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A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid

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ABSTRACT

The Smart Grid (SG) is a technological transformation from conventional electric grid, electro-mechanically controlled system, to smart, intelligent, and electronically controlled system called the "Smart Grid" (SG). There are about 20–30% losses present in the conventional electric grid due to substandard operations at generation, transmission and distribution side. The major players in the transformation are: **(a)** increased electricity cost, **(b)** aging infrastructure, **(c)** carbon footprint, **(d)** Green House Gas emissions, **(e)** climate change, and **(f)** less efficient electrical network. The promising features of the Smart Grid are: **(a)** intelligent de-centralized control, **(b)** resilience, **(c)** flexibility, **(d)** sustainability, **(e)** digitalization, **(f)** intelligence, **(g)** consumer empowerment, **(h)** green energy, and **(i)** smart infrastructure. The fundamental issues and open challenges in the SG are lack of awareness, consumer acceptance, cyber terrorism, data collection management, energy metering, dynamic optimization and energy control. Considering above, in this paper, a comprehensive review exploring information of development, technologies, and techniques in the SG. The main goal is to investigate and reveal the key enabling technologies, to obtain better picture about the current status of SG development. The focus areas of this review study are Architectural Model focusing Consumer Empowerment (CE), Demand Response Program (DRP), and Demand Side Management (DSM). Our survey discusses in detail the Communication Technologies, such as Wireless Advance Metering Infrastructure (AMI), Phasor Measurement Unit (PMU), Supervisory Control and Data Acquisition (SCADA), and Machine to Machine Communication (M2M). The power systems such as Micro Grid, Nano Grid, Pico Grid, Inter Grid, Virtual Power Plants, and Distributed Generation are also elaborated in this review study. Renewable Energy Resources (RERs) Integration with the SG and Integration issues related to Distributed generation (DG) are presented in this survey. This survey also analyzes Architectural Model of the Smart Grid focusing consumer empowerment and prosumers interaction. The aim of this study is to provide deep understanding of technologies and their applications in the SG.

1. Introduction

"The term 'Smart Grid' (SG) refers to a modernization of t monitor, protect, and optimize the operation of its interconnected elements. Through the high-voltage network and distribution system. The industrial user and building automation systems, energy storage installations and end-use consumers and their thermostats, electric vehicles, appliances and other household devices" will perform intelligent, robust, and optimized operation for energy managment [1]. The anticipated benefits and requirements of the SG are defined by US National Institute of Standards and Technology (NIST) in [1]. The SG reflects a transition from the conventional power system to advance electric grid. The SG is a complex system, including desired features of consumer's empowerment, user friendly and automated response during contingency. The advanced SG assists Distributed Generation (DG) and immune to cyber-attack.

The bi-directional power and communication flow is another attractive feature of the SG, thus favouring prosumers as a part of

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Nomenclature

Acronyms	Definition
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AES	Advance Encryption System
AEP	American Electric Power
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
ADSL	Asymmetric Digital Subscriber Line
BT	Blue Tooth
BW	Band Width
BPLC	Broadband Power Line Communication
CE	Consumer Empowerment
CR	Cognitive Radio
CDMA	Code Division Multiple Access
DG	Distributed Generation
DRP	Demand Response Program
DSM	Demand Side Management
DSL	Digital Subsciber Line
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission System
GPS	Global Positioning System
GSM	Global System for Mobile
HAN	Home Area Network
HVDC	High Voltage DC
HEM	Home Energy Management
IP	Internet Protocol
LTE	Long Term Evolution
LMI	Linear Matrix Inequility
M2M	Machine to Machine
MBWA	Mobile Broadband Wireless Access
MAC	Medium Access Control
MCT	Microwave Communication Technology
MPPT	Maximum Power Point Tracking
MAS	Multi-Agent System
MPC	Model Predictive Control
NAN	Near Area Network
NIST	National Institute of Standards and Technology
NETL	National Energy Technology Laboratory
OFC	Optical Fiber Communication
OFDM	Orthognal Frequency Division Multiplexing
OFDMA	Orthognal Frequency Division Multiple Access
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PLC	Power Line Communication
PHEVs	Plug In Hybrid Electric Vehicles
PON	Passive Optical Networks
PV	Photo Voltaic
QoS	Quality of Service
RERs	Renewable Energy Resources
SC	Sattelite Communication
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
STATCOM	Static Synchronous Compensator
SOC	State of Charge
TTU	Tennessee Technology University
UMTS	Universal Mobile Tellecommunication System
VSAT	Very Small Aperture Terminal
VDSL	Very high Digital Subsciber Line
V2G	Vehicle to Grid
WDMA	Wavelength Division Multiple Access
WMN	Wireless Mesh Network
WiMax	Worldwide Interoperability for Microwave Access
Wi-Fi	Wireless Fidelity

the SG. The consumers, prosumers, and utilities can modify the terms of business deals through incentives and disincentives within SG [2]. Using efficient Demand Response Program (DRP) with DG, the prosumers interaction in SG will improve the sustainability of the electric grid. Therefore, in order to achieve efficient, reliable, and economic power generation, the SG is the requirement of the time [3]. Table 1 presents a comparison between existing electric grid structure and the SG [64].

The concept of the SG originated with notion of Advance Metering Infrastructure (AMI). The idea of AMI aims for improving energy efficiency and Demand Side Management (DSM). The AMI technology leads to the concept of electric grid with automatic fault detection and self-healing capabilities. The DSM is characterized by consumer's ability to efficiently monitor and control the energy consumption. The flatter electricity consumption profile reduces the load stress on electric grid achieved by utilizing efficient DSM program [4]. The present electric grid is a centralized system, that is highly susceptible to the security threats. The SG in contrast to the present electric grid is a combination of smart infrastructure, smart management, and smart protection systems. Using efficient DSM, DG or de-centralized generation can be added to the SG. The de-centralized generation provides effective control and monitoring system during faults without effecting the whole transmission and distribution system [5].

The distribution system in the earlier days was radial and poor. The future distribution system is meshed and intelligent [6]. Numerous names are being attributed to a modern distribution framework, yet the dual idea of mesh and intelligence makes the SG a favored term of the creator [7]. The technologies playing an important role for the advancement of the distribution system, such as: **(a)** Distribution Automation, **(b)** Advanced Digital Meters, **(c)** Distributed Generated Energy Resources, and **(d)** Optimal-Cost Communication systems. The Advanced Distribution Automation (ADA) Programs, visualizes circulation frameworks as Exceptionally Automated Frameworks (EAF) with adaptable electrical framework construction. The EAF works with open architecture of communication and control [8]. The SG is a foundational innovation that will impart significant changes to the current power grid.

The megatrends in the field of energy, such as in information technology, infrastructure, and government polices affect electrical industry. Moreover, consumer empowerment, and new improved communication technologies are the root cause for transforming the present electrical grid to the SG [9]. The conventional electirc grid is unable to handle new trends and indicates some degree of saturation. The control data in the presence of communication bottle necks with lack of advance control techniques in centralized generation is susceptible to security threats, thus an evidence of saturation [9]. In Fig. 1, a generalized overview of the SG is presented.

Many state-of-the-art surveys and reviews on the SG features exist

Table 1
Comparison between conventional electric grid and the SG [64].

Conventional electric grid	Smart Grid
Electric Machinery	Digital
One way Communication	Two way Communication
Centralized Power Generation	Distributed Power Generation
A small number of sensors	Full grid sensor layout
Manual monitoring	Automatic monitoring
Manual recovery	Automatic recovery
Failuares and voltage outages	Adaptive and Islanded
Few user option	More user option

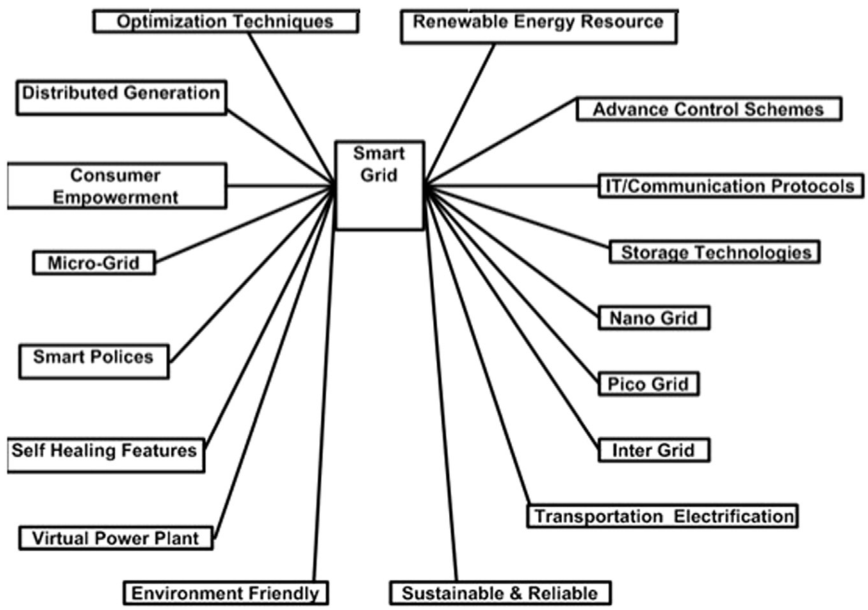

Fig. 1. Generalized over view of the SG.

within the literature. For example, Sebastian et al. [10] discussed the importance of standardization in the SG and suggested some recommendations. Wencong Su et al. [11] presented a comprehensive overview of transportation electrification in the SG focusing on Electrical Vehicle (EVs). Moreover, Hashmi et al. [12] described the SG architectures, associated technologies implemented worldwide, and the SG concepts. Furthermore, Maher Guizani et al. [13] uncovered the RER integration related issues, review available technologies, suggested and solutions to address above problems. Abolfazl Azari [14] reviewed the SG from power and communication aspects. While Per Goncalves et al. [15] presented a survey for understanding prosumers and discussed on how to provide end users with value added energy services within the SG domain? Florian Skopik et al. [16] described the threats and vulnerabilities of metering infrastructure in the SG. Tahir Mehmood et al. [17] surveyed distribution system reliability in the SG. Reddy et al. [18] discussed communication technologies and their advantages and disadvantages in the SG scenario. Arun Kumar Nanda et al. [19] presented reviewed study on smart energy management system and purposed smart home energy management system. Although the aforementioned surveys presented a complete overview of the SG, but they lack in aggregating the SG features from different domains, such as communication, control, consumer interaction, and power systems in one study. Selected surveys are summarized in the Table 2. In Table 2, ✓ justifies the presence of features, × while represents that the feature is absent in the referred study.

In the light of above stated issues, the main objectives of our survey are:

- ***Objective 1:*** Currently, the conventional electric grid is replacing by efficient, reliable, and resilient SG. In order to explore the concept of technological advancement in SG, this survey thoroughly investigates the architectural model of SG considering **(a)** CE, **(b)** DSM, and **(c)** DRP.
- ***Objective 2:*** Our survey presents the communication technologies, such as: **(a)** Wireless communication technologies, **(b)** Wired communication technologies, **(c)** AMI, **(d)** WAMS, **(e)** SCADA, and **(f)** M2M. Furthermore, wireless and wired communication technologies are discussed in detail.
- ***Objective 3:*** We elaborate the utilization of RER and DG in the SG. The DG is quantitatively analyzed by incorporating **(a)** classification of DG technologies, **(b)** DG storage technologies, **(c)** RER based DG, and **(d)** integration benefits of DG. This survey also study the technical issues in the integration of DG technology with the SG.
- ***Objective 4:*** We survey advance control techniques deployed in SG, such as: **(a)** the interplay of intelligence and control techniques, **(b)** voltage and stability control, **(c)** droop control, **(d)** hierarchical control, **(e)** fuzzy control, and **(f)** multi-agent based control. Furthermore, this survey reviews the role of Micro Grid, Nano Grid, Pico Grid, DG, Inter Grid, and VPP.
- ***Objective 5:*** This Survey incorporates a study of future development areas of SG. The key future development areas are: **(a)** Power and energy domain, **(b)** Communication Technologies, **(c)** Battery storage systems, **(d)** Renewable energy system, and **(e)** V2G and grid to vehicle (G2V) interaction with SG.

The rest of paper is structured as follows: Section 2 presents an architectural model of the SG focusing CE. The communication technologies for the SG is investigated in Section 3. In the Section 4 power systems and advance control schemes are presented. Section 5 concludes the paper with brief summery.

2. Architectural model of the SG

2.1. Consumer empowerment (CE)

The most effective and attractive feature of the SG is CE and AMI is an advanced system for monitoring, measuring, and management of consumer's energy profile [54]. The bi-directional power and communication flow will help to buy (consumers) and sell (prosumers) electrical energy from utility, as a server and client [55]. The server receives a request for energy supply, and on approval, client will receive energy. The energy usage at right time will the result in client and server interaction. The consumers can directly supervise energy by monitoring their energy usage profile [56]. The direct supervision of the energy usage profile will also enhance the empowerment of decentralized distribution system of prosumers and consumers.

The prosumers interaction is another attractive feature of CE that provides incentives to consumers on exporting excess of generated electricity from RERs. Fig. 2 presents consumers profile monitoring with number of units utilized per hour and pastenergy utilization statistics [57]. The per hour usage information of the electric energy will help consumers in energy cost estimations for next month. The

Table 2
Summary of some generic state-of-art surveys.

Ref.	AMI	RI	CT	MG	NG	DG	VPP	DR	DSM	PI	ACSG	AM
[14]	×	✓	×	×	×	×	✓	✓	×	×	×	×
[12]	×	×	×	×	×	×	×	×	×	×	×	×
[13]	✓	✓	✓	×	×	×	×	×	×	×	×	×
[22]	✓	×	✓	×	×	×	×	×	×	×	×	×
[23]	✓	✓	✓	×	×	×	×	×	×	×	×	×
[15]	×	✓	×	×	×	✓	✓	×	✓	×	×	×
[24]	✓	✓	✓	×	×	×	✓	×	×	×	×	×
[25]	×	✓	×	×	×	×	×	×	×	×	×	×
[26]	×	×	×	×	×	×	×	✓	×	×	×	×
[27]	×	×	×	×	×	×	×	✓	×	×	×	×
[16]	✓	×	✓	×	×	✓	✓	×	×	×	×	×
[28]	✓	×	✓	×	×	×	×	×	×	×	×	×
[19]	✓	×	×	✓	×	×	×	×	×	×	×	×
[29]	×	×	×	✓	×	✓	✓	✓	✓	×	✓	×
[30]	✓	✓	×	×	×	✓	×	×	×	×	×	×
[21]	×	×	×	×	×	×	×	×	✓	×	×	×
[20]	×	×	✓	×	×	×	×	×	✓	×	×	×
[31]	×	×	×	×	×	×	×	×	✓	×	×	×
[18]	✓	×	×	×	×	×	×	×	×	×	×	×
[17]	✓	×	×	×	×	×	✓	✓	✓	✓	×	×
[32]	✓	×	✓	×	×	×	×	✓	✓	×	×	×
[33]	✓	×	✓	×	×	×	×	✓	×	×	×	×
[34]	×	✓	✓	×	×	✓	×	×	×	×	✓	×
[35]	×	×	×	×	×	×	×	×	×	×	×	×
[36]	×	×	×	✓	×	✓	×	✓	✓	×	×	×
[37]	×	✓	×	×	×	×	×	×	×	×	×	×
[38]	✓	×	✓	×	×	×	×	×	×	×	×	×
[39]	✓	✓	✓	✓	×	✓	×	✓	✓	×	×	×
[40]	×	×	✓	×	×	×	×	✓	×	×	×	×
[41]	✓	×	✓	×	×	×	×	×	×	×	×	×
[42]	✓	×	✓	×	×	×	×	×	✓	×	×	×
[43]	×	✓	×	✓	×	✓	×	×	×	×	×	×
[44]	×	✓	×	✓	×	×	×	×	×	×	✓	×
[45]	✓	✓	×	✓	×	✓	×	✓	✓	×	×	×
[46]	✓	×	×	×	×	✓	×	×	×	×	×	✓
[47]	✓	✓	×	✓	×	✓	×	✓	×	×	×	×
[48]	✓	✓	✓	×	×	✓	×	×	×	×	×	×
[49]	×	×	✓	✓	×	✓	×	×	×	×	×	×
[50]	×	×	✓	×	×	×	×	×	×	×	×	×
[51]	✓	✓	×	×	×	✓	×	✓	✓	×	×	×
[52]	×	✓	×	×	×	×	×	×	×	×	×	×
[53]	✓	×	✓	×	×	×	×	×	×	×	×	×
[54]	✓	×	✓	×	×	×	×	×	×	×	×	×
[55]	✓	×	✓	×	×	×	×	×	×	×	×	×
OS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Abbreviations
AMI: Advance Metering Infrastructure
RI: Renewable Energy Resources Integration
CT: Communication Technologies
DA: Distribution Automation
MG: Micro Grid
NG: Nano Grid
DG: Distribution Generation
VPP: Virtual Power Plant
OS: Our Survey
DSM: Demand Side Management
PI: Prosumers Interaction
ACSG: Advance control for Smart Grid
AM: Architectural Model
DR: Demand Response

concept of smart consumers can be deployed in the SG, enhancing the CE features, such as DSM and DRP. The CE provides a way to consumers for optimizing their energy usage profile more effectively. The consumer's on spot decision making ability and direct load control features lead towards energy saving. The direct monitoring and visibility of demand with DRP features will bring a positive impact on the electric grid [58].

The conventional electric grid charge consumers on the basis of flat rate, while in the SG scenario, real time based charging idea is applied [59]. The CE not only creates a user-friendly environment but also helps in reducing the cost by utilizing various optimization techniques. The trust factor between utility and consumers is a major challenge in the complete implementation of CE features. The proposed architecture for CE demonstrates towards the security issues for accessing the users and prosumers profile. The application based defined software (apps) are immune to unauthorized access gives a positive addition in CE, thus making utility, consumers or prosumers, satisfied. Fig. 3 demonstrates the proposed architecture focusing CE with complete flow of information between utility, and consumers (or prosumers).

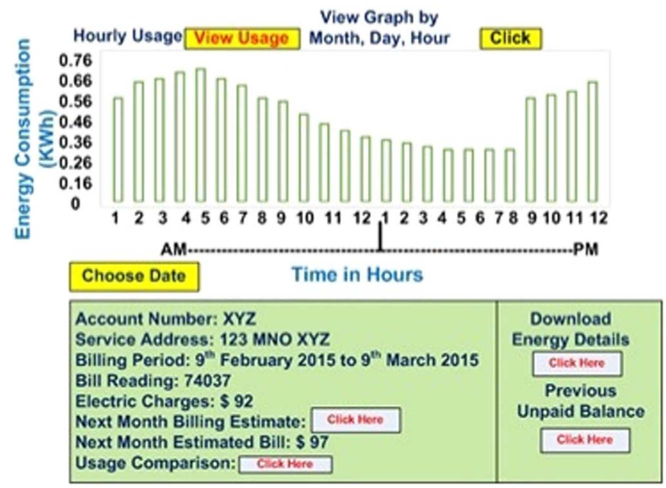

Fig. 2. Energy usage profile monitoring [66,67].

The bi-direction power flow is not shown in Fig. 3; only two-way communication flow is presented between utility, consumers, and prosumers. The AMI sends and receives information between utility,

Consumers, and prosumers. The energy usage information is sent to the utility through AMI apps that can be accessed by consumers or prosumers. The specially designed apps for accessing the energy usage and other information immune to hackers and unauthorized access must be denied.

The third party access can be monitored by generating special security codes. After accessing the energy usage profile and other information, consumers and prosumers can monitor their energy units utilized per hour. The consumers and prosumers can estimate next month billing and can compare the statistics with previous energy usage. This smart architecture design in its real implementation will help to maintain and increase the trust factor between utilities, consumers, and prosumers. The prosumers will get satisfied and energy sold by them from RERs will help in sustainable grid-support. This above implementation will result in optimized energy usage and increase the energy efficiency by mitigating the energy crisis in developing countries. Fig. 4 illustrate the evolutionary characteristics of CE.

2.2. *Demand Side Management (DSM)*

The interaction between consumers and utilities turns out very effective with the utilization of DSM. The DSM in the SG environment will be able to meet the social development gauge and enables consumers to use energy efficiently. The improved DSM structure help utilities to monitor, control, and repair power network in real time [60]. The peak load shifting (load management) is possible with the deployment of DSM in the SG. The load management feature by CE and DSM considerably reduces the peak (load) stress on the electric grid. Fig. 5 demonstrate the peak (load) stress reduction on the electric grid.

The active participation of consumers in the SG is potentially possible by utilizing large number of distributed sensors, thus making a strong feedback system. This feedback system ensures a timely response in the SG environment. The SG takes DSM in its feedback

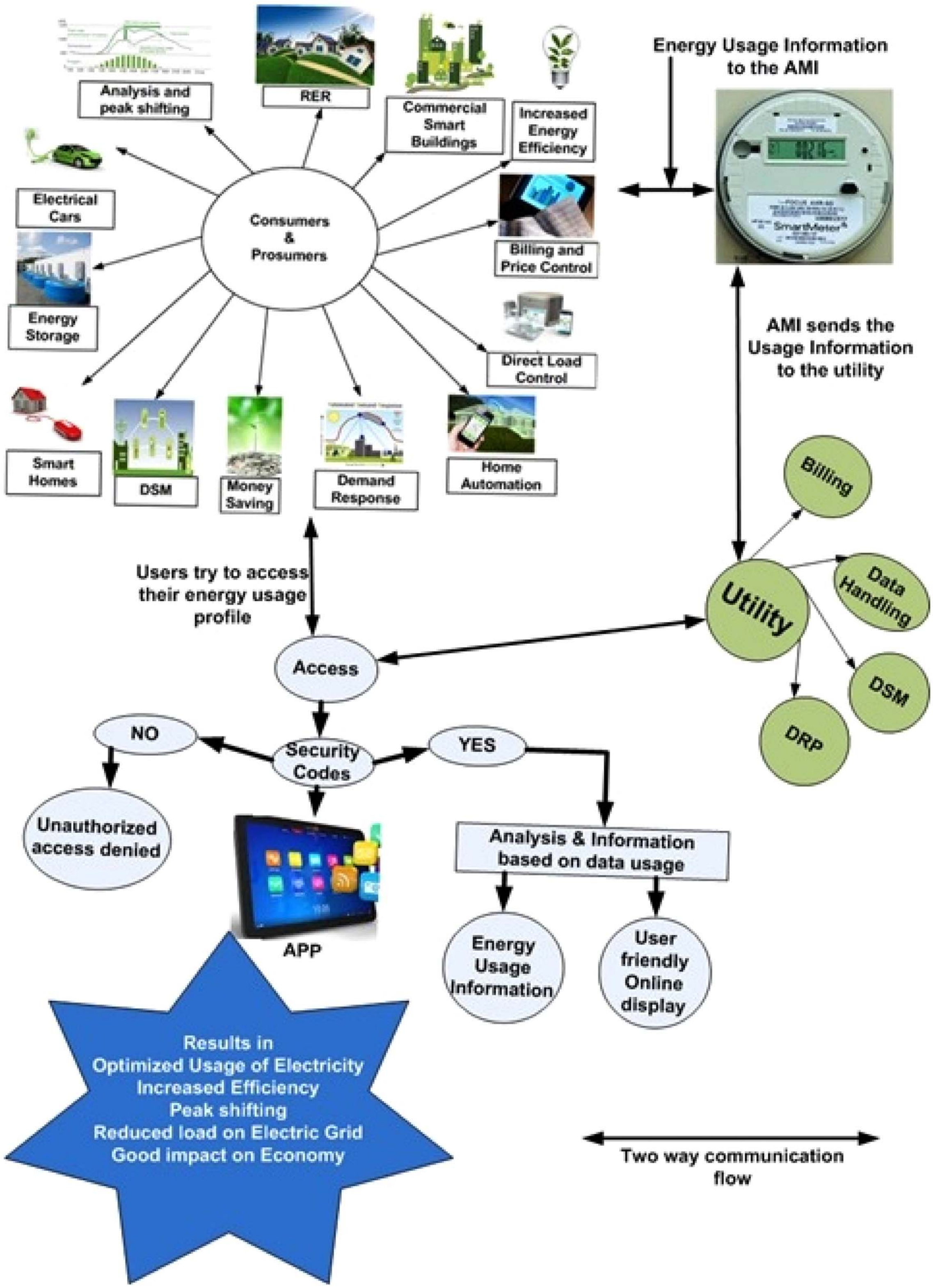

Fig. 3. Architectural Model of the SG focusing CE.

system, hence optimizing the energy usage by continuously monitoring the DSM loop.

The study in [62] presents the results of AMR for DSM to meet consumer requirements. The fundamental benefits of AMR for power system include **(a)** better control, **(b)** efficient monitoring, and **(c)** timely response. The efficient monitoring of power system and timely response considerably assists in load management and thus minimizes the outages and losses. Fig. 6 illustrates the appreciable results of load management using DSM [63].

The green line in Fig. 8 indicates the energy utalization with DSM. The red line depicts the energy usage with efficient electricity equipment, while blue line presents the energy usage without DSM. From Fig. 8, huge energy difference can be easily visualized in absences of DSM. DSM has a great impact on peak load time and assists in

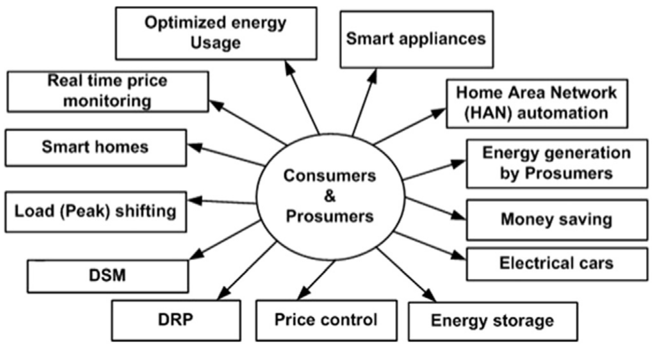

Fig. 4. Evolutionary characteristics of CE.

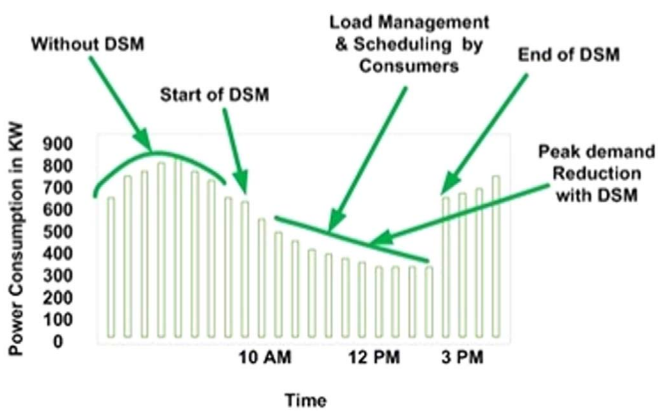

Fig. 5. Load management and reduction of peak stress on electric grid by DSM [61].

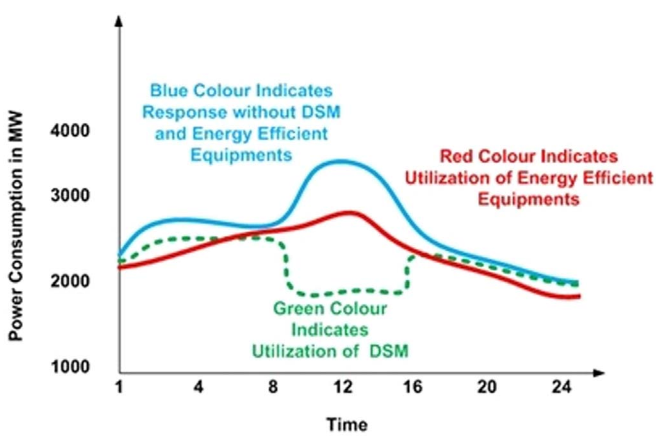

Fig. 6. Appreciable results of DSM [63].

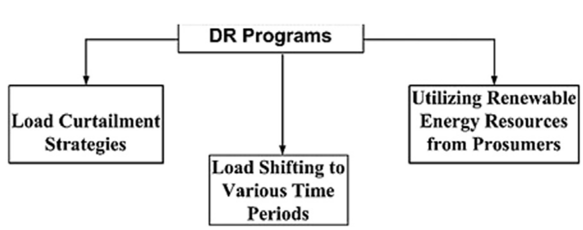

Fig. 7. Ways of customer participation in DRP [66].

attaining the optimized energy usage. The results in Fig. 6 illustrate DSM puts more positive impact on consumers profiles rather than buying energy efficient equipment. The energy efficient equipment has a positive impact on the electric grid but during peak load compared to DSM proves more worthy. The results will be nearer to ideality with combined utilization of energy efficient devices and DSM. The DSM in a wider picture will be helpful in transparency on consumer end and emphasizes on active control, compared to passive control [63].

2.3. Demand Response Programs (DRP)

DRP are algorithms that plays a vital role in effective energy management of the SG. The DRP are defined as “Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [65].

The DRP will lead to economic benefits by regulating the short term impacts on the energy market and endorse the interaction of consumers with the utility. The active participation of consumers in DRP can be possible in three different ways, as demonstrated in Fig. 7 [66].

The three modalities of DRP are price-based, incentive-based, and demand reduction bids [66]. These approaches and algorithm will deliver a better idea of consumer's energy usage. Demand electricity curve is a great count to forecast future demands of consumers. Smart energy models based algorithms are being applied to DRP. Mathematical models are very helpful in optimized demand-supply management. Distribution estimation is a statistical estimation that reveals long term and short term elastic or inelastic (two levels) DRP behavior of consumers. DRP algorithms play imperative responsibility for the improvement of electric grid and make effective use of the electricity energy in future [67].

3. Communication technologies in the SG

The management of massive data requires a secure, reliable, and cost effective communication technology in the SG. The communication technologies enable a bi-directional flow of information between various entities in the SG. The debate on “how and what communication technology should be implemented in the SG is still in the process?” [68]. The communication technologies in the SG are classified in two main types, such as Wireless and Wired. Fig. 8 presents the classification of communication technologies implemented in the SG. Table 3 briefly summarizes the characteristics of communication technologies deployed in the SG.

The information flow in the SG is classified in two categories. The first information flow is from sensors to metering infrastructures. The widely held system for this connectivity is PLC or Wireless Communication. The second information flow is from metering infrastructure to the data center; carry out through Cellular Networks or the Internet [69]. In this Section, Communication Technologies deployed in the SG are investigated.

3.1. Wireless Communication

The main advantages of Wireless Communication over Wired Communication are mobility, easy replenishment, and low cost. The wireless technology is the most appropriate for remote applications [70].

3.1.1. Wireless Mesh Network (WMN)

The wireless communication network organized in a mesh topology named as Wireless Mesh Network (WMN). The WMN consists of groups of radio nodes and every single node act as an independent router. The self-healing nature of WMN enables information signal to communicate through another active node, if any node drops out of the mesh network. The WMN is a significant technology for the subsequent wireless technology generation [71]. In WMN, and the capability of multi-hop routing with extended coverage is possible. The meters in WMN acts as a repeaters with further addition of repeaters provide wide coverage accompanied by increased capacity. The WMN possesses

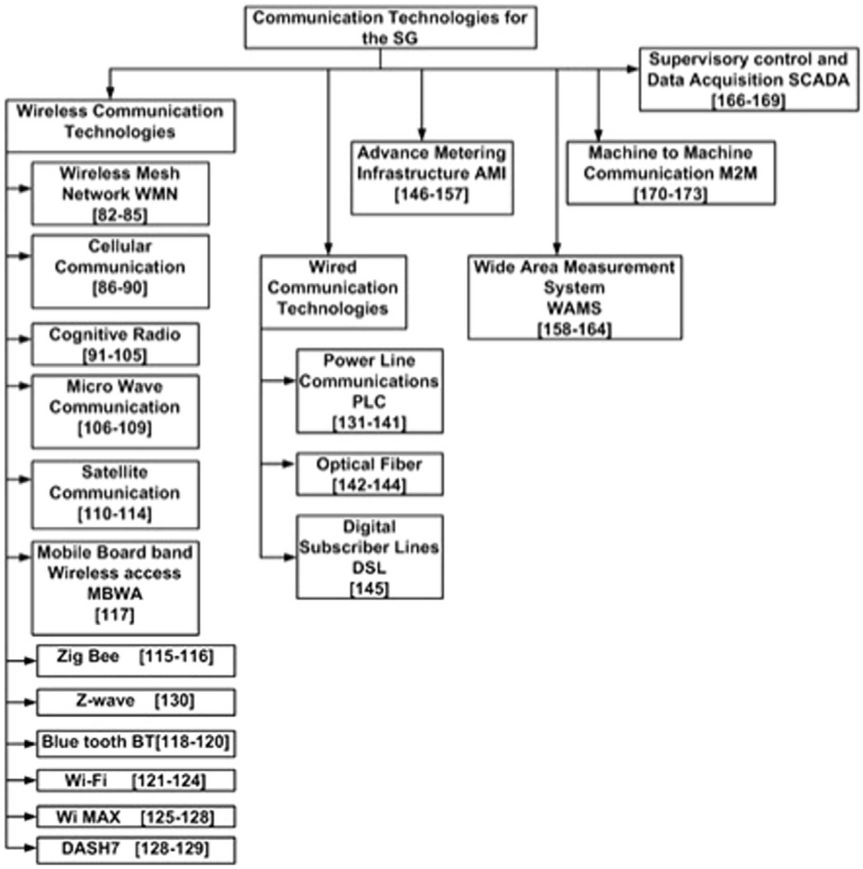

Fig. 8. Classification of Communication Technologies for the SG.

ability to be dynamically self-organized, self-healing, and self-configured. The aforementioned features of WMN provide reliable network coverage, load balancing and improved performance [72]. The application domains of WMN are: **(a)** Advance Metering Infrastructure (AMI), and **(b)** Home Energy Management (HEM) system. The Radio frequency based mesh topology gained high popularity in North America. The Sky Pilot Networks (Private Company) utilize a mesh network for the SG applications. The foremost challenges for WMN are: **(a)** interferences, **(b)** fading, and **(c)** capacity. Furthermore, adequate numbers of smart nodes, flexible routing, reliability, encryption techniques further increases network complexity. The travel of data packets around many neighbours cause additional problems of loops, resulting in bandwidth reduction [73,74].

3.1.2. Cellular communication

The cellular communication technology is the best option for communication between far nodes, utility, and smart meters. Currently, 2G, 2.5G, 3G [75], 4G, GSM [76], LTE, and WiMAX are the available cellular communication technologies. The cellular communication for data transfer is a mature technology proven over decades. Typically, 15-min interval generates the huge amount of data between utility and smart meters. This huge amount of data requires a high-speed data transfer medium. 3G or 4G with fast and cost effective coverage for large geographical locations [77]. IEEEP2030/D7.0 recommends using 3G cellular communication technology as a backhaul network [78]. The problem of network congestion may arise due to customer market share [79].

3.1.3. Cognitive Radio

Cognitive Radio (CR) is a software defined radio intelligent technology. The dynamic, efficient, and reliable use of an underused radio spectrum is facilitated by CR. The bandwidth scarcity problem is also being resolved by utilizing CR. The CR technology prohibits unauthorized interferences to authorized users transmitting unlicensed devices to unused licensed spectrum holes [79]. The combination of different protocols, operating frequencies, and waveforms are being configured by CR technology. The ongoing research in the field of CR includes: **(a)** channel estimation, **(b)** medium access control (MAC), **(c)** spectrum sensing, and **(d)** spectrum sharing. In November 2004, IEEE 802.22 working group was formed to develop standards for CRs [80]. The authors in [81] discussed that a new way of implementation of real-time CR can enhance the SG network security. Another study in [82] proposed a CR link for communicating between the control center of the SG and sensors at the consumer's side. The test bed for CR at Tennessee Technology University (TTU) is being built [83,84]. Fig. 9 present silent features of applying CR to the SG [85,86].

3.1.4. Microwave Communication Technology

For obtaining secure transmission of information at higher bandwidths, Microwave Communication Technologies (MCT) are widely used. MCT are point-to-point communication technologies. The point-to-point MCT is used for communicating over 50% of world's mobile base stations [88]. MCT resolved primary issues for rolling out economical mobile infrastructure, during past 20 years [89]. The portability, anti-interferences, and high transmission capability are distant features of MCT. The coverage over 50miles distance can be easily provided by MCT. The undesirable transmission loss, line of sight propagation, and low diffraction reduce the MCT performance. Multi-path interferences and precipitation are two types of signal fading faced by MCT [87]. The SG applications of MCT are transfer trips between distribution feeder protection relays, distributed energy resources, AMI, and DRP [90].

Table 3
Summary of communication technologies deployed in the SG.

Ref.	Technology	Standard	Pros	Cons	Frequency	Coverage	Data Rae	Cost	Application	Technology Maturity
[71–74,135]	WMN	Data not available	MIMO Integrated antennas,	High Latency and Cost, Complex Protocols.	900MHZ, 2.4 GHz, 5.8 GHz,	15 miles (maximum possible)	Similar to 802.11 b/g/n.	Moderate	Last-Mile access, AMI, DR, Automation, Remote Monitoring	Mature
[75,135]	3G	UMTS CDMA 2000, EV-DO, EDGE	Readily Available, Inexpens-ive, Widely Deployed, Large number of vendors	Not Secure, Not suitable for higher bandwidth applica-tion	With GSM range is 380 MHz to 1.9 GHz CDMA/EV-DO range is 800 MHz to 1.9 GHz	3–5 miles (hilly terrain) 30–45 miles (flat-terrain)	Up to 14.7 Mbps 28 Mbps and 22 Mbps	Moderate – High	AMI Backhaul, Communicat-ions Network, Mobile Workforce	Very mature
[135]	LTE	3GP release 9	Reduced Latency, Higher Capacity, Enhanced Mobility, Lower Power consump-tion.	Still in Testing phases, Less expertise- in designing.	700 MHz, AWS 1700/2100 MHz, IMT 2500 MHz, GSM 900 MHz, UMTS 1900/ 2100 MHz, Cellular 850 MHz	2–3 miles(radius) [urban area] 5–7miles radius [rural area].	100 Mbps 50 Mbps 326.4 Mbps 84.6 Mbps.	High	AMI backhaul, SACADA backhaul, DRP, Mobile workforce, Video surveillance.	New
[87,90,135]	MCT	FCC part 101, Part 15	Wide ranges, Well understood, Highly secure	Point to Point configureation, Frequency congestion	E-band 70 GHz To 80 GHz, Unlicensed up to 5.8 GHz	50miles.	Throughput of 310/360 M bits/s.	Moderate	SCADA backhaul, AMI, DRP, Automation.	Mature
[136]	GPRS	Data not available	Cost Effective, Remote access and control.	Low Data Rates.	900–1800 MHz	1–10 km.	170 kbps	Moderate	AMI, DR, HAN (Home Area Network)	Mature
[136]	GSM	Data not available	Cost effective	Low data rates	900–1800 MHz	1–10 km	14.4 kbps	Moderate	AMI, DR, HAN	Mature
[93,94,135]	ZigBee	IEEE 802.15.4–2003, ZigBee Alliance.	Lower power consump-tion, Self-organized, Secure and Reliable, Supports large number of users	Limited internal memory. Slow processi-ng.	2.4 GHz worldwide	10–100 m	250 kbps worldwide	Low	HAN, AMI	New
[95]	MBWA	IEEE802.20	Improved Bandwid-th, Low latency, Fast	Data not available	Data not available	Vehicular std.	1–20 Mbps	Moderate	Remote monitoring. Plug in Hybrid Electrical Vehicle's communicate-on.	Mature
[98–101]	Wi-Fi	IEEE 802.11	Data not available	High power consump-tion	2.4–5 GHz	Extended coverage	1–150 Mbps	Moderate	Vehicle to Grid	Mature
[102,105,135]	WiMAX	IEEE802.16d–2004, IEEE802.16e–2005, IEEE802.16 m	Reliable and secure, Simple, Improved scalability	Lower bitrate over large distance, Asymmetrical sharing of bandwidth	2.3 GHz, 2.5 GHZ, 3.5 GHz	4 miles	4–16 Mbps, Up to 100 Mbps with IEEE 802.16 m	Moderate	DRP, AMI, SCADA	Mature
[106]	DASH7	ISO/IEC 1800–7	Extended Battery life , Lower power consump-tion	Lower Data rates	433 MHz	250 m to 5 km	28–2400 kbps	Moderate	Control of Electrical Vehicles, As an alternative to ZigBee	New
[117]	Z-Wave	Z-Wave Standards	Lower power consump-tion,	Lower Bandwid-th	900 MHz	Similar to ZigBee	0.1 Mbps	Low	Home Automation	New

(continued on next page)

Table 3 (*continued*)

Ref.	Technology	Standard	Pros	Cons	Frequency	Coverage	Data Rae	Cost	Application	Technology Maturity
[74,114,135]	PLC	IEEE P1901 G.hn/G.99	simple Cost effective	Higher electro-magnetic interferences	BPLC 30 MHz, Radio Frequency 1.7 MHz to 80 MHz	15 km	10 Mbps	High	AMI, Substation automation, Remote Monitoring, Automation.	Mature
[135]	WLAN	IEEE802.11b/g/n	Reliable, Inexpens-ive	Not secure, Low coverage	2.4 GHz, 5 GHz	10 m indoor 250 m outdoor	11 Mbps, 54 Mbps, 100 Mbps	Low	HAN, Automation,	Mature
[96]	Blue Tooth	IEEE 802.15.1.	Low Power Consump-tion.	Weak Security.	2.4–2.4835 GHz.	1–100 m.	721 kbps	Low	Local online monitoring of substation.	Mature

3.1.5. Satellite Communication

The global coverage by Satellite Communication (SC) provides a best solution to remote access control and monitoring [54]. The SC is the cost effective communication for remote DG resources and substations, where no communication infrastructure exists. Some utilities install SC equipment for monitoring the rural substations. A service called Very Small Aperture Terminal (VSAT) by SC is also available for connecting remote substations [91]. Global Positing System (GPS) is used for accurate location updates and time synchronization. In case of link failure or emergency situation, SC can be used as a backup for communication networks [92]. The associated shortcomings with SC are higher delay [54] and channel fading [183]. The channel characteristics of SC are uncertain and weather dependent, results in performance degradation of whole SC system.

3.1.6. ZigBee

For a short range of 10–100 m and low data rate networking applications, ZigBee Alliance developed a protocol called “ZigBee”. The ZigBee technology has IEEE802.15.4 standard based Media Access Control (MAC) and physical layer. Operating bands for this protocol are 864 MHz for Europe, 915 MHz for USA and Australia and 2.4 GHz worldwide. The data rate for Europe is 20 kbps, for USA and Australia, the data rate is 40 kbps and 250 kbps worldwide. The ZigBee consists of three types of devices, such as ZigBee coordinator, ZigBee router, and ZigBee end device. The coordinator device act as a base (root) node in tree topology and as a bridge for further networks. The ZigBee routers pass on information from other devices they receive and can run application functions. The 128 bit Advance Encryption Standard (AES) is being utilized for security in ZigBee [93]. The SG application area of ZigBee includes: **(a)** direct load control, **(b)** control of home appliances, **(c)** remote meter reading, and **(d)** security systems. The limited internal memory, slow processing capacity, limited battery supply are the major problems encountered by ZigBee. The application domain of this technology is limited for home automation system, and is not well documented for industrial use [94].

3.1.7. Mobile Broadband Wireless Access (MBWA)

Mobile Broadband Wireless Access (MBWA) is also known as Mobile-Fi, with a data rate of 1 Mbps to 20 Mbps. The MBWA is based on IEEE 802.20 standard and is a new emerging technology. The IEEE 802.20 Standard aggregates IEEE 802.11 and IEEE 802.16 positive features. The MBWA offers: **(a)** high bandwidth, **(b)** low latency, and **(c)** fast mobility. The SG applications of IEEE 802.20 standard includes: **(a)** communication for Plug In Hybrid Electric Vehicles (PHEVs), **(b)** SCADA systems, and **(c)** wireless backhaul for monitoring electric grid [95].

3.1.8. Blue Tooth (BT)

Blue Tooth (BT) is an IEEE 802.15.1 based personal wireless area network standard. BT is a short range and low power radio frequency standard with a data rate of 721 kbps. The IEEE 802.15.1 technology can facilitate both points to multi-point and point-to-point communication with a distance coverage of 1–100 m. BT is highly susceptible

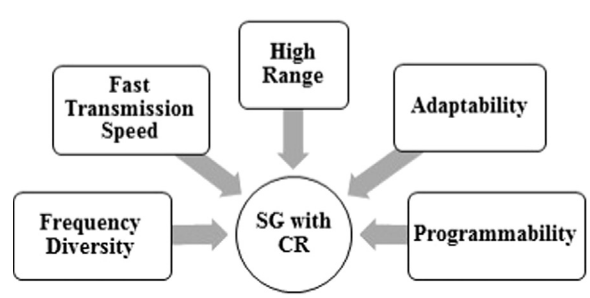

Fig. 9. Silent features of applying CR to the SG [86].

to interferences of surroundings communication links, such as IEEE802.11 based Local Area Networks (LAN) wireless network [140]. The application areas of BT in the SG are substation automation for local online monitoring [97].

3.1.9. Wi-Fi

Communication technologies used for Wireless Local Area Networks (WLANs) based on IEEE802.11 standards, are known as Wi-Fi. The operating unlicensed frequency band for these standard lies between 2.4 GHz and 5 GHz [98]. The latest release of 802.11 family standards is 802.11n with a data rate of 150 Mbps. The standard 80.11e on the account of Quality of Service (QoS) is important for the SG applications [99]. The standard 802.11p is substantial for V2G [100] and 802.11 s allows multi-hop application [101].

3.1.10. WiMAX

WiMAX is based on IEEE 802.16 standard and support distance coverage up to 10 km with a data rate of 100 Mbps [102]. The recent version of this standard is 802.16j that is multi-hop and multi-cast technique for mobile users [103]. Another version of WiMAX is 802.16 m suppose to provide mobility up to 350 km/h with a data rate of 100 Mbps [104]. The WiMAX technology appears to be most suitable for the SG distribution domain, compared to cellular and wired solution [105].

3.1.11. DASH 7

DASH 7 technology is ISO/IEC 1800-7 standard based and used in wireless sensors networks with 433 MHz frequency range. The ISO/IEC 1800-7 standard based technology has a distance coverage extendable to 5 km, with a data rate of 28–2400 kbps. In the SG domain, the application area of DASH 7 includes: **(a)** PHEVs, **(b)** control, **(c)** monitoring, and **(d)** an alternative to ZigBee. DASH 7 requires a wake up signal of 30–60 μw and latency around 2.5–5 s [106].

3.1.12. Z-wave

A respectable alternative to ZigBee is a Z–wave standard, developed by Z-wave alliance. The operating frequency range of this standard is 900 MHz with data rate of 0.1 Mbps. Z-wave requires low band width and is a low cost and simple technology. In home automation applications, Z-wave is the leading wireless technology [107].

3.2. Wired Communication

The Wired Communication Technology (WCT) includes: **(a)** Power Line Communication (PLC), **(b)** Optical-Fiber Communications (OFC), and **(c)** Digital Subscriber Lines (DSL). In the following, briefly these WCT are explained.

3.2.1. Power Line Communication (PLC)

The modulated carrier signal transmitted through an electrical wiring system is called “Power Line Communication” (PLC). The direct connection of PLC with meters, make it a first choice for communication in electrical environment [74]. The SG will be widely adapting PLC due to power distribution lines and low cost installations [108]. PLC has two major categories, such as Narrow band PLC and Broad Band PLC (BPLC) with data rate of 2–3 Mbps. PLC is a cost effective technique that allows utilities to use power infrastructure for data flow and metering applications [109]. This technology is a highly reliable technique, but it is not suitable for applications in Home Area Networks (HAN) due to lack of standards and interoperability [110,111]. The low voltage distribution network based PLC system is being utilized for the SG in China [112]. The shortcoming of this technique is low band width characteristics, that restrict the use of PLC in applications that require higher band widths [113]. The author in [114] presents a new protocol stack that will transform low speed physical layer of PLC to robust model. The enhanced features of BPL over High Voltage lines can bring momentum to information transmission within SG [115].

3.2.2. Optical-Fiber Communication (OFC)

Optical-Fiber Communication (OFC) systems provide strict Quality of Service (QoS) with nearly unlimited Band Width (BW). OFC is one of the promising communication infrastructures that offer reliable data transmission [116]. This technology is highly immune towards radio frequency and other electromagnetic interferences. The amplification of data requires fewer numbers of repeaters in this technique. The initial cost of OFC is high, but sharing capability of OFC among various users can recover this cost in short time span. In SG scenario for last mile communication, OFC may be the cost effective and reliable solution. The Ethernet PON is being utilized with electrical transmission and distribution lines for data communication within SG [117].

3.2.3. Digital Subscriber Lines (DSL)

Digital Subscriber Line (DSL) permits data transfer over existing telephone lines. The DSL technology includes: **(a)** Asymmetrical DSL (ADSL), **(b)** ADSL2+, **(c)** and Very high DSL (VDSL). The ADSL supports 8 Mbps for downlink and 64 kbps for uplink. ADSL2+ permits 24 Mbps for downlink and 1 Mbps for uplink. The VDSL allows 54 Mbps and 16 Mbps for up and down link respectively. In the SG context, DSL can be advantageous, simple, and cost effective owing to the utilization of existing wired communication infrastructure [118].

3.3. Advance Metering Infrastructure (AMI)

Advance Metering Infrastructure (AMI) is a two-way communication infrastructure between utility, smart meters, and consumers. AMI collects and distributes information, this enhancing CE features for energy consumption and management. AMI is the integration of computer software, hardware, data management, monitoring systems, and smart meters [119]. AMI can be defined as “Smart Meter” [120] and can communicate with utility and consumers through PLC [121]. The real time monitoring requires higher BW per device; PLC may be insufficient for those applications of AMI. The employed parameters for AMI are real and reactive power, power factor, voltage and current, energy consumptions, and maximum demand [122]. The household activities in form of energy statistic can be recorded in AMI [123]. The advantages of AMI are regulated energy demands, reduction in frauds related to electricity market, precise billing, and consumer's awareness [124]. The essential requirements for AMI are low latency and higher BW. The AMI latency for real time monitoring should be 12–20 ms [125].

3.4. Wide Area Measurement System (WAMS)

The WAMS is implemented around world with PMU and PDC

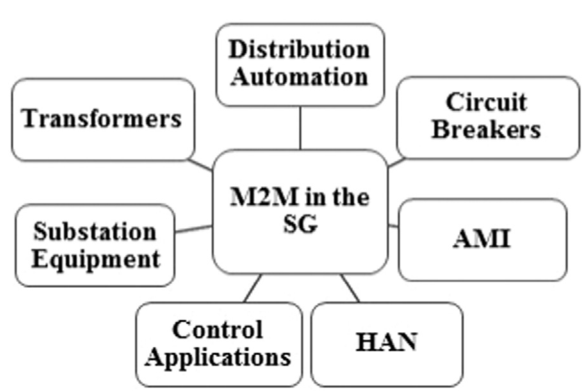

Fig. 10. Key areas of M2M applications in the SG.

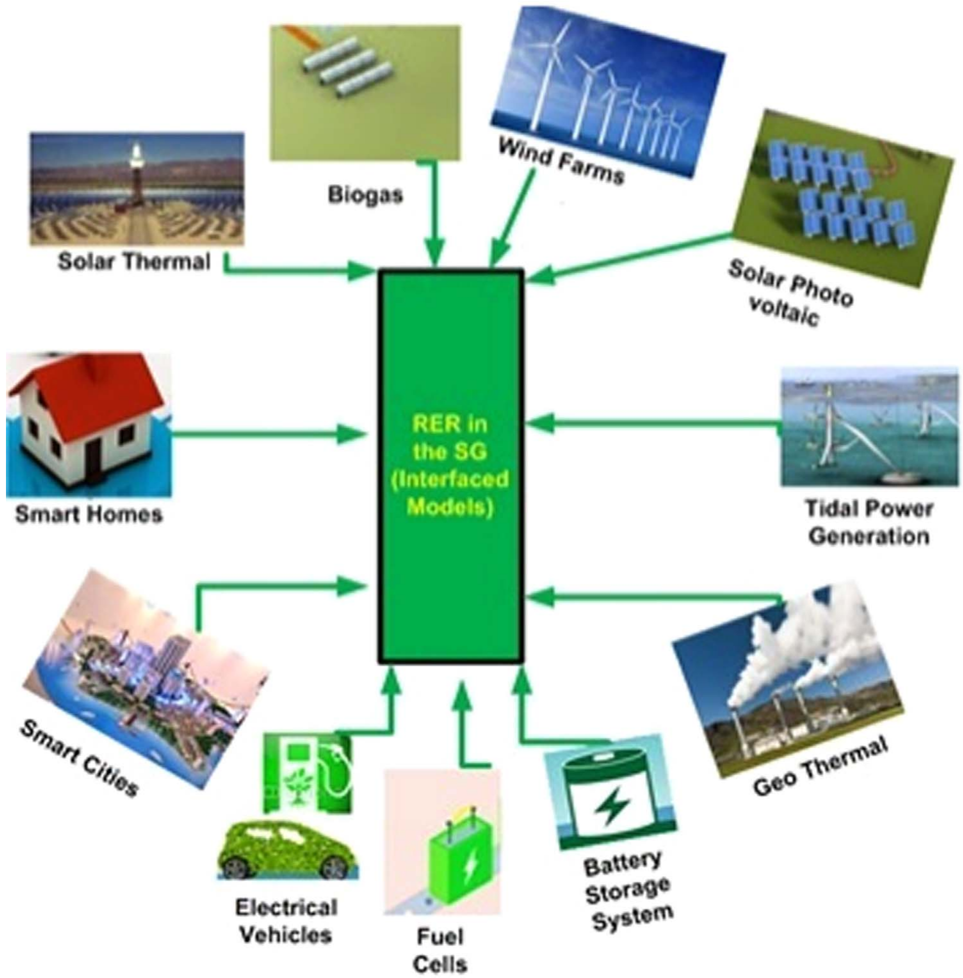

Fig. 11. RER in the SG.

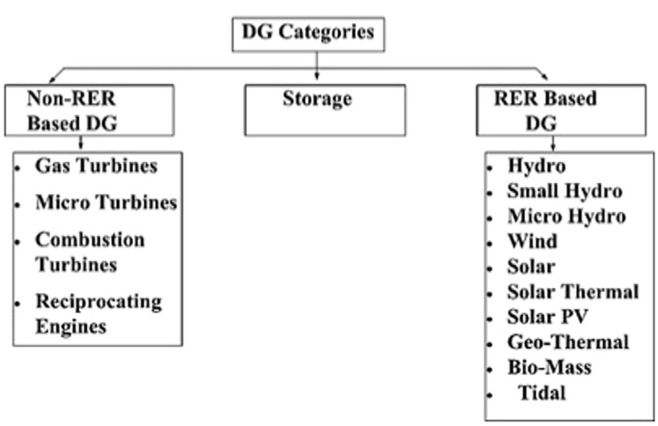

Fig. 12. DG Categories.

[126]. PMU provides accurate data to exactly pinpoint the sequences of exact events that contribute to power system failures [127]. The increased complexity of the electric transmission system demand for new technologies, such as Synchronized PMU [127]. The PMU directly measures the phase angle and magnitude of voltage and current and eliminates the short circuit requirement for analysis [128]. The PMU data on average is less than 1 kb in size [129]. The time-synchronized data of PMU is sent to PDC. The PDC then checks the errors during transmission using CRC realign the data, and stores in its internal memory. The internal binary counter is accessed by PDC and coordinates with coordinated UTC clock starts. The PDC then start comparing time-tagged data received by various PMUs. The PDC can also act as a decision maker in some applications and may pass on time tagged data to higher level, Super PDC. The Super PDC has the ability to store, illustrate and analyze measured data. The substations with PMUs consists of digital relays and intelligent electronic devices (IEDs). The Ethernet protocol based on IEC 61580 standards is used to link these devices [130].

3.5. Supervisory Control and Data Acquisition (SCADA)

SCADA systems provide field devices control and centralized monitoring. SCADA networks are used in applications where isolation and timely data delivery are the requirement. The use of QoS solutions allows reliable integration of SCADA service over the single network. This approach results in reduced management overhead on control centers. The extensive research in the area of QoS and resource management can be found in the literatures [131].

3.6. Machine to Machine Communication (M2M)

The data communication without human interaction between devices is called "M2M" communication. The M2M evolved from SCADA in 1980s [132]. M2M applications are in various sectors, such as medical, industry, public safety and consumer's products. One of the best potential growth areas of M2M is in the SG. Fig. 10 shows the key areas of M2M application in the SG [133].

M2M creates the Internet of things (IoT) that is referred as "interconnections of networked devices". M2M established by advanced wireless communication system is extensively preferred around the world. The IEEE 802.11 standard based Wi-Fi is the most attractive for implementing M2M due to scalability and easy installation. IEEE 802.15.4 standard offers cost effective, low power, and self-healing solution for establishing M2M. IEEE 802.5.1, IEEE 802.15.3a, and IrDA are other existing solutions for M2M implementation [134]. The author in [134] preferred ZigBee for M2M due to easy configuration, scalability and low power consumption.

4. Power systems and advance control schemes deployed in the SG

4.1. Renewable Energy Resource (RER) Integration

Recently, the utilization of RERs tremendusly increased within SG. The improvement and advancement in power electronics technology provided a controlled and simple integration of RER with the SG. Utilizing the concept of RER integration in the SG provides better sustainable and reliable electricity at low cost, compared to conventional electric grid. The RER has a strong potential towards feeding the growing appetite of energy [136]. The designs of RER interfaced models with the SG need variations according to location and other factors of installed location. The RER are highly uncertain in nature and dependent on weather conditions. The required variations and uncertain nature of RERs contributes towards the complexity of RER integration [219]. The aforementioned issues in the integration process of the RERs attracted the researchers from the world towards this research [137].

The RER includes: **(a)** Solar Photo-Voltaic (PV), **(b)** Wind Energy generation, and **(c)** Biomass. The strongly recommended RER for the integration with the SG is Solar PV. Wind Energy generation owing to its de-centralized nature is also an attractive candidate for the SG integration [138]. Biomass is a long lasting solution but possesses lower utilization (only 20% of the mass can be converted). However, Biomass is still a smart choice for electrification of the grid because of its clean environmental effects [139]. Wind energy generation is the world's fastest growing power generation source among all RERs [140]. Fig. 11 show the RERs in the SG patronage.

The RER interfacing is accomplised using power converter technology. The potentional of energy generation from RER requires a properly integrated controlled structure [141]. The de-centralized system is more secure and relaible instead of centralized system. The major challenge faced in RER integration is optimization, since RER are very dynamic and highly complex system [141]. The major concerns and factors affecting the integration of RER are: **(a)** reliability, **(b)** power quality, **(c)** effieciency, and **(d)** volatage profile. The uncertain nature of RER results in voltage fluctuations and is the main challenge for RER integration in the SG [142]. The authors in [143] demonstrated the integration issues of storage devices. Each storage component required a separate control technique that resulted in dump and slow response. The authors in [144] emphasised on major issues, namely economy, quality, and reliability. In [145], the authors discussed the security issues related to RER in SG applications. The authors in [146] illustrated the integration issues, focusing on Solar PV and wind generation. The integration of solar PV requires power-conditioning unit because of variable DC output. The authors in [146] also formulate an AC-DC hybrid Micro Grid, using power electronics interfacing. The study in [147] presented a hybrid structure with storage technology and used neural networks for forecasting. The data were collected from meteorological department and designs were implemented using the multi agent system. Thus, the effectiveness of RER can be enhanced by designing a better control and interfacing technology for RER integration.

4.2. Distributed Generation (DG)

DG constitutes small power generation operated near utility consumers, and prosumers premises. DG is an efficient alternative of the centralized electricity generation system [5]. The RER based DG is simple to operate, less complex, and environment friendly. DG integration with the SG affects the performance of the system in terms of losses, voltage profile, reliability, and sustainability [148]. The uncertain and weather dependent nature of RER based DG integration with the SG poses additional challenges.

In literature, many DG definitions exist based on generation capacity and location [5]. Ackermann et al. [5] defines DG as "one of the distributed energy generation source near consumer or load". International Energy Agency (IEA), Griffin et al. [149], Borges CLT et al. [148], and Kim Jo et al. [149] define DG as a "generation unit near consumers". Electric Power Research Institute (EPRI) and International Council on Large Electric System (CIGRE) describe DG with , with maximum capacity of 50 MW to 100 MW. IEEE also suggests that DG should be defined in terms of capacity. Dondi P et al. [151] explains DG based on capacity and location.

4.2.1. Classification of DG Technologies

Broadly classified, DG schemes are categorized into three streams. Fig. 12 presents the DG categories.

Belonging to the category of reciprocating engines, diesel engines are the most famous non-RER based DG and best suitable for autonomous application. Diesel engines have low inertia that make them a suitable choice for application, such as backup power supply [152]. Micro turbines are high-speed mechanical devices with simple and single shaft. Micro turbines are not environment friendly owing to

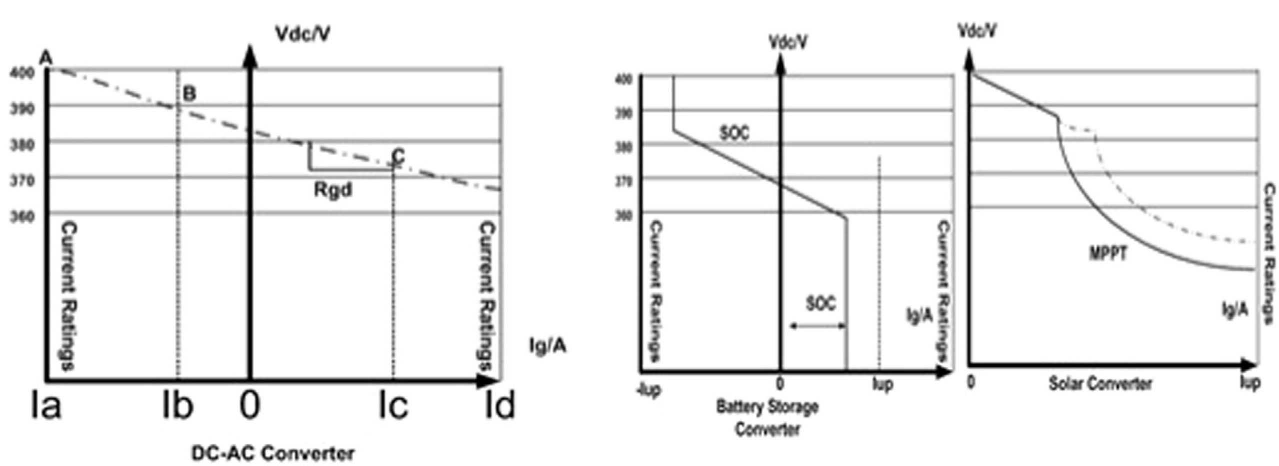

Fig. 13. DC-AC, SOC and MPPT converters operating modes with droop control strategy in DC Micro Grid.

their harmful emissions. Primary gases used for Micro Turbines are natural gas and biogas. Fuel cells based DG are fast, efficient, and environment friendly [153]. This type of fuel cells for DG includes: **(a)** phosphoric acid, **(b)** proton exchange membrane, **(c)** solid oxide, **(d)** molten carbonate, **(e)** direct methanol, and **(f)** alkaline fuel cells. All these differ in the nature of electrolytic material. Hydrogen is used as a fuel that can be extracted using fuel reformers.

4.2.2. Storage Technology for DG

The DG storage technologies are categorized as: **(a)** mechanical, **(b)** chemical, and **(c)** physical. The storage technologies act as a bridge between source and load during the period of uncertainty. The application domain of storage technologies includes RER based generation system, end users, and grid system.

In RER based generation , storage technologies mitigate the uncertainsupplying the power or storing the surplus generated energy. The storage technologies in the end user's domain increase the power system reliability and quality. At the grid side, storage technologies provide ancillary services that assist in up-gradation of transmission and distribution system [154]. The major issue associated with storage technologies is cost.

4.2.3. RER based DG

The RERs are gaining popularity as a consequence of their decentralized nature and rapid availability in nature. The deployment of RER based DG shows a significant increase during recent years. The two main contributing factors of this significant increase are low cost and flexible architecture [155]. Based on literature study, most of the RER based DGs consist of solar PV and wind energy generation.

4.2.4. Integration Benefits of DG Technology

Integration of DG with the SG offers benefits in domains of economic, environment, and technical. The DG offers technical benefits, such as enhanced security, increased reliability, improved power quality, and better voltage profile. The economic benefits of DG Technologies include: **(a)** reduced line losses, **(b)** low cost for maintenance, and **(c)** operation. The RER based DG integration offers clean environment, reducing emission of harmful pollutants. The RER based DG also lowers the fuel and operating/operational cost.

4.2.4.1. Integration Issues. The DG integration pose additional challenges in protection, reactive power management, and voltage fluctuation [156]. Moreover, the weather dependent nature of RER based DG raise the reliability concern of the system. The authors in [157] categorized the integration issues into three types, such as **(a)** Technical, **(b)** Regulatory, and **(c)** Commercial issues. The survey focus on the parameters of Technical issues, since regulatory and commercial issues are affected by government and social issues. They are discussed as:

4.2.4.1.1. Voltage Regulation. The DG integration may lead to over the voltage problem. The intermittent nature of RER based DG integration may worsen this issue. The overvoltage issues are of particular concern for weakly loaded system [148]. The remdial measures includes: **(a)** primary substation voltage reduction, **(b)** voltage regulators installation, **(c)** in light load condition shutting down of DG, **(d)** autotransformer installation, and **(e)** increasing the size of the conductor [157].

4.2.4.1.2. Protection Coordination. The conventional electric grid consists of uni-directional power flow. The DGs results in bi-directional power flow, affecting the protection system. The bi-directional power flow may results in fault current mis-match between DG and power system. This will result in reduced breaker capacity due to increased short circuit current. The DG may also surpass the sensitivity of relays, during faults [148].

4.2.4.1.3. Harmonics. The RER based DG requires power electronic interface. The power converter technology may inject harmonics in the power system. The limit for harmonic distortion is defined by "IEEE 1547" standards [150]. The improved design of power electronic converters and filters can results in limited harmonic distortion.

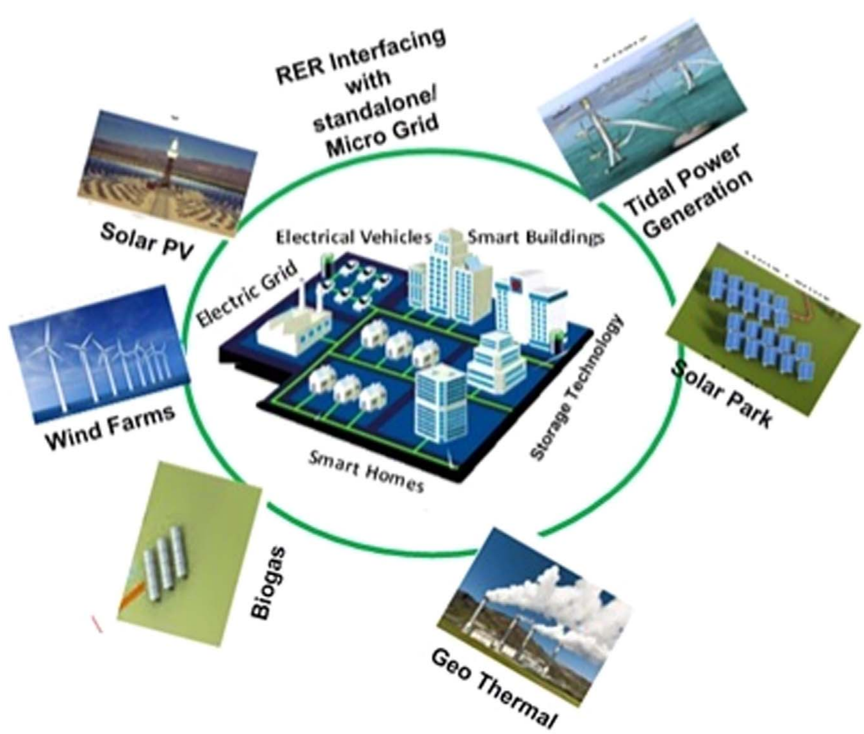

Fig. 14. The Micro Grid [187].

4.2.4.1.4. *Reactive Power Management*. The RER based DGs incorporate the problem of reactive power management by interfacing asynchronous generators [158]. The DGs integration uses power electronics converter technology that delivers the electric power, this DG units may supply and consume reactive power. To ensure the smooth mechanism, advance and intelligent control techniques are required.

4.2.4.1.5. *Reliability Issues*. The uncertain and weather dependent nature of RER based DGs pose additional challenges of reliability, voltage fluctuations, increased cost, and losses [159]. The aforementioned issues can be smartly controlled by optimal placement of DGs units. In order to get maximum benefits from DG units, the optimal placement of DG requires the utilization of state-of-the art optimization techniques. To provide a better feasible solution these optimization techniques should handle multi objective problem simultaneously.

4.3. Control techniques deployed in the SG

4.3.1. The Interplay of Intelligence and Control Techniques in the SG

The SG is a highly dynamic system that causes challenges of artificial intelligence and intelligent advance control integration. The

Table 4
Examples of Micro Grids all over the world.

Place	Country	Managed By	Type	Control Scheme	Structure
Bornholm island	Denmark	Managed by More Micro Grid project	Real	Data not available	AC
Lyon	France	Managed by NEDO	Test-bed	Data not available	AC
Kassel	In Germany	The Institute fur Solar Energy ieversorgungstechnik (ISET), Institute of Electrical Energy, Kassel.	Test-bed	Centralized	AC
Mannheim Wallstadt	In Germany	Managed by More Micro Grid project	Real	Decentralized	Data not available
In Stutensee	In Germany	By DISPOWER	Real	Centralized	AC
In Atenas	In Greece	Technical University of Athens	Test-bed	Decentralized	AC
In Milan	Italy	Sistema Energetico	Test-bed	Centralized	DC
In Agria	In Macedonia	Managed by More Micro Grid project	Real	Data not available	AC
Bronsbergen	Netherlands	Managed by More Micro Grid project	Real	Centralized	AC
Groningen	Netherlands	KEMA	Real	Decentralized	AC
Utsira	Norway	Statoil Hydro and Enercon	Real	Centralized	AC
Ilhavo	Portugal	Managed by More Micro Grid project	Real	Data not available	AC
In Barcelona	In Spain	Institute De Recerca	Test-bed	Data not available	AC
In Derio	In Spain	Managed by More Micro Grid project	Test-bed	Centralized & decentralized	AC
Minano	Spain	Ikerlan	Test-bed	Centralized	AC
Manchester	United Kingdom (UK)	H_2O(pe)	Real	Data not available	Data not available
In Manchester	UK	Manchester University	Real	Centralized	AC
In Newcastle	In Australia	Energy Center	Test-bed	Centralized	AC
In Hefei	In China	University of Technology, Hefei	Real & Test-Bed	Decentralized	Data not available
Tianjin	China	Tianjin university	Test-bed	Centralized	AC
In Changwon	In Korea	Electro Technology Research Institute, Korea	Test-bed	Centralized	AC
Utter Pardesh	In India	Gao Power	Test-bed	Centralized	AC
In Aichi	In Japan	Institute of technology, Aichi	Real	Data not available	Data not available
Akagi	Japan	NEDO	Real & Test-bed	Decentralized	Data not available
Hachinoche	Japan	NEDO	Real	Centralized	AC
Kyoto Eco-Energy	Japan	NEDO	Test-bed	Centralized	AC
Sendai	Japan	NEDO	Real	Centralized & decentralized	
In Boston bar	In Canada	Hydro (BC)	Real	Decentralized	AC
In Sennetere	In Canada	Quebec Hydro	Real	Decentralized	AC
Mexico	United States of America (USA)	New Mexico University & Japanese companies.	Test-bed	Data not available	Data not available
In Ansonia	(USA)	Connecticut center for Advance Technology and Pareto Energy Ltd.	Real	Data not available	Data not available
California	(USA)	SDG & E San Diego gas and electric	Real	Centralized	AC
In Columbus	(USA)	Technology center Dolan	Test-bed	Decentralized	AC
In Washington DC	(USA)	University (Howard)	Test-bed	Data not available	Data not available
In Chicago	(USA)	Institute of Technology, Illinois	Test-bed	Decentralized	Data not available
New Mexico	(USA)	NEDO	Test-bed	Data not available	Data not available
In Mdison	(USA)	Wisonsin University	Test-bed	Decentralized	AC
In Califronia	(USA)	Infotility Inc.	Real	Decentralized	AC
In California	(USA)	University (Santa Clara)	Test-bed	Data not available	AC
Stanford	(USA)	Energy (Pareto)	Real	Data not available	Data not available
In SanDiego	(USA)	California University	Test-bed	Data not available	Data not available
California	(USA)	Electric General	Real	Centralized	AC

smartness of the SG is highly dependent on intelligent control techniques, such as Neural Networks, Fuzzy Logics, Non–Linear Control, and Multi-Agent System based control techniques. The intelligent control techniques play a key role in anticipating the faults and helps in self-healing and self-learning of the SG [160].

4.3.2. High Voltage DC (HVDC) & Flexible AC Transmission System (FACTS)

To enhance the controllability with increase power transfer ability, FACTS based controllers are used [161]. The best preventive measure against voltage fluctuations and intermittent nature of RER is the utilization of FACTS controllers that consist self-commuted static converter. FACTS controllers are capable of fast controllability exchanging active ends independently.

The FACTS reactive power controllers group consists of series and shunt controllers. Series controllers are also called Dynamic Voltage Restores (DVR). DVR is connected directly in series to influence line voltage [172]. Static Synchronous Compensator (STATCOM) controllers are shunt controllers. STATCOM indirectly controls the line voltage by injecting the current [173].

The intermitted nature of RERs can cause uncontrollable power flow in the electric power system. The uncontrollable power flow results in voltage and angle stability issues, such as: line tripping, and black outs. High Voltage DC (HVDC) and FACTS devices can be used to overcome the aforementioned challenges, this mitigating the cascading disturbances [162].

4.3.3. Voltage and Stability Control

To increase the power system reliability and efficiency, the magnitude of bus voltage needs to be in an acceptable level. For monitoring the control devices, different algorithms, converter based FACTS devices, and synchronous generators are mostly used. The optimum power flow reduces the transmission losses (produced by active power) and controls the circulating VARs results in flatter voltage profile. For the FACTS based damping controller design, the major issue is finding the path of damping torques and feedback signals. The LMI (Linear Matrix Inequality) based FACTS controller can manage the aforementioned issues and results in a robust FACTS controller design. The LMI based method consisting of two steps, needs to utilize for multi-model system controller design. The two level based LMI method can also be used for the design of STATCOM controller for damping purpose [163].

4.3.4. Droop Control

Droop controllers operate in droop mode or in current limiting mode. The output resistance of these controllers directly varies with the feedback current. Droop control techniques widely used in AC-DC, DC-AC, and DC-DC converte parallel operation. These control techniques have high reliability [164]. Fig. 13 shows DC-AC converter, State- of-Charge (SOC), and Maximum Power Point Tracking (MPPT) operating modes with droop control strategy in DC Micro Grid. The operating voltage range for converter is 360–400 V.

Batteries in this DC Micro Grid also operate in droop mode. The charge and discharge current ratings are dependent upon state-of-charge (SOC) represented by ($\boldsymbol{I_{up}}$) and (-$\boldsymbol{I_{up}}$) respectively. For solar renewable generation with MPPT , this converter starts operating as a constant power source [165].

4.3.5. Hierarchical Control

The architecture of hierarchical control consists of three levels of hierarchy, such as primary, central, and tertiary control. The primary controller level consists of micro-source and load controller. The DC bus voltage level is controlled by primary level. The central level controllers are responsible to maintain the electrical levels within the required limits. The power flow of the DC Micro Grid is being maintained by tertiary controllers that is also a distribution management system [166].

The authors in [167] presented a three level hierarchical control scheme for DSM. Another study in [168] presented a 4-terminal

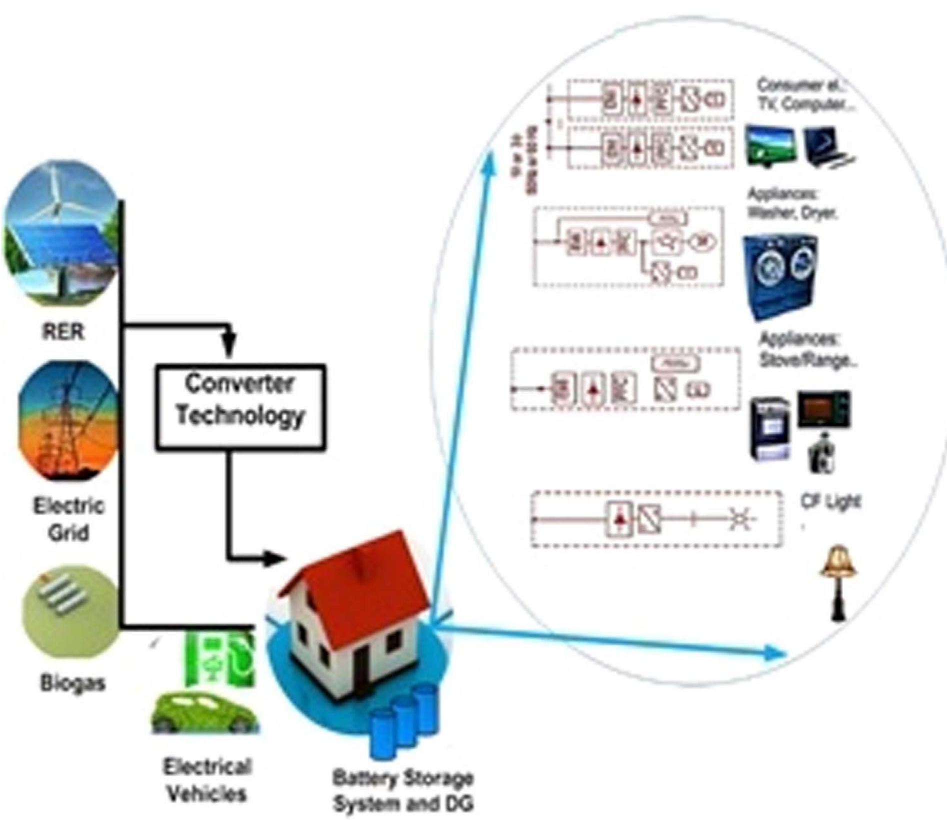

Fig. 15. AC Nano Grid [192].

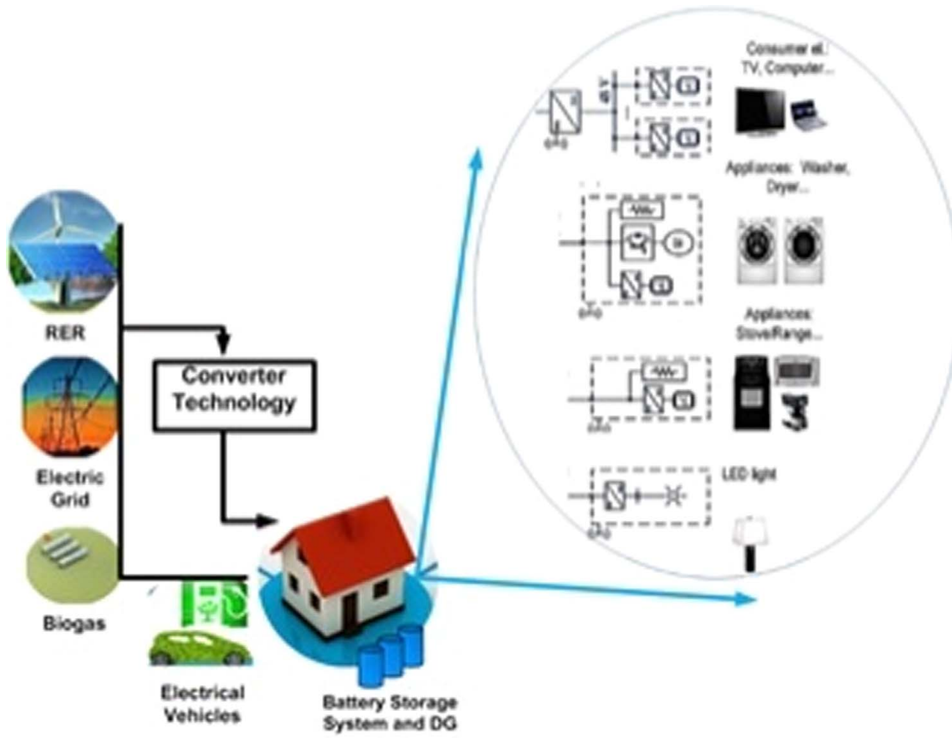

Fig. 16. DC Nano Grid [192].

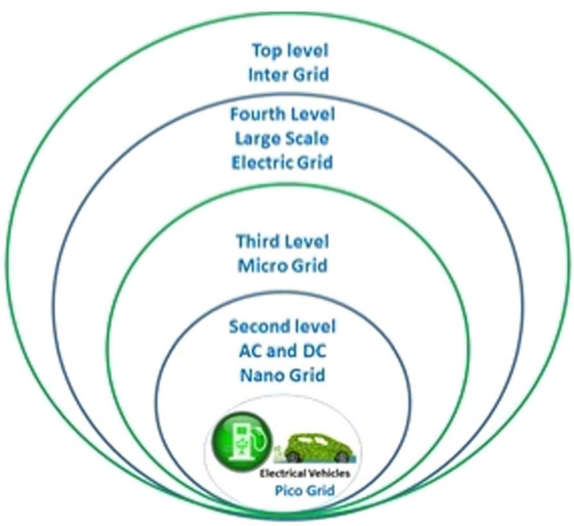

Fig. 17. Hierarchal structure of Inter Grid [192].

hierarchy control scheme for the management of DC Micro Grid. The hierarchy control of [168] is applied to different modes of operations, such as islanding and load shading.

4.3.6. Fuzzy Control

Fuzzy theory was introduced to handle highly complex, dynamic, and nonlinear systems [169]. The fuzzy system operates on the fuzzy logic system, this analyzing the analogue inputs. Fuzzy controllers are intelligent controllers that works like human thinking process. Fuzzy system brings improvements to a certain extent in fault tolerance and uncertain information [170]. Study in [172] demonstrated a fuzzy based control scheme for managing the stored energies of capacitors. The fuzzy logic controller for DC Micro Grid is presented in [171]. Fuzzy system can help in attaining flatter voltage profile, thus may become a solution for DC Micro Grid stabilization problem [173].

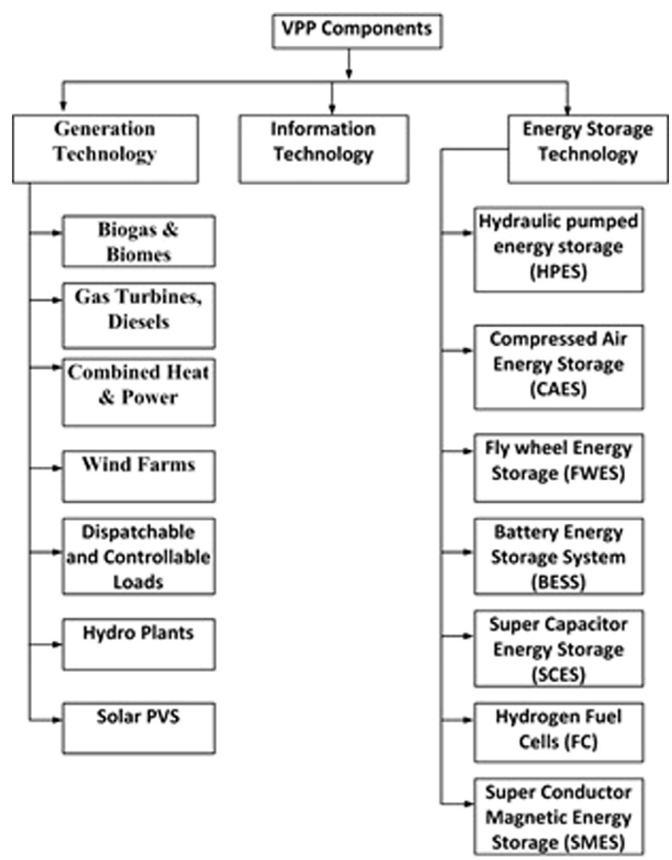

Fig. 18. Components of VPP [194].

4.3.7. The Multi-Agent System (MAS) Control

MAS control comprises of distributed intelligent entities with limited control abilities,but can coordinate globally within system [174]. The distributed intelligent entities are called “agents”. The agents can work with the artificial intelligence, advance control techniques, and conventional control techniques. The advancement and development of communication technologies greatly assist in integrating MAS system more efficiently to the power system [175]. The study in [176] illustrated various agent based MAS system. The proper-designed MAS based control system helped DG units to work efficiently in different modes of operation. For the stabilization of DC Micro Grid, a fault tolerant system is purposed in [177].The system in [178] ensured the stability even during MAS agent loss. The hardware simulation based DC Micro Grid is presented in [179]. The authors in [179] took the power controller as a hardware device, while DG unit and power grid were developed in software simulations.

4.3.8. Model Predictive Control (MPC)

MPC is an industrial standard control. The MPC technique can handle multi-variable control problems with ease of tuning and handling constraint [180]. The MPC based unbalanced Micro Grids strategy for reactive power control was presented in [181]. In [181] control scheme, a linearized model was derived in the first step and then the predication of voltage profile was made for next time steps. The prediction adjusted voltage and reactive power according to the set points to attain a smooth voltage profile. The optimization problem in [182] was further divided into two sub problems, such as: **(a)** transient mode, and **(b)** steady-state mode. This decomposition of the optimization problem provided low computational burden on the system. The authors in [183] purposed an economic MPC to minimize the cost through peak shifting and concluded that an economic MPC strategy couldexploit the weather forecast, besides peak shifting, and reduce the operational cost.

4.4. Power system

4.4.1. Micro Grid (MG)

With the emerging trend of DG, a novel way to view this MG as a system of multi generation with multi load. MG is a contingency plan during grid failure and a new notion in the era of green and clean power generation [184]. A low voltage network with distributed generators, controllable load, and energy storage devices is a key contributor of the MG. To achieve hourly demand of electricity, MG can act as a feasible alternative to boost trustworthiness and efficiency of electrical power systems [56,185]. The MG can be operated in remote areas lessen the outage time. Proximity of DG intensifies the implementation of MG [186].

The anticipated benefits of MG are: **(a)** higher degree of fault tolerance, **(b)** reliability, **(c)** robustness, and **(d)** efficiency. Reduced carbon footprints by intelligently incorporating RER based DGs is another advantage of MG. The application areas of MG are: **(a)** commercial, **(b)** industrial, and **(c)** academic level. The MG structure makes possible to reduce energy cost by generating energy during peak loads or other emergency situations [56]. Fig. 14 presents the structure of MG. Table 4 presents the Examples of Micro Grids all over the world [188].

4.4.2. Nano Grid (NG)

Isolated electric grid with low load bearing ability is called NG requires less investment, compared to MG [189]. NG are introduced to fulfill the electricity need of areas where large number of outages occurs. MG are isolated grids with output power ranging from KiloWatts (KW) to MegaWatts (MW) with several hundreds of consumers. Nano Grids are small scale grids with output power ranging from watts to a few KiloWatts with lesser than 150 household consumers [189]. NG is used to power mobile phones, laptop chargers, fans, and illuminating lights NG improves the electricity service to consumers and enormously contributes towards the real implementation of smart building concept [190]. Centralized and decentralized control strategies are used for controlling the supply scheduling of NG according to supply side control law [191]. NG is further divided into two categories: **(a)** AC NG presented in Fig. 15, and **(b)** DC NG presented in Fig. 16. The DC NG has many advantages over AC NG , such as fewer numbers of converters, easy interfacing of RER based DG, and zero skin effects.

4.4.3. Inter Grid (IG)

The IG is novel power grid architecture that consists of hierarchically interconnected system, such as Pico, Nano, Micro, Sub-Grid, and Main-Grid system, respectively. This hierarchical system is also called as hybrid mix of AC and DC electric power system architectures. The hierarchy starts from Pico Grid (PG) Comprising of Electric Vehicles (EVs) while NG is at second level. Micro Grid is defined as the third level and sub-grid is at the fourth level [192]. Finally, the main grid is at the top level of this hierarchy. Fig. 17 demonstrates the hierarchal structure for Inter Grid.

4.4.4. Pico Grid (PG)

PG is Plug-In-Hybrid Electric Vehicles (PHEVs) and Electrical Vehicles (EVs) electric system with bi-directional charging/discharging capabilities. The PHEV system has on/off board batteries and electronic loads. In Fig. 17 a hierarchy from PG to the main grid is defined [192].

4.4.5. Virtual Power Plant (VPP)

The power plant comprising of various generation units, and controllable loads with a storage system called "VPP". The generation unit can be renewable energy based or conventional. The bi-directional communication in VPP allows to control and monitors the objects and receives the information regarding the current status of the system [193]. The energy management system plays a key role in VPP. The energy management system operates according to mentioned targets, such as the reduction of GHG, profit maximization and generation cost minimization [193]. VPP have three main components, presented in Fig. 18.

5. Future development areas of SG

This section thoroughly investigates the prominent future development areas and recent research domains of SG, such as: **(a)** Power and energy domain, **(b)** Communication technologies, **(c)** Battery storage systems, **(d)** Renewable Energy Systems, and **(e)** V2G/G2V interaction within smart grid. Based on latest technical study, these domains are discussed emphasizing on current trends and future development. Future SG is capable of adopting the technological developments in these areas. The detail discussion of future developments areas of SG is presented in following subsections.

5.1. Power and energy domain

The future SG for distribution technologies and applications, such as: **(a)** Micro Grids, **(b)** DSM, and **(c)** advance voltage control possible and expected consequences of power quality is introduced in [195]. The power quality control and monitoring based on instrumentation values in smart meters is presented. These smart maters ensure market correlated services and real time operation of network [196]. The electric spring with batteries based on operating principles and current input control, improved the power quality, such as: **(a)** harmonic reduction, and **(b)** power factor correction in SG. Further, the second generation of electric spring assists the SG in dealing the intermittency of renewable power generation [197]. The impact of power quality issues, such as: **(a)** harmonics, **(b)** unbalances, **(c)** sags, **(d)** flickers, and **(e)** resonances is important to be considered in implementation of future SG. Moreover, the power quality in future SG is elaborated by including the topics, namely: **(a)** control schemes for improved power quality, **(b)** synchronization methods, **(c)** advance techniques for power quality evaluation, and **(d)** investigation of power quality problems [198].

The intelligent SG consumes energy in efficient manner to provide benefits to end users and power grid, and assure the electric flow to end users in case of grid failure. Strategies and technologies for energy management in future SG are also discussed. Due to deficit of RERs and efficient use of existing energy, energy efficiency concept is vital and attainable in future SG [199]. The observation of end user energy usage pattern and using this information assist in lowering the cost and enhancing the energy supply stability of future SG [197]. The renewable and conventional energy technologies are account in future SG and efficiently designed to stimulate DG and Micro Grid with a SG. The feasibility study of smart energy technology employment in future SG is incorporated in [200]. Finally, the transportation of energy to urban center from remote areas is assured through Electric Vehicle Network (VEN) [201].

5.2. Communication technologies

The SUN technology known as IEEE 802.15.4 g standard provides reliable data transmission in future SG. However, this technology interfere existence WLAN channels. That is critical issue and investigated by employing multiple schemes [202]. The handling and processing of huge data and limited communication infrastructure is major challenge for future SG. So, to overcome this challenge the distribution communication architecture is proposed to handle the data locally [203]. Communication infrastructure play vital role in energy management of future SG. The communication infrastructure for wide area control and future SG is proposed in [204]. The integration of IoT with future SG will intelligently control the power supply.

The PLC architecture with existing ZigBee and WiMax is proposed for future SG [205]. The Energy Internet (EI) with permanent communication architecture due to aroused worldwide concern is proposed in [206]. Wireless Communication Technology (WCT) is the most suitable communication structure for future SG. The PLC used in SG offer high initial cost and is replaced by WCT. To ensure optimal power capacity, the full duplex communication technologies are suggested for future SG [207]. The implementation of appropriate communication infrastructure that meets the communication requirements of future SG is the key challenge faced by all utilities. The communication architectures defined by NIST, ITU, and IEEE are proposed for future SG [208].

5.3. Battery Energy Storage Systems (BESS)

The data exchange and real time information between all SG entities is the fundamental principle of future SG. The deployment of advanced non linear control schemes in complex electric grid requires BESS implementation to ensure power system stability. In future SG, BESS will play vital role in provision of electric buffer in normal and contingency events [209]. The use of BESS in generation, transmission, and distribution guarantee the regulation of grid frequency, smoothing and leveling of renewable energy, power quality improvement, and reliability. Furthermore, various new models of BESS technology are implemented in power transmission system. The BESS provide better results and responded quite well in perturbation and disturbance conditions that clearly indicate the use of BESS in future SG [210]. The battery storage system for efficient energy is presented in [199]. The integration of BESS in the future SG is reported in [200]. The cascaded multilevel converter with LC branch based energy storage system is designed that allow the exchange of active power among the cells in SG [211]. The generalized battery model to evaluate the flexibility of energy storage and buildings loads is presented in [212].

5.4. Renewable Energy System

The power sector is focusing on RERs generation to meet the future SG demands due to development in RERs technologies [199]. The integration of large scale RERs within SG is an important feature in SG development worldwide. Therefore, the islanded power grids are the finest platform for RERs accommodation due to: **(a)** scarcity of conventional energy, **(b)** abundant RERs, and **(c)** technical trouble with intermittent RERs accommodation. The optimal scheduling and multitime frame robust dispatch system for RERs integration within SG is considered in [213]. In SG context, the smart manufacturing plants integration as a critical DRP with high RER penetration has attracted both industry and academia. The impact of DRP on smart manufacturing plants in power system is investigated using numerical case study [214]. The control system and energy management for Micro Grid based on solar, wind, and battery is presented [215].

The smart loads control and modeling for DRP in increased penetration of distributed RER generation is presented. Moreover, the smart loads improve the voltage profile in SG [216]. The SG is a typical application assisted by IoT. The efficient integration of RER and storage system to meet the energy service requirement is achieved through IoT infrastructure. The implementation of IoT in SG reduced the cost of power generation and transmission [217]. The data centers with high carbon footprint consume excessive energy from electric grid. The RER decarbonizes the operation of data center reported in latest practice. The demand response influence on distributed group of data centers for exploitation of RER generation diversity and energy prices in future SG is presented. Further, the optimal solution for renewable energy dispatch and workload allocation in distributed data centers is derived [218].

5.5. V2G/G2V Interaction

The electrical transportation, such as: **(a)** V2G and **(b)** G2V is the promising option to reduce the urban life dependency on fossil fuels. The concept of SG in a power system is broadly clarified by considering the V2G/G2V interactions in power distribution sector. The employment of V2G and G2V in future SG produces technical issues, particularly disturbing the low voltage sector in overall power system. Further, more technical issues related to EV interaction within future SG are reviewed [219]. The EVs development and interaction within future SG is the finest replacement to conventional fueled vehicles. The scheduling methods of EV online charging are introduced to minimize the uncertainty and randomness in SG. Future research indication for controlled EV charging is highlighted [220].

The load frequency control strategy that enables EVs to assist thermal turbine units in stability enhancement is presented [221]. A quantitative evaluation technique for V2G capacity in large scale plug in EV is incorporated using aggregate model. Due to the control action of aggregator, the V2G work as a storage system [222]. The potential of V2G/G2V for small term power imbalance in SG is investigated to resolve the issue of supply and demand mismatch occurred due to increased penetration of RERS in power grid. A straightforward bidding algorithm is proposed for interaction of V2G/G2V within SG [223]. The online energy management issue for distributed DCs and EVs in SG is presented [224]. A compact quick charging system letting V2G/G2V operations in future SG is investigated. In the context of future SG, the EV charger must ensure fast charging and ancillary services to grid to attain duplex power flow [225].

An optimized architecture for charger station involvement, cost minimization, and EVs integration in SG is proposed. The smart charging and V2G technology have been focused in [226]. The novel bidding technique for V2G interaction into Micro Grid with energy management scheme is highlighted [227]. EV charging patterns and charging station energy consumption are vital to evaluate the V2G/G2V impact on future SG. The world wide adaptation of EVs is possible through statistical analysis of charging data [228]. Autonomous vehicles will play vital role in future transportation system of SG and will dominate the ground transport. These vehicles will take part in V2G system to maintain different V2G services through the implementation of intelligent parking system [229].

6. Conclusion and future directions

The SG evolved as an improved and green grid with a new era of opportunities that greatly attracted academia, industry, and government during recent years. The new trends in government policies affect electricity industry that makes the SG a hot research topic in research. The SG is a combination of smart infrastructure, smart management, and smart protection system. The smart protection is the interaction of intelligent and distributed control, optimization, and communication techniques. The SG protection is a smart way of anticipating the faults and failures making high system reliability even in uncertain environmental conditions. The smart protection system consists of failure identification, data recovery, self-healing, smart diagnoses, and prevention. The smart management system increase the energy efficiency by an active participation of customers. The optimization techniques, such as integer programming, convex programming, stochastic programming, robust and particle swarm techniques and machine learning are being applied in the management of the SG.

In this survey, a comprehensive review of technologies and their applications in the SG are discussed. Analyzing the SG architecture focusing consumer's empowerment; that include: **(a)** AMI, **(b)** DR, and **(c)** DSM. The SG faces various levels of challenges, such as consumer awareness, their interest, and acceptance of consumer empowerment features.

Investigation of the various ICT followed in SG applications, such as wired, wireless, AMI, SCADA, and M2M are discussed in detail. The review of these ICT, indicates that the complete establishment of the SG in an efficient way is only possible with the reliable and secure ICT. There still exists a room for development due to bottle necks in ICT.

Furthermore the RER and advance control schemes deployed in the SG are presented. RERs are the first step forward towards the clean and green grid. RER integration issues, such as voltage fluctuations, harmonics, reactive power management, stability, needs and system protection issues are elaborated. Our survey also reviewed the role of MG , PG , NG , IG, VPP and DG. These systems will open a new paradigm in the SG to achieve standalone energy system. The SG also offers flexible implementation of a de-centralized generation system. The de-centralized generation systems are more reliable compared to centralized systems. Technical issues in the integration of DG with the SG include: **(a)** voltage regulation, **(b)** protection coordination, **(c)** harmonics, **(d)** reactive power management, and **(e)** reliability issues.

The practical implementation of the SG still have a long way to go with numerous technical and socio-economic challenges, such as the consumer's awareness, advance and efficient control scheme, efficient dynamic optimization techniques, efficient storage devices, managment of EVs penetartions, reliable communication infrastructure, an intelligently optimize SG consumer energy managment, facilitate and manage the prosumers activities, precise weather forecasting techniques, and other social, security and privacy issues. The vision of a SG can only be realized after resolving aforementioned issues. The anticipated benefits from the SG defined by NIST are: **(a)** improved power quality and reliability, **(b)** better DSM, **(c)** reduced GHG emission, **(d)** better automated operation, **(e)** anticipated faults, **(f)** reduce oil consumption, and **(g)** increased consumer choices. In coming two decades, the SG's real implementation will be the foremost requirement due to its promissing benefits and a reliable energy supply. The SG will radically revolutionize the electrical networks that are vital to any nation's infrastructure. The technologies acting as base functionalities for the SG implementation need a more research in above SG domains.

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