is proposed in [168].

Application of CC in smart energy management and information management in power systems is presented in [169]. In this regard, the system is used to monitor the active and reactive power of the system and provide reactive power compensation. The emergence of EVs provides several advantages to the power and transportation domain, but it may affect the system reliability through consuming massive energy. However, the plug-in of EVs at the utility supply system must be controlled and scheduled with the intention of reducing the peak-demand. Considering the problems of plug-in EVs, a novel communication architecture for grids in CC environment is presented in [170]. The problem of EVs charging and discharging process is framed, and a well-organized scheduling method using CC infrastructure is designed. A distributed multi-layer cloud-fog computing infrastructure for optimal energy management in electric grids with high penetration of plug-in EVs is presented in [171]. Three major layouts of EVs charging layout are studied and compared in this work such as smart charging, controlled charging, and uncontrolled charging.

An efficient energy management system to fulfil the peak electricity demand of clients using cloud and fog computing is designed in [172]. Similarly, the cloud & fog-based architecture for effective resource management is utilized in [173]. Moreover, in order to increase the performance of the CC, few major algorithms such as round robin, throttled, artificial bee colony, ant colony optimization, and particle swarm optimization are used for load balancing between grid users' request and service providers.

A novel CC based infrastructure to store and manipulate the data of the grid has been developed in [174]. In this regard, an extensive architecture integrated with AMI, providing several crucial services and enabling new application in the power systems is proposed. Using this principle, a novel application to decrease the multiple estimation of fault location in the distribution system using ML techniques over SM's data is proposed.

Data obtained by monitoring a small scale microgrid was referred to cloud and analyzed in [175] in order to achieve the demand side management. The experimental results clearly indicate the improvement in load balancing.

For application in power systems, CC is found to be advantageous for analyzing and solving the security issues. Considering this advantage, a security game assessment model is proposed in [176]. The proposed model was used for analyzing the cloud-based grid in terms of security, defense and malicious attackers. The obtained results showed that the proposed framework is able to analyses the risk of the SG nodes more accurately and improve the defense strategy. The CC service model usually includes a third party provision to audit the security of the data. Therefore based on this provision, how to analyze the data security risk of the CC-enabled smart grid system is an important point toward futuristic investigation.

With the application of CC, the networked data centers turn into an integrated part of modern power systems. An advanced approach to locate and determine the capacities of the interconnected internet data centers and battery energy storage systems is proposed in [177]. By conducting several case studies authors have demonstrated the usefulness of the stated integrated planning strategy.

Cloud- and cloud-Fog-based methodologies for analyzing the GCI with real-time monitoring are proposed in [178]. This publication is primarily focused on the development of communication system models to be used for voltage profile monitoring and power loss estimation in power systems. However, a cost-benefit analysis toward the application of energy efficient devices in order to reduce computational complexity needs to be carried out to prove the applicability of edge-computing in smart grid environment.

With an intention to decrease the electricity demand in the modern grid environment, a dynamic programming model with a CC framework, which produced a tiny energy hub with clients and presented the clients' participation in demand side management programs, is proposed in [179].

F. BIG-DATA ANALYTICS OF POWER-GRID IN THE CONTEXT OF I-4.0

Integrations of IoT technology and CPS in the power-grid architecture is regarded as an important step of building EIU-4.0 in the era of I-4.0. Through this integration, different power system devices are able to communicate data/information between each other and with control centers. As a result, an exceptional quantity of data is generated, creating challenges to the standard approaches of data transfer, storage, and analysis. In EIU-4.0, an enormous amount of data is collected as an output of ubiquitous integration of devices such as sensors, actuators, controllers, radio frequency identification, web-based application, transactional application and communicating server used for several grid applications, for example electricity pricing data, metering data, energy uses data, grid systems health data, demand and response, advanced control and monitoring and others [25].

Big data (BD) stands for huge volume of data that needs more advanced approaches to capture, curate, handle, and analyze than the conventional apparatus. The question regarding 'the amount of data, referred to as big data, is not well-defined [180]. Usually, big data can be characterized through the following three major features: (i) Large volume, (ii) High velocity in data generation, storage and transmission and (iii) High variability in the dataset. In this regard, five major characteristics of big data are shown in Fig. 8 [181]. Here, 'Value' is regarded as consistency of the data. The nature and type of data is under the characteristic's 'variety'. The 'veracity' covers the quality of the collected data. The term 'volume' is related to the amount of generated data and 'velocity' describes the speed at which the data is produced and being processed [182].

FIGURE 8. **Five major characteristics of Big Data.**

1) BIG DATA ANALYTICS

In power systems, data analytics has got an important place to support smart/intelligent decision-making through proper identification of patterns and interdependencies from a massive amount of data. Moreover, this will help EUI to monitor, analyze and diagnose their inefficiencies in an effective way [183]. Therefore, with the application of big-data analytics, the electrical generation and distribution process can be controlled and managed in a more efficient and transparent way in EUI-4.0.

Big Data analytics is generally comprised of massive data and its related analytic methods, Fig. 9. These methods are based on different computer platforms such as Windows, Linux, Mac etc. and they involve certain level of expertise.

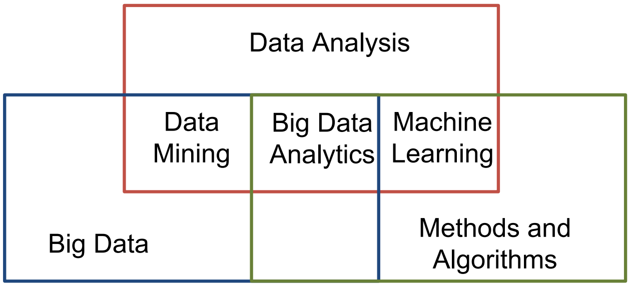

FIGURE 9. **Components of big data analytics [182].**

The present EUI statistics of big data implementation are shown in Fig. 10 [184]. It can be clearly seen from the figure that only 20% of utilities have implemented big data analytics. Nevertheless, it is also important to note that out of these 20% utilities, most of them used the big data analytics through tapping only a fraction of its potential [184].

Furthermore, as highly structured bodies, EUIs generally tend to be inclined towards system reliability instead of endeavoring towards new technology. Thus, they are slightly reluctant to implement big data analytics. Moreover, a few other factors, such as lack of management support, skill shortage, data management issues, and lack of proper business models, also act against the implementations of big data analytics.

2) KEY CHALLENGES TO APPLY BIG DATA ANALYTICS

Application of big-data analytics in power system environment may face several key challenges in real world situation, Fig.11 [184].

Presently, the quantity of data being produced by EUIs is growing at an exponential rate. Due to this increased volume of data, there is a huge demand for data storage and computing resources. The potential solution to this issue can be stated as: development of dimensionality reduction techniques, parallel computing, edge computing, and cloud computing.

Data uncertainty is one of the key features of real-world power system data. This is mostly due to incomplete information and operational understanding. Due to this, the quality of data followed by quality of decision making get hampered badly followed by decrease in accuracy, completeness, and consistency of data. Probabilistic and stochastic analysis, data cleaning (e.g., dealing with missing values, smoothing noise, outliers, and inconsistent data) are few possible solutions to this data quality issue.

Data security (for example, privacy, integrity and authentication) has a vital role in system architecture in order to

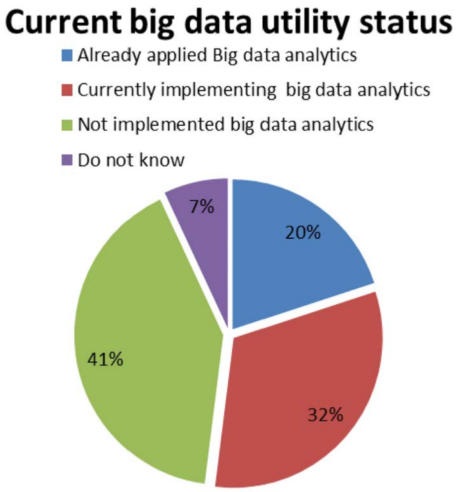

FIGURE 10. Status of big data implementation.

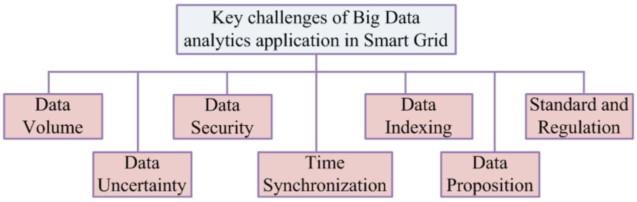

FIGURE 11. Key Challenges to apply big data analytics in EUI.

secure private information of consumers and utilities. Failure in data privacy may lead to malicious attack and compromise consumer privacy. Similarly, data integrity challenges lead to cyber-attack followed by misleading operational decision and financial transactions. Techniques available to deal with privacy, integrity and authentication issues are data aggregation, privacy-preserving data aggregation and data encryption, respectively.

Time synchronization is a major concern in modern power systems owing to the increased need of real-time control and communication. Time synchronized data helps to draw significant information from the current and past events through real-time situational awareness, and subsequently provide prognostic decisions. However, the unsynchronized data misleads the decision through erroneous analysis of data, and wrong diagnostic of earlier events. At the present time, devices are synchronized based on same radio clock, as synchrophasors and PMUs provide time synchronized data.

The problem concerning data indexing and query processing in power systems data increased computational complexity and processing time of the system. The existing techniques against this problem generally use generic tools, for example SQL server and SAP for query purposes, which may not be sufficient from the system application viewpoint, mostly if real-time applications are sought from the big data. However, few other advanced data indexing methods such as R-trees, B-trees, and Quad-trees can be used to deal with the problem of data indexing in big data in power systems.

Successful deployment of big data analytics necessitates proper business models for all stockholders including utilities, system operators and the clients. In this regard, the utilities should provide sufficient training about the long-term economic and technical values of big data.

Several standards and communication protocols (e.g., IEC 61850, IEC 61850-90-7, IEC 61970/61968, IEEE 1815, and IEEE 2030.5) are specifically designed for power system interoperability. However, no effort is being made yet on interoperability among big data analytics platforms, architectures, and system operational frames. In its place, different utilities are applying big data analytics with different storage, computing, processing platforms. All these diversified uses of big data analytics protocol delay the adoption of big data analytics to power grid with its full potential. In this regard, there is a strong need of focus from both EUI and academia, to develop standards for big data analytics architecture, platforms, and interoperability.

3) APPLICATION OF BIG DATA IN EUI

Steps of big data analytics are described in Fig. 12. Data acquisition is the primary step that handles data collection task. Initially, the system data is collected from numerous and varied sources in different formats and features. In the data storage step, all assembled data gets cleaned, analyzed to retrieve authentic facts and integrated in a workable format. Data analytics step includes mining, modeling and application of new approaches to extract useful information from the system data. The following important algorithms are used in this step; clustering, correlation, classification, categorization, regression, and feature extraction. In the application step, the operational data is integrated with a system to obtain a decision or gain result.

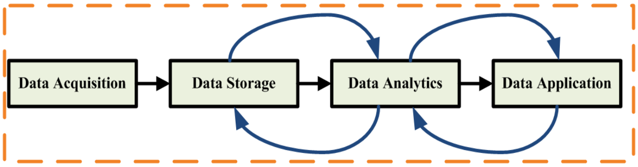

FIGURE 12. Key Stages of big data analytics.

The application of big data analytics in power systems will be helpful towards (i) making the power grid more reliable and resilient, (ii) delivering optimal asset management and operation, (iii) improved decision making through proper sharing of information and (iv) improved performance of the system. Following are few major application areas/subarea of big data analytics in power systems: Generation control center (generation planning, economic load dispatch), transmission operator (wide area control, state estimation, stability enhancement, real-time monitoring), distribution system (real-time operation, equipment health monitoring, asset management, planning, forecasting), end users (demand response, load forecasting, real-time energy management, customer behavior) and market operation (energy forecasting, price forecasting, risk analysis, revenue management). Out of these application domains, a few recent studies are summarized below.

Real-time energy management can be possible by managing large volume of data in an efficient and intelligent manner [185]. Moreover, several other tools or methods (such as improved forecasting tools, advanced demand response techniques, well-organized data management structure and data analytics) also play an important role in the energy management of the grid in an optimized manner. Several ways of information extraction process from big data to achieve efficient energy management in the grid are reported in [186].

An advanced architecture based on big data to support the creation, development, maintenance and exploitation of smart energy services through the utilization of cross-domain data is proposed in [187]. An internet-enabled decision support system is also established as stated by the suggested model, utilizing diversified data within a smart city framework to the design the energy management action strategies. This ''user driven'' decision support system can assist utility executives and municipal authorities for handling their building energy services' in an efficient manner. However, a real-word implementation dealing with real-time data is further important to justify the authors claim. Similarly, a big data enabled mobile edge computing based EV charging scheme is proposed in [188]. The mobile edge computing servers employ big data mining and aggregation in a dispersed way to lessen the size of data to be handled by the global EV controller. By this process the computational cost of the controller get reduced.

Demand response is a fundamental module of any energy management process. A clustering technique based on time-series data collected from SMs in order to recognize appropriate customers and historical energy consumption patterns inside the DR program is designed in [189]. Similarly, a method based on SM data, implementation of a time-based Markov model and clustering algorithms to recognize the customer energy consumption dynamic is proposed in [190]. The stated work has addressed the challenges of massive high dimensional electricity consumption data in diversified and efficient ways. However, the effect of peripheral factors (such as temperature, day-type, and the economy of power consumption) was not analyzed in this work. A tensor-based big data management technique for dimensionality reduction of data collected from internet-of-energy environment in a smart city is presented in [191]. An SVM based technique to recognize the customer behavior (normal, overload and underload) in order to take part in the DR program is also proposed here. The overall result shows that the tenser based method outperforms conventional DR management schemes in term of accuracy. However, the computational complexity needs to be analyzed further in the case of large-scale implementation such as smart city network. Similarly, a methodology based on big data to extract the energy consumption pattern in smart city is proposed in [192].

Non-electrical big data, collected from social media like Twitter, is applied to detect and locate the power outage in [193]. In this regard, the authors have proposed a supervised topic model with a heterogeneous data network. The method has been tested with actual tweets and outage events. The supremacy of the stated approach compared to other related work is also reported with numerical results. In future prospective, the method can be coupled with the current distribution management system to empower a social user-driven outage management. Importance of geographical information system-based data, global positioning system-based data, weather and lightning data, seismic data, animal migration data, and electricity market data in outage management is studied in [194]. Applicability of SCADA and PMU based big data in voltage stability prediction is discussed in [195]. Data related to PMU based big data is applied in many more applications, such as transient stability margin detection [196], data-driven mode oscillation detection [197], fault location [198], improvement of reliability and stability [195], [196], [197], [198], and fault event detection [199].

SM based big data is utilized for anomaly detection in [200]. Moreover, the big data technologies have been found to be beneficial for several other applications: for example: transmission constraint management or monitoring of generator performance to improve market and operational efficiency. From applications viewpoint, advanced visualization is an important area of big data analytics. Big data analytics with the visualization technologies is used for real-time power system monitoring. Commercial tools like real-time dynamics monitoring systems (RTDMS) are used for visualization using PMU- big data [201].

Power grid state estimation is becoming a challenging task owing to the availability of huge amount of data. A calibrated model for distribution feeder based on the collected big data from SMs and photovoltaic micro-inverters is suggested in [202]. Several other applications of big data analytics in power grid state estimation are presented in [203], [204], [205], and [206].

V. MAJOR FINDINGS AND FUTURE RESEARCH DIRECTION IN EUI-4.0

Based on the above survey, some possible future research directions, that could help the prospective researcher in this area, are outlined below.

A. ARTIFICIAL INTELLIGENCE TOWARD EUI-4.0

1. A continuous development or improvement in the existing AI technologies is necessary, as their role is important in the current industrial manufacturing processes like improved product quality, production efficiency and overall speed.
2. Use of collaborative robots (or Cobots) is presently becoming increasingly common in industrial as well as

in research laboratories and commerce. Cobots function by taking instructions from humans so as to work more efficiently with them, including commands that were not primarily anticipated in the initial programming. Robots don't get fed up, hungry or drained. The abilities of AI are better than human capability when considering such things as miniaturization and accurate measurements, and they provide improved quality assurance. The major objective of robots and Cobots in the electrical utility industry is to achieve complete autonomy, without demanding human interference, to execute inspection, maintenance, and repair deeds at hazardous areas or sites. Development of such robots through integrating AI is one of the interesting directions that require more attention.

3. The current power system infrastructure enables the application of AMI, micro-PMU and DERs in the conventional grid that provides unlimited potential to improve system observability and controllability. AI technologies (for example, data-driven and machine learning) can recognize the power consumption behaviour of end-users, develop situational consciousness, and support system operators through providing accurate decisions, exclusively in adverse circumstances. This has immense capability in improving system reliability and resiliency, that need further attention.
4. Data collected from the grid may involve varied dimensions of data quality. Several methods to increase the data quality dimensions have been reported [207]. Assessment and measurement of these dimensions is dependent on individual analyses and user feedback [208] because of their association with prejudiced and situational judgements for quantification. Therefore, in further research improvement in different dimensions of data quality is essential for enhancing the monitoring and optimization process. This will likely have a direct impact towards improving the performance of Industrial AI applications leveraging these data [209].

B. INTERNET OF THING TOWARD EUI-4.0

1. The IoT based devices generally work under diverse and adverse environments (for examples, extreme high/low temperature, high voltage, contacts with electromagnetic waves, in water, etc.) and they must fulfil necessary reliability and compatibility requirements.
2. In several applications, IoT based devices and sensors run on batteries (for example, different kinds of measuring device that are used to monitor transmission lines). Therefore, proper energy harvesting methods should be used or invented.
3. In the modern grid communication infrastructure, IoT based apparatus should support essential communication protocols with the intention of transmitting data from SMs to the control station.
4. IoT based devices have insufficient supplies and facilities for example batteries, processing power, storage, and bandwidth. Therefore, some data fusion method should be adopted to compress and combine valuable data, which helps to achieve energy saving and bandwidth usages.
5. Delay and packet loss are vital issues that limit the performance of the power system. Further, congestion is the reason of delay and packet loss that lowers the system performance (since IoT devices and/or gateways IoT devices have got to resend data which instigates additional delay and increases the possibility of congestion), and prescribed prerequisites, for instance, maximum tolerable delay, cannot be assured. Thus, it becomes essential to optimize delay and network design by obtaining an optimal number of gateways and IoT devices, and minimize the number of connections to each gateway.
6. Power systems are starting to be comprised of several gateways and IoT devices with diverse specifications. Therefore, interoperability amongst these devices to exchange data is really essential. Internet protocol-based network is one important solution in order to achieve this interoperability. Moreover, it is also important that IoT devices should aid various communication protocols and designs.
7. Currently, unavailability of specific and unified standard for IoT devices in power system applications leads to security, reliability, and interoperability issues. Therefore, special attention should be devoted to standardize this effort.
8. During the monitoring and controlling of IoT appliances, internet connectivity is essential although it is vulnerable against cyber-attack followed by financial and security loses. Therefore, development of secure communications for IoT devices in the smarter grid and determination of some security measures for these devices are some essential requirements in the future prospective.

C. CYBER PHYSICAL SYSTEM TOWARD EUI-4.0

1. Reliability study on the optimization of links between communication infrastructure such as HAN-NANs and NANs-WANs for several applications.
2. An extended research should be possible to identify appropriate topologies for these communication networks.
3. Design of adoptable routing protocols for secure and quality-of-service-ware data collection from numerous system applications.
4. Dimensionality and complexity are two major challenges to incorporate cyber failures and malfunctions in composite power system reliability evaluation [210].
5. To enhance security of power grid, grid personnel should not use default or semi-difficult password to access critical data. In this way, the cyber security issues can be avoided. In this context, face recognition technology can be adopted with complex password to access the desired data.
6. Efficient energy storage is one of the important parts of power system with RESs. In any case, if such a section of the system is attacked, there should be some necessary guidelines that a defender should take to avoid any system interruption [211]. Future work should provide an in-depth

risk assessment of the energy storage systems and their impact on grid operation.

D. COMMUNICATION INFRASTRUCTURE TOWARD EUI-4.0

1. Reliability study on the optimization of links between different components of communication infrastructure, such as HAN-NANs and NANs-WANs, for several system applications. An extended research should be undertaken to identify appropriate topologies for these communication networks.
2. Design of adoptable routing protocols for secure and quality-of-service (QoS)-ware data collection from numerous systems uses.
3. The software defined network (SDN) technology is found to be an advanced communication networking solution in modern power system environment. SDN with the complete information of the overall network and the configuration status of network elements is capable of improving network productivity and flexibility, in order to facilitate traffic routing in the grid communication networks [12].
4. Major communication provisions include security, interoperability, QoS and experience, and scalability. A number of recent works in this area are available in literature but they are still at their initial stages.
5. The forthcoming 5G of communication networks includes numerous attributes, for example, ultrahigh capacity, ultra large bandwidths, ultra-dense sites, and ultra-reliability, and with various existing ICT technologies [167]. With the advancement of 5G, mobile cellular networks are progressively emerging toward a strong platform for omnipresent massive information acquisition, storage, analysis, and communication.

E. CLOUD COMPUTING TOWARD EUI-4.0

1. Security is one of the key issues for EUI. Data inside the cloud shouldn't be compromised. However, when hackers try to compromise the internal system, the risk of data security increases. In this situation, providing security to counter these hackers has become a challenge for cloud services. Thus, a proper safety framework based on authentication is necessary to increase security when cloud computing is employed for power system applications.
2. Public cloud can be combined with the private cloud for significant and economic development of the system. Nevertheless, security and privacy are two significant questions during the necessary data exchange between private and public clouds.
3. In the vein of energy scheduling, data traffic scheduling is also vital in order to maintain acceptable data traffic rate in the grid with CC environment.
4. Application of multi-mobile agent (MMA) integrated with CC for cost-effective system operation. Owing to varied communication structural design [2] of the grid, MMA can be deployed to communicate through unique layers. Thus, proposing a suitable mobile scheme for the agent is necessary for profitable information management in the grid.
5. There is a need to improve the delay suffered by the SMs using CC architecture. Therefore, it is necessary to develop a cloud network, wherein smart elements can recuperate their delay by replacing their selected path.
6. The basic concept of a smarter grid is decentralized power distribution through an accessible centralized structure. The advanced CC protocol based structural design will definitely support distributed character of the grid. Thus, active participation of CC based services by the customers should be boosted in order to achieve reliability and profitability in services.
7. Large amount of data or information flow is generally seen inside the modern utility systems. Thus, as soon as a failure occurs in these utility systems, the network connectivity gets affected followed by letting-down of data centre operations. In this type of disaster situations CC may be used to recover network failures and restore data.
8. In the present architecture, integrating the energy components with cloud computing is not possible. So, in the advanced architecture, new protocols should be defined to make a proper interconnection between the cloud platform and the electric grid components. Under such a scenario, the efficiency of both CC service providers as well as users will be enhanced. In the advanced architecture, the optimum utilization of network can only be possible through a defined model where access to the grid services is allowed only to the subscribers and others are blocked to access the services.

F. BIG DATA TOWARD EUI-4.0

Big data analytics is more than just the technical challenges of handling big data. The architecture of electrical grid is complex in nature and has a close interdependency with other critical infrastructure, for example transportation, gas, water, heating, IoT and CPS. A few forthcoming research directions to efficiently implement big data in EUI are given below.

1. Owing to the power system infrastructure, there is a huge growth of energy big data. This brings several thoughtful challenges for the long-established IT infrastructure with regard to data collection, pre-processing and efficient uses [212]. Therefore, IT infrastructure needs to be upgraded in several aspects such as, network transmission capacity, data storage capacity, data processing capability, data exchange ability, data visualization capability and data communication capability in order to support big data driven smart energy solution.
2. The volume of big-data is generally large and comprised of valued information. However, the quality of data in many cases may not reach a desired standard. In this regard, the relevance, reliability, accuracy and consistency of energy big-data needs large improvement [213]. The big-data driven power system management system needs a comprehensive data governance policy, along with organization

and control measures. Good quality, standardization and consistent organization are the fundamental requirements of many big-data-enabled uses.

3. Integration and sharing of energy big data from different sources of the grid is one of the most challenging issue that needs to be focused.
4. Old-fashioned data analysis procedures in data-mining, ML, statistical analysis, data management and data visualization may run into some technical hitches in dealing with the energy big data. Therefore, research toward development of novel, fast and efficient data processing as well as analysis tools should be carried out in order to support smart energy management in the grid.
5. Power system is vulnerable to cyber-threat and attack, and a lot of privacy information is embroiled in energy big data. For that reason, security and privacy is one of the essential concerns in big data driven power system management.

VI. CONCLUSION

A detailed survey on I-4.0 including its importance to electrical utility industry is reported in this paper. Altogether, a large volume of existing literature in similar domain is reviewed critically. It is noted that I-4.0 is being more effective and applicable in the present market owing to its capability, adjustability, re-configurability, flexibility and dispersed manufacturing pattern.

Effort has been made in the survey to highlight the role of different I-4.0 technologies in electrical power domain. In this regard, initially, a brief literature survey on the concept and design of I-4.0 from general perspective followed by electrical utility prospective, is presented. Subsequently, a detailed study has been carried out for each individual component of I-4.0 such as Internet of Things, cyber physical system, cloud computing, big data and communication infrastructures, from the perspective of power systems. Then, several benefits and challenges, and open research issues associated with EUI-4.0 are analyzed.

Few of the important finding can be highlighted as:

- Presently, EUI is tackling a robust need to upgrade the power-grid energy generation, transmission, and distribution capability by incorporating newly evolving technologies.
- It is observed that the implementation of key technologies of I-4.0 in power system infrastructure is gaining momentum gradually. Due to this, the present power system is gradually inclined towards shifting the energy market trend, development of intellectual strategies, rise of innovative tools and electricity generation, distribution, and consumption to a flexible and decentralized structure.
- In I-4.0 framework, power system with the integration of cutting-edge technology, such as ICTs, CPS, IoT, IIP, AMI and IoE, will provide numerous facilities to gratify the client requests and financial profits.
- Nevertheless, the application of these mechanisms to attain safe and consistent electricity generation to utilization functionalities and services in an inexpensive manner will not be easy.
- Research toward development of novel, fast and efficient data processing as well as analysis tools should be carried out in order to support smart energy management in the grid.

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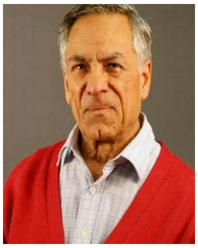

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