Received October 15, 2020, accepted November 5, 2020, date of publication November 10, 2020, date of current version November 27, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3037196

Communication Systems in Distributed Generation: A Bibliographical Review and Frameworks

ZIMRAN RAFIQUE[1], (Member, IEEE), HARIS M. KHALID[1], (Senior Member, IEEE), AND S. M. MUYEEN[2], (Senior Member, IEEE)

[1]Department of Electrical and Electronics Engineering, Higher Colleges of Technology–Sharjah Campuses, Sharjah 27272, United Arab Emirates
[2]School of Electrical Engineering Computing and Mathematical Sciences, Curtin University, Perth, WA 6102, Australia

Corresponding author: Haris M. Khalid (harism.khalid@yahoo.com)

ABSTRACT The exhaustion of natural energy and oil reserves has initiated the concept of renewable energy systems (RESs). This has expanded the vision of energy sector towards a diversified power grid while introducing the distributed energy resources (DERs) and distributed generation (DG). Though, this diversification is achieved by adding new energy generation sources and a two-way power flow, it opens the channel of production and trading with alternating current (AC) and direct current (DC) energy formats. But DC-based energy, due to its sporadic nature, can be further stored easily by energy storage devices. However, in recent years, a compelling need has arisen to understand the communication systems in distributed generation (DG) for better performance management, control and parallel power transfer. In this article, a bibliographic review on communication systems in distributed generations (DGs) is provided. The study identifies various communication technologies, standards, and protocols used in AC and DC-based DGs. Moreover, it contains the classification of different frameworks and methods involved. The methodology of different approaches and their likely combination are discussed for different types of communication networks. This study also represents useful information for readers, thereby demonstrate the complete life-cycle of digital data in sensors/actuators, transmitter, receiver, filter, decoder for control of DG elements and identifies future challenges as well. A comprehensive list of publications to date are compiled to provide a complete picture of different developments in this area.

INDEX TERMS Bibliographical review, communication network, communication technologies, distributed energy resources (DERs), distributed generation (DG), literature review, network control, power line communication (PLC), renewable energy, renewable energy system (RES).

NOMENCLATURE

ASK	amplitude shift keying
BAN	building area network
BER	bit error rate
BMS	battery management system
BPLC	broadband power line communication
CAN	controller area network
CPAN	consumers premises area network
DALI	digital adressable lightening interface
DCPO	DC-DC power optimizer
DERs	distributed energy resources
DFT	discrete fourier transform
DG	distributed generation
DPSK	differential phase shift keying
DSL	digital subscriber line
DSN	demand side network
DSO	distribution system operator
EM	electro-magnetic
EMS	energy management system
ESS	energy storage system
FOC	fiber optic communication
FSK	frequency shift keying
HAN	home area networks
IAN	industrial area network
ICT	information and communication technology

The associate editor coordinating the review of this manuscript and approving it for publication was Junjie Hu.

IOE	internet of energy
IP	internet protocol
LED	light emitting diode
LD	laser diode
Li-Fi	light fidelity
LIN	local interconnected network
LoWPAN	low power wireless personal area network
MIMO	multi-input multi-output
NAN	neighborhood area network
NPLC	narrow-band power line communication
OFDM	orthogonal frequency division multiplexing
OWC	optical wireless communication
FOC	fiber optic communication
PEC	Power electronics converter
PLC	power line communication
PSD	power spectral density
PV	photo voltaic
PWM	pulse width modulation
RES	renewable energy system
RF	radio frequency
SCADA	supervisory control and data acquisition
SFM	switching frequency modulation
SISO	single input single output
SWIPT	simultaneous power information and power transfer
TSO	transmission system operator
VLC	visible light communication
VPP	virtual power plant
VPPM	variable pulse position modulation
WAN	wide area networks
WLAN	wireless local area network
WPAN	wireless personal area network
WPF	wind power farm
WSN	wireless sensor network
WWAN	wireless wide area network

I. INTRODUCTION

Renewable energy systems (RESs) are getting more importance during the last two decades [1]. This is due to the hazardous concerns of: 1) depletion of traditional energy resources such as coal, diesel, oil, gas, 2) getting clean and healthy environment, and 3) increasing demand of energy with the population growth and changing life style. Since most of the RES are inherently DG-based, the resources such as photovoltaic (PV) panels, wind turbines, e-plants, energy storage systems (ESSs) can be directly connected to a DG [2]–[9]. In DER, voltage levels can be easily managed. On the other hand, in conventional AC grid system, transformers are used to step down the voltage levels, DC voltage levels can be changed by using DC-DC converter [10]. Moreover, DC power systems require no reactive power compensation and bear no skin and proximity effects [11]. A conceptual view of distributed power generation system can be seen in Fig. 1.[1] A DER is generating DC or AC power and doing energy interaction with renewable energy resources and AC grid [12] through distribution transformers and power electronic converter (PEC). The concept invites integration of all elements of electricity systems to improve operations, efficiency and resilience while reducing conversion and distribution losses [13], [14]. This involves integration with: 1) centralized power and heat generation units, which provide power to DERs using AC to AC conversion, 2) renewable energy resources using DC to DC conversion, 3) bi-directional integration with smart transmission and distribution, EMS, ESS, transportation electrification using DC to DC conversion, 4) storage devices such as hydro-storage [15] and batteries using DC to DC conversion. Although DG systems do not get instant power from AC grid, a communication system for instant information exchange may still be handy during power intermittency to decide on its reconnection with AC source for power exchange.

Based on instant communication, another component which could tackle the sporadic nature of renewable energy sources and difference in demand-supply is the ESS [16]. ESS can easily store the produced DC-based energy in DC batteries. This is to tackle and control the power fluctuation during irregular periods and RES connection in a DER [17]. Despite of the feasibility provided by ESS towards the intermittency of RES, there are some limitations which could be faced due to: 1) the impact of environment, 2) aging-cost, 3) technology at hand [18]. The alternates to overcome these limitations should be utilized. For large-scale RES plants, such as wind and solar farms, the pumped storage hydro-electricity station and lead acid batteries are respectively the best alternates to energy storage [15], [19]. Note an alternate to the pumped storage hydroelectricity could be a combination of fuel cells and hydrogen tanks electrolyzers [19]. The alternate technologies and instant power availability from AC grid can enhance the coordination of DERs by maintaining acceptable levels of voltage and frequency stability in power distribution systems [20]. However, it requires a reliable communication infrastructure to optimize the use of renewable energy systems for high penetration levels, which is the main motivation of this article.

In the earlier era, this communication was handled in power systems by supervisory control and data acquisition (SCADA) to transfer data between field devices, control units, and computers in the SCADA central host. A ring system was also introduced to connect DGs to the consumers by a grid [21]–[23]. Later, PMUs were also introduced for SCADA enhancement in smart power grid [24], [25].

Information and communication technologies (ICTs) can be used in a DGs and DER systems for optimal and secure bi-directional flow of power with dynamic loads [26]. However, communication systems in DC microgrid and smart grid systems should meet some specific requirements based on grid applications such as reliability, latency, bandwidth and security [27], [28]. The selection of proper communication network is a big challenge in DG due to many variables and different component requirements, which depend on

[1] In this figure, PEC is the acronym of power electronics converter.

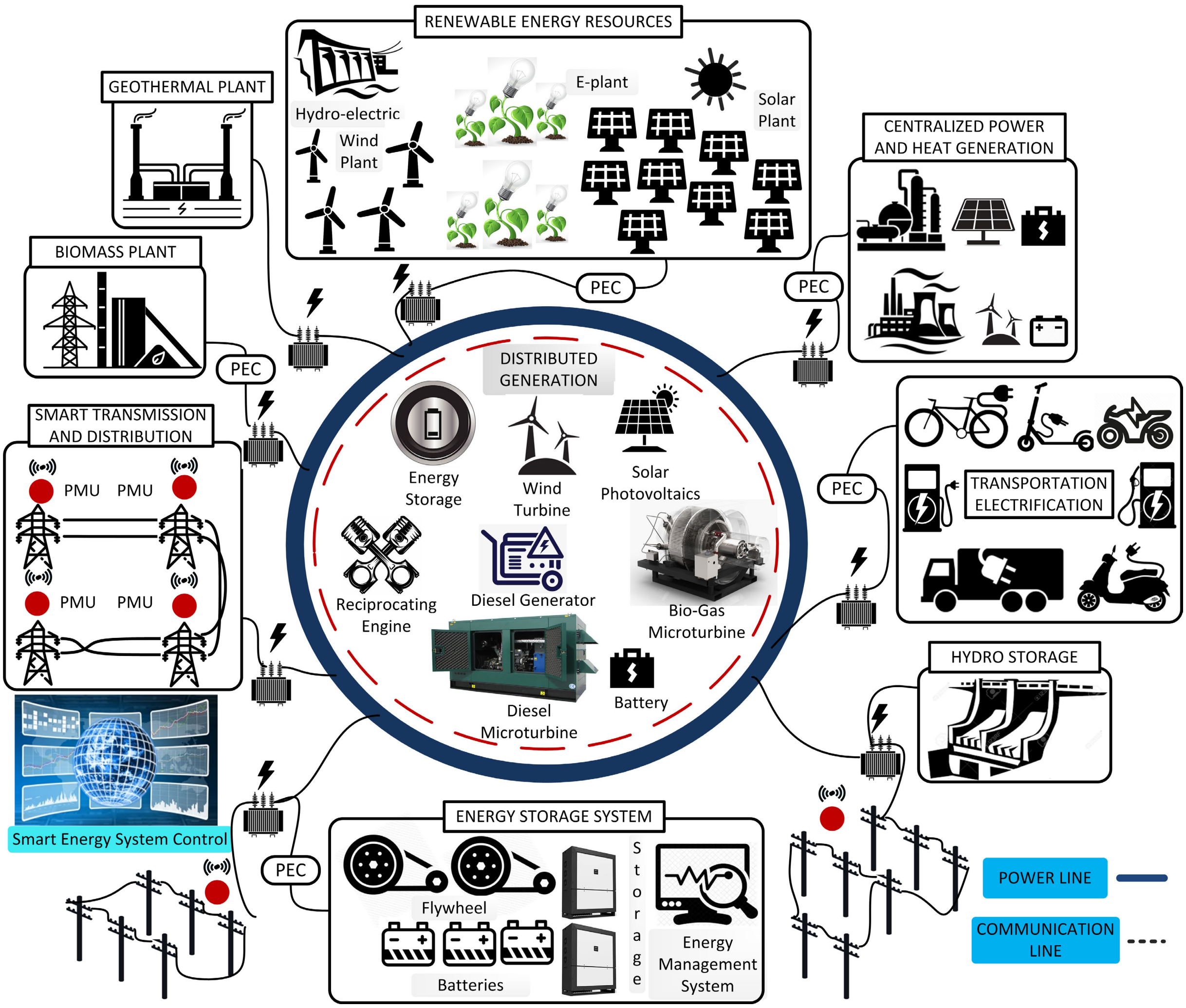

FIGURE 1. DG – A concept of distributed power generation system.

applications and utility expectations [29]–[34]. Fig. 2 shows a brief timeline of utilization and technology developments of communication system in DGs to date. The three pillars of communication systems have their development phases as follows: 1) Communication infrastructure (2011–2014), 2) Communication networks (2002–2020), 3) Communication technologies (1998–2020). The prominent contributions of each development phase has been highlighted.

The main contribution of this article is to explore and identify the development of communication infrastructures in DG systems. The article aims to bridge the gap of different applications of communication frameworks in DGs by: 1) communication infrastructures, 2) mathematical representation of such an infrastructure, 3) the respective networks and technologies, and 4) analysis of different validation approaches carried out by different applications. From the perspective of DG, a bibliographic review on communication systems is provided covering technologies, standards, protocols and classification of different frameworks.

The rest of the article is structured as follows: Section II introduces the communication system and standards.

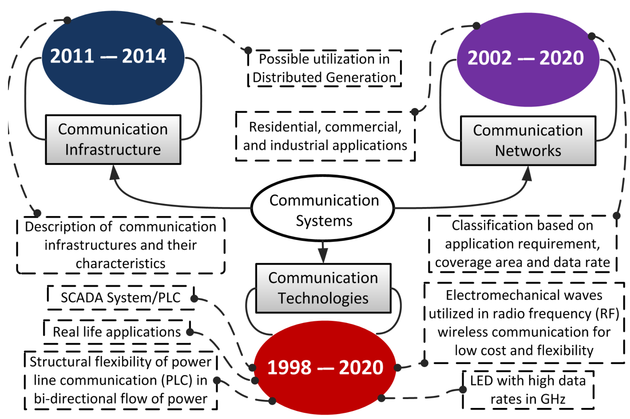

FIGURE 2. Timeline of communication systems in DG.

The infrastructure and mathematical representation is explained in Section III. Section IV and V discuss the different communication networks and technologies respectively. Finally, the concluding remarks and future challenges are illustrated in Section VI.

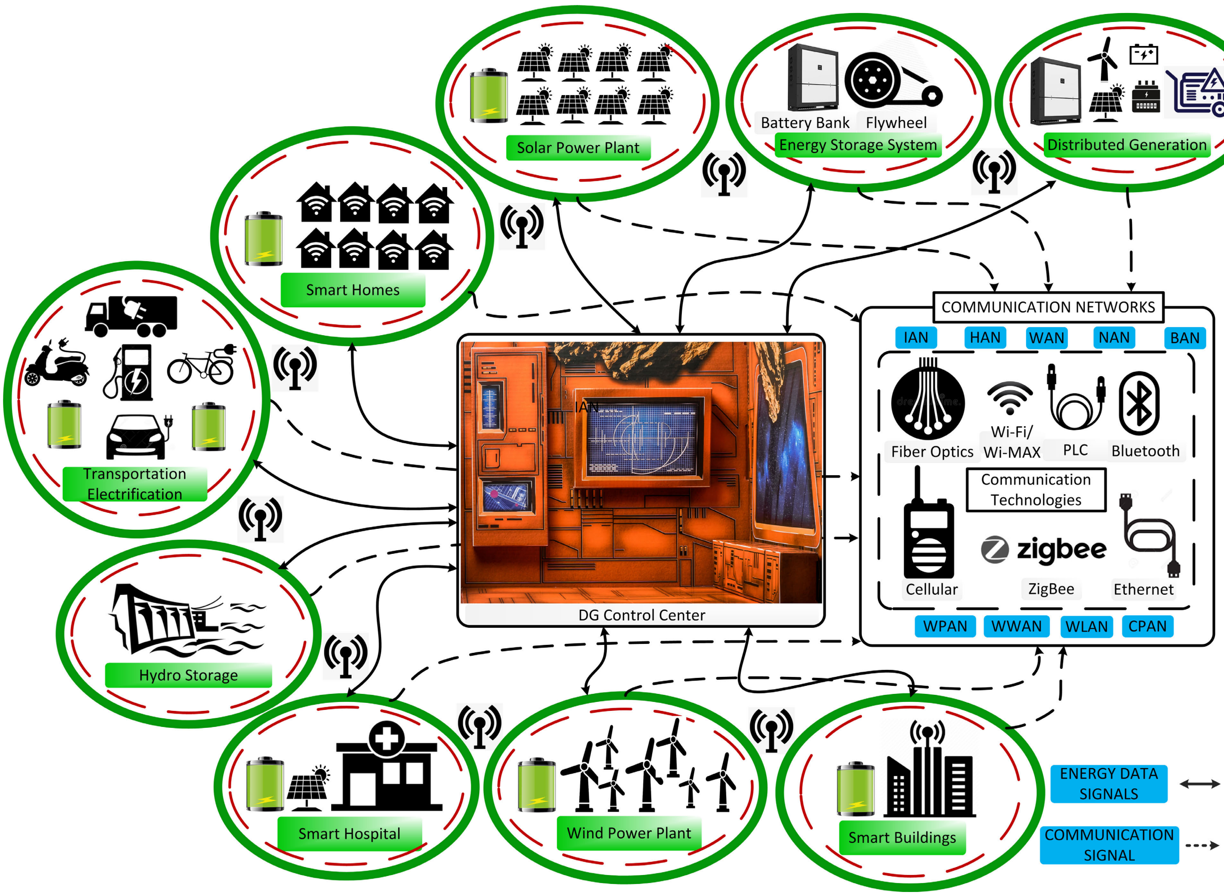

FIGURE 3. Communication systems in DG.

II. COMMUNICATION SYSTEM AND STANDARDS

The delivery of energy to remote geographical locations has urged the development of communication system[2] in distributed power generation systems. A comprehensive communication system can be seen in Fig. 3. It is showing a DG power system with different available communication technologies and networks accompanied by a DG control center. It particularly comprises of the following components: a) a communication infrastructure, b) communication networks, and c) communication technologies. All these components effectively contribute towards the control, monitoring and management of the DG system for a reliable delivery of energy to customers and industry end-users.

From the perspective of communication standards, different RESs-based DGs can use different communication standards based on: 1) requirements, 2) applications, and 3) available resources. For instance, the IEC61850-7-410 is a communication standard considered for monitoring and control using different logical nodes classes and data objects [37]. Some other communication standards with their utilization and applications are summarized in Tables 1 and 2 respectively. Communication standards IEC 61850-7-410/420/500/510 cover communication for monitoring, control and logical nodes. Communication standards IEC 61850-90-1/2/3/4/5/6/7/8/9/10 looks into communication between control centers, substations, object models etc. Communication standards IEC 61400-25-1/2/3/4/5/6 considers wind turbine and applications of information models, mapping, node/data classes etc.

[2]Note the communication system of a renewable power generation plants follow communication standards (Table 1 and 2). These standards are also used in virtual power plant (VPP) concepts [35], [36]

The components of the communication system, i.e. communication infrastructure, communication networks, and communication technologies are further classified in the following sections. The classification is further illustrated with applications, technologies involved and their architectures.

III. COMMUNICATION INFRASTRUCTURE AND MATHEMATICAL MODELING

In DER-based grids, communication infrastructures are considered to be the backbone of all the information exchange and telecommunication services. There are some articles which describe the need of communication infrastructures, their required characteristics and traffic requirements [38]–[42]. Authors in [43] have covered various available wired and wireless communication technologies with their possible use in smart grid applications. In DER-based grid systems, though the information subsystem (e.g. smart meter and sensors) will be different than the traditional AC system,

TABLE 1. Communication standards for various renewable power generation plants.

Standard	Utilization
IEC 61850-7-410	Communication for monitoring and control
IEC 61850-7-420	Communications systems for DER - Logical nodes
IEC 61850-7-500	Substation Automation system - Logical nodes
IEC 61850-7-510	Hydro Power Plant - Logical nodes
IEC 61850-90-1	Communication between Substations
IEC 61850-90-2	Communication between Control Centers and Substations
IEC 61850-90-3	Condition Monitoring
IEC 61850-90-4	Network Engineering Guidelines
IEC 61850-90-5	Transmit Synchrophasor Information
IEC 61850-90-6	Distribution Feeder Automation System
IEC 61850-90-7	Photovoltaic, Storage, DER inverters - Object models
IEC 61850-90-8	Electrical Transportation - Object models
IEC 61850-90-9	Batteries - Object models
IEC 61850-90-10	Scheduling - Object models
IEC 61850-80-1	Exchanging information from a CDC-based data model
IEC 61869-9	Digital interface for Instrument Transformers
IEC 62271-3	Communication for High-Voltage switch-gear

TABLE 2. Communication standards for wind turbines and applications.

Standard	Applications
IEC 61400-25-1	Overall Description of Principles and Models
IEC 61400-25-2	Information Models
IEC 61400-25-3	Information Exchange Models
IEC 61400-25-4	Mapping to Communication Profile
IEC 61400-25-5	Conformance Testing
IEC 61400-25-6	Logical Node Classes and Data Classes

same communication infrastructure can be used in both AC and DC systems.

An insight of communication infrastructure will be represented with a mathematical model.

1) Communication Infrastructure of a DG – Mathematical Representation: The mathematical representation of a communication infrastructure and its connection with networks and technologies is expressed. Consider communication infrastructure of a DG as shown in Fig. 3. A set of various renewable energy resources are represented as base stations. The base stations are equipped with energy storage devices, which can be utilized when the conventional system cannot provide sufficient power. All the base stations are communicating with DG control center. A two-way communication is facilitated with communication technologies.

2) Communication Channel Model: For the wireless communication technologies like cellular, Zigbee, Wi-Fi, Wi-Max, and bluetooth, consider transmission and reception with $\mathcal{W}_{L,T}$ and $\mathcal{W}_{L,R}$ antennas respectively. $\mathcal{W}_{L,T}$ is deployed at each RES. A sample of information transferred through communication channel can be represented as:

$$s_{t,i} = z_{t,i}\big(\mathcal{C}_t\mathcal{B}_{t,i}\mathcal{T}_{t,i} + \mathcal{W}_{t,i}\big) \quad (1)$$

where $s_{t,i}$ is the i-th information received at time-instant t, $z_{t,i} \in R^{\mathcal{W}_{L,R}}$ is the combiner to scale the received information, $\mathcal{C}_t$ is the multi-communication channel. $\mathcal{B}_{t,i} \in R^{\mathcal{W}_{\mathcal{L},\mathcal{T}}}$ is the beamformer for directional signal transmission for transmitter $\mathcal{T}_{t,i} \in R$. $\mathcal{W}_{t,i} \in R^{\mathcal{W}_{L,R}}$ is the independent and identically distributed noise across space and time.

3) Observation Model: To monitor the communication channel in (1), an observation model for a state x_t is represented. This representation requires transformation from a complex number to a real number, which involves property of Kronecker product[3] as:

$$vec[z_{t,i}\mathcal{C}_t(x_t)\mathcal{B}_{t,i}] = \big(\mathcal{B}_{t,i}^T \otimes z_{t,i}\big)vec[\mathcal{C}_t(x_t)] \quad (2)$$

where vec represents the vectorization. This gives observation model as:

$$y_t = \mathcal{B}_{t,i}^T \otimes z_{t,i} \;\; vec[\mathcal{C}_t(x_t)] + v_t \quad (3)$$

where $y_t \in R^m$ is the observation output, and $v_t \in R^m$ is the white-Gaussian observation noise.

For wired communication technologies, the beamformer and the antennas are not considered in the communication infrastructure.

Once the base of a communication system is defined by its infrastructure, the role of communication network and technology comes in. The selection of a particular communication network in particular depends on the required data rate and coverage range of any specific application.

IV. COMMUNICATION NETWORKS

The communication networks in DG can be classified into four sub-networks: A. Consumer's Premises Area Network (CPAN), B. Neighborhood Area Network (NAN), C. Wide-area Network (WAN), and D. Hybrid Network (HAN/NAN). This classification is based on their 1) application requirement, 2) coverage area, 3) data rate, and 4) communication technologies [28], [43]. Fig. 4 shows the illustration of this classification.

A. CONSUMERS' PREMISES AREA NETWORKS (CPAN)

CPAN can be further classified into: a) Home area network (HAN), b) Building area network (BAN), and c) Industrial area networks (IAN). This sub-classification is based on residential, commercial and industrial applications respectively. The coverage area is 1–100 m, and data rate is 1–100 kbps. The technologies used by these networks are low powered wireless personal area network (LoWPAN), PLC technologies (narrowband PLC (NPLC) and broadband PLC (BPLC)), Ethernet, Zigbee and Wi-Fi [44]–[50]. LoWPAN and Zigbee can interact with internet protocol (IP)-based system. 6LoWPAN is an acronym of IPV6 [51], [52].

B. NEIGHBORHOOD AREA NETWORKS (NAN)

The NAN is utilized for DER monitoring information. The high coverage area (100 m–10 km) and data rate (1–100 kpbs) allows control signals at smart meters to be relayed to distribution system operators (DSOs) and transmission system operators (TSOs). The technologies used by NAN are PLC, Zigbee, mesh-network, Wi-Fi, cellular, digital subscriber line (DSL) and Wi-Max [44]–[50], [53]–[57].

[3]Note the Kronecker product property enables the generalization of complex number with respect to standard choice of basis. This generalization gives an expression of linear combination of elements.

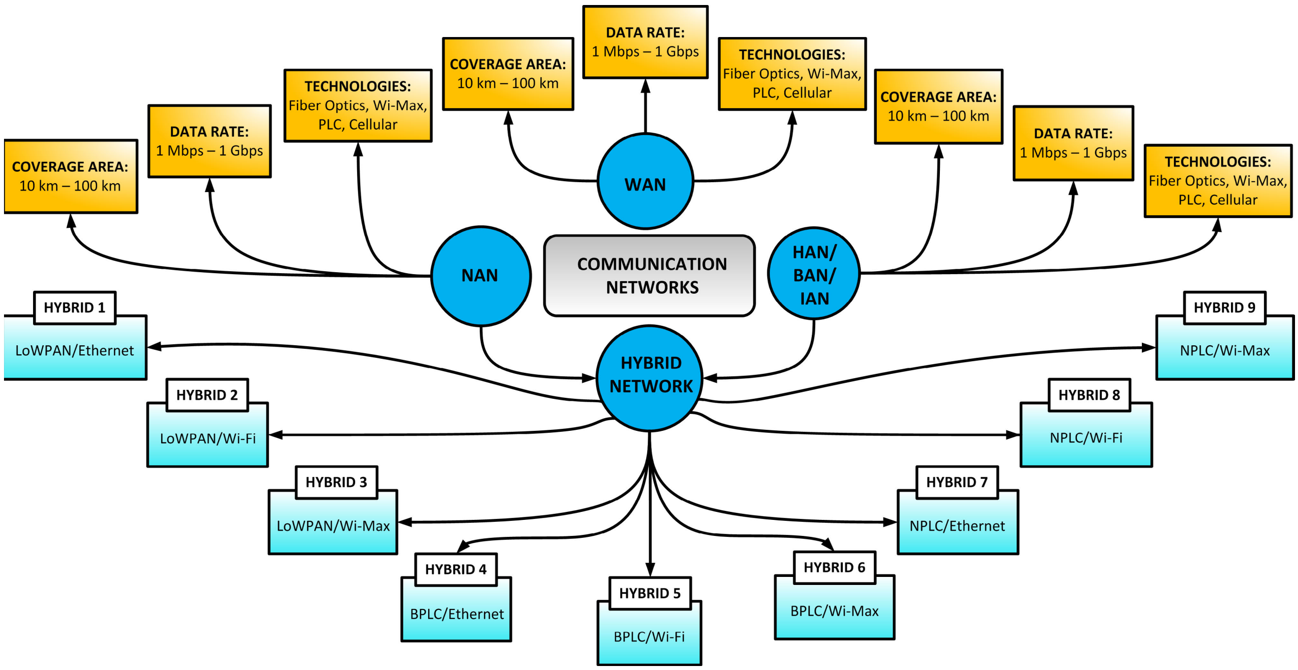

FIGURE 4. Classification of communication networks.

C. WIDE AREA NETWORKS (WAN)

The WAN is used to exchange information with DG systems to enhance visibility into DERS [58], [59]. This is due to its high coverage area (10 km–100 km) and data rate (1 Mbps–1 Gbps). WAN primarily prefers to use high-speed optic cable [60]. Other options could be Wi-Max, PLC and cellular [44]–[46], [55], [57], [61].

D. HYBRID NETWORK (HAN/NAN)

The hybrid network is designed to multiple HANs and NANs. It provides nine architectures [60] as shown in Fig. 4. This includes combination of various technologies as: 1) Hybrid 1: LoWPAN (HAN) and ethernet cable (NAN), 2) Hybrid 2: LoWPAN (HAN) and Wi-Fi (NAN), 3) Hybrid 3: LoWPAN (HAN) and Wi-Max (NAN), 4) Hybrid 4: BPLC (HAN) and ethernet cable (NAN), 5) Hybrid 5: BPLC (HAN) and Wi-Fi (NAN), 6) Hybrid 6: BPLC (HAN) and Wi-Max (NAN), 7) Hybrid 7: NPLC (HAN) and ethernet cable (NAN), 8) Hybrid 8: NPLC (HAN) and Wi-Fi (NAN), 9) Hybrid 9: NPLC (HAN) and Wi-Max (NAN).

V. COMMUNICATION TECHNOLOGIES

In this section, communication technologies with DG will be reviewed for better performance management, control and parallel power transfer with different real life applications. A framework of this section can be seen in Fig. 5. Generally, the DG system can be classified for communication technologies as: 1) wired communication, and 2) wireless communication. Well established communication techniques are being explored in a DG system as well as in AC grid systems. Researchers are also exploring new techniques specifically for DERs including channel modeling [62]–[65] and different communication networks protocols like DC local interconnected network (DC-LIN) [66] or controller area network (CAN) protocol [67]. ESS is an essential part of any DER for energy storage. This is due to the intermittent nature of renewable energy sources and difference in demand-supply [68]. Different communication techniques have been proposed for energy management system (EMS) to reduce cost and resource wastage [69], [70]. Energy efficiency of different communication systems (cellular, WSNs etc.) connected to a DG, can also be increased with the concept of energy harvesting [71], [72]. Different communication techniques are being proposed and implemented for DG with different benefits from power line communication (PLC), wireless communication, internet of energy (IOE) [73]–[79] etc.

PLC is considered to be a strong candidate in DG system followed by visible light communication (VLC), Wi-Fi, Wi-Max, Zigbee, internet of energy (IOE), fiber optic communication (FOC) or combination of any of these communication techniques.

A. WIRED COMMUNICATION – POWER LINE COMMUNICATION (PLC)

PLC is used in different applications for low voltage power system, such as automatic meter reading, demand side networks (DSN) [80] etc. It is due to this property that PLC is considered to be the most commendable option for DERs. Its structural flexibility in expansion and readily available infrastructure has allowed it to deal with the bi-directional flow of power, varying nature of DC/AC loads, and for better signaling in DERs [81]–[90]. A DC transmitter and receiver block diagram is shown in Fig. 6.

1) Utilization and Architecture: The major advantage of using PLC in a grid is its low installation cost because power lines are already deployed and no amount has to be paid to any

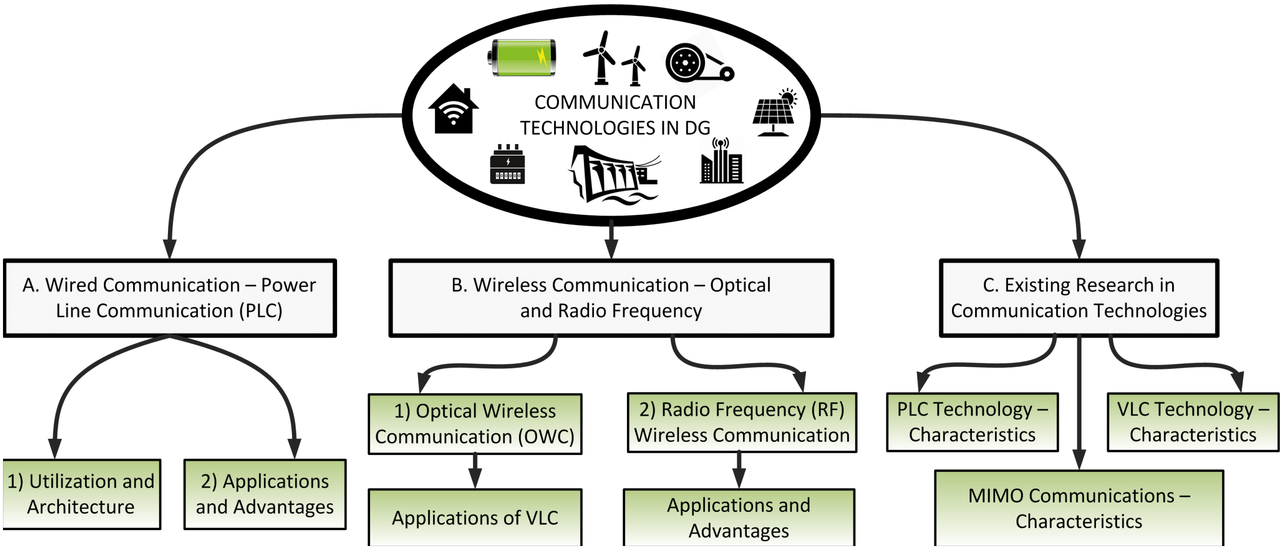

FIGURE 5. Communication technologies in DG.

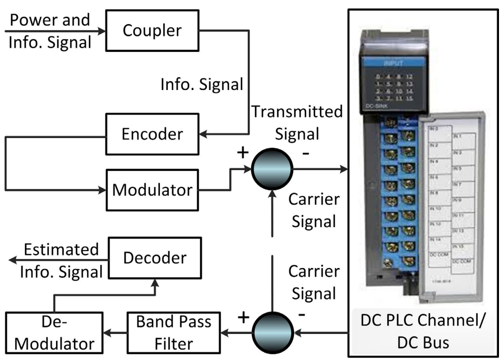

FIGURE 6. A PLC transceiver/module with bus/PLC channel.

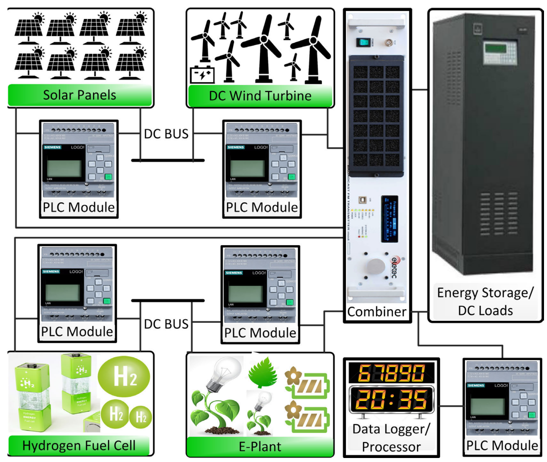

FIGURE 7. DER with bus, PLC-modules, data logger and processor.

communication service provider [91]. Though PLC suffers from different noises, attenuation and distortion problems [92], it is considered to be more secure from cyber-attacks as compared to wireless communication systems [93]. A coupler/de-coupler in a PLC transceiver is used to inject or extract information signal from a grid [94]. A coder and decoder will improve the bit error rate (BER) [69] at the cost of transceiver complexity. A modulator along with carrier signal is used to map the signal properties to communication channel properties. Moreover, the interaction of PLC with: 1) different DERs, such as solar panels, wind turbines, e-plant and hydrogen fuel cell [95]–[97], 2) DC bus, 3) data logger, and 4) processor, are shown in Fig. 7.

2) Applications and Advantages: Table 3 lists PLC with its applications and advantages. In [81], PLC is used for control signal communication in a DER-based grid for load sharing. The authors have proposed switching frequency modulation (SFM) techniques to overcome power convertor limitations and also to enhance PLC performance. The performance is also verified by using 3.3 kW dual active bridge prototype. In [98], an intelligent PV module was proposed with PLC by using frequency shift keying (FSK) modulation. This is to reduce the electricity losses by full monitoring and to help in predictive maintenance of a PV system. This work was further extended in [99] for residential consumer with home plug communication architecture in which orthogonal frequency division multiplexing (OFDM) modulation technique is used to enhance noise immunity [100] in PLC. A low cost solution was discussed in [101] in which PLC module is used by using amplitude shift keying (ASK) without communication modem. A smart graphical user interface was also designed and tested with sixteen panel each with monitoring module. This work was further extended in [102] by having one monitoring module for four PV panels to reduce the cost. A scheme was also discussed to localize the faulty panel with the help of data gathered through PLC and synchronization of monitoring time. To enhance the performance of DC-DC power optimizer (DCPO) in a DG system with PV panels, PLC was used with differential phase shift keying (DPSK) modulation technique along with discrete fourier transform (DFT) [103]. By sharing the data of PV panels connected in series in string using existing DC cables, an algorithm is run to achieve maximum power from PV panels because

TABLE 3. PLC with applications.

Reference	Application	Technology	Characteristic
[81]	Control Signal Communication	DER System	Overcome power converter limitations, enhance PLC performance
[98]	FSK Modulation Technique	PV module	Reduce electricity losses, Enhance predictive maintenance
[99]	Home Plug Communication	PV module	Save energy cost
[100]	Comparison of CDMA and OFDM systems	PLC module	Enhance noise immunity
[101]	communication modem	PLC module	A low cost solution, a smart graphical user interface
[102]	Monitoring Module	PV panels	Reduce the cost, localize the faulty panel
[103]	DPSK Modulation Technique	DFT	Maximum power from PV strings
[104]	PLC onboard Vehicles	DER System	makes maintenance and diagnosis easy
[105]	Modeling and Analysis of background and impulsive noise	PLC	Better performance during observed power line noise
[67]	Small Scale Radial Distribution	Industrial Applications	Road Signs, Street Lights, Parking Systems
[106]	Variation in noise PSDs analyzed	PLC channel	Suitable method for grids
[107]	prediction of EM noises	PLC channel	analysis of loads shedding in a microgrid
[108]	Data Transmission	PWM network	Overcome transmission limitations
[109]	fusion of PLC and PWN	PWN network	information exchange in a grid
[110]	control and coordination	PLC	dual modulation of DC-DC converters
[111]	control and coordination	PLC	power/signal dual modulation
[112]	information signal attenuation	PLC	fractional harmonic domain-based signaling

current can be reduced in a string due to non-uniform ageing, shading or manufacturing differences of PV panels. The proposed technique performance is verified with string of six PV panels connected in series. DG system for EV is discussed with PLC: 1) in-vehicle, 2) between vehicle and grid [104], and 3) using multi-carrier modulation technique [105]. Using PLC in EV will reduce weight and space and it will also make the maintenance and diagnosis, easy. Channel modeling is done in: 1) in-vehicle, and 2) grid-to-vehicle. Noise modeling in time and frequency domains, produced by motor drives and AC/DC converters, is also proposed. PLC can be used for trip information, entertainment, vehicle diagnosis in DC grid and Plug-in EV. Small scale radial distribution system (for industrial applications) is implemented with photo voltaic (PV) DER-based grid system in [67] by using PLC between energy management system (EMS) and several battery management systems (BMS). Single carrier is generated and then modulated by the Bus bar impedance to have different carrier signals. The proposed system can be used with different applications such as road signs, street lightening or parking meter systems. Street lightening system can work smoothly with maximum 10kb/sec. In [106], noise power spectral densities (PSDs) are derived to enhance data transmission in LVDC based grid. Electro-magnetic (EM) noises are also predicted while using PLC in a DERs-based grid to optimize the management and performance of the system. These EM noises are usually generated by house hold devices [107]. In [108], PLC is deployed to analyze data transmission over pulse width modulation (PWM) network. This is utilized by using a PWM-based filter. PMW is also used with PLC in [109] to exchange information between invertor and a motor in a grid. PLC is widely used to exchange information for control and coordination among different convertors in DRES based grids [110], [111]. To deal with information signal attenuation issue and also to design an economical PLC transceiver, a fractional harmonic domain based technique is proposed in [112]. The primary control loop and modulation algorithm of the convertor is used for encoding and decoding of information data.

B. WIRELESS COMMUNICATION – OPTICAL AND RADIO FREQUENCY

Wireless communication can be classified into: a) optical, and b) radio-frequency (RF) wireless communication.

1) Optical Wireless Communication (OWC): Light-emitting diodes (LEDs) have already captured the conventional lightening devices usage market due to its low energy consumption. LEDs are also used for communication purposes along with illumination at the same to achieve high data rates in the range of GHz as compared to conventional RF communication [113]. Note OWC is also called as visible light communication (VLC) or light-fidelity (Li-Fi) [114]. It is considered to be harmless for human body and more secure because it cannot penetrate in walls. The data rate can further be increased by using Visible light laser diodes (LDs) [115] or by developing multi-input multi-output (MIMO) communication architecture [116]. The major limitation of VLC is that its data rate can decrease significantly with the increase in distance between transmitter and receiver.

Applications of VLC: A simple block diagram of a VLC transceiver is shown in Fig. 8. Information signal is first modulated and then amplified according to the channel conditions. A photo diode is used at receiver side to detect the modulated signal and then demodulation is done to estimate the information signal. A solar powered home with VLC is shown in Fig. 9. Little modifications are required in LED bulbs and other user's devices such as smart phones, laptops and smart sound system to get full advantage of this high data rate communication technique. Approximately 8% of the total energy consumption is used for lightening purposes in commercial and residential buildings [117]. Table 4 summarizes the applications of VLC with its advantages. VLC is proposed in [118] for personalization and localization using LEDs for building management, considering indoor environment. The variable pulse position modulation (VPPM) was used for secure communication and location information transmission and authorization with different dimming levels of LEDs. DG system with smart DC LED-based intelligent lighting system named EDISON was discussed with different

TABLE 4. VLC with applications.

Reference	Application	Technology	Characteristic
[118]	personalization and localization using LEDs	VLC	secure communication, local information transmission
[119]	intelligent lighting system	LED	enhances control signal transmission, optimal modulation
[117]	study of total energy consumption	VLC	high data rate communication

TABLE 5. RF wireless communication technologies.

Network Type	Technology	Standard	RF Bands
WLAN	Wi-Fi	IEEE 802.11	900 MHz, 2.4 GHz, 5 GHz, 5.9 GHz, 60 GHz
WPAN	Bluetooth	IEEE 802.15.1	2.4 GHz
WPAN	Zigbee / WSN	IEEE 802.15.4	2.4 GHz
WWAN	Mobile / Cellular	1G–5G, IEEE 802.20	800 MHz, 900 MHz, 1800 MHz, 3.5 GHz
WWAN	Wi-MAX / WMAN	IEEE 802.16	2.5 GHz, 3.5 GHz, 5.8 GHz

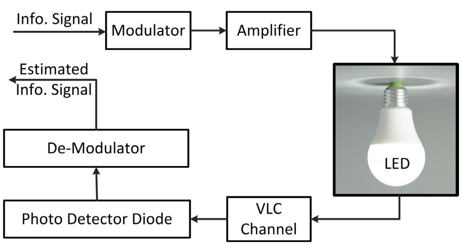

FIGURE 8. A VLC transceiver.

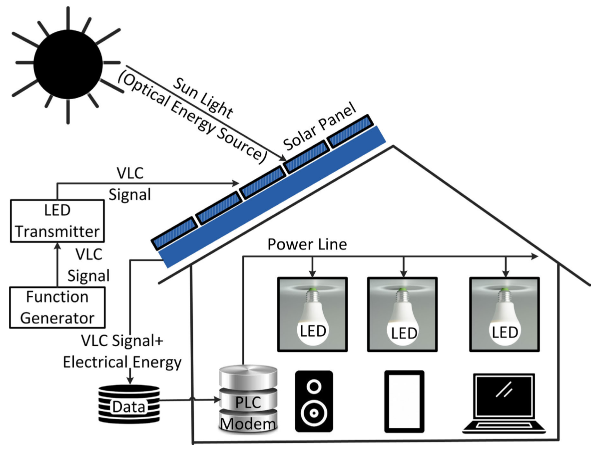

FIGURE 9. Solar powered home.

communication techniques including VLC [119]. VLC was used for control signal transmission with high Bandwidth efficiency as compared to other communication techniques. The modulation technique even works when the LEDs are almost dimmed and appeared to be off to human eye.

2) Radio Frequency (RF) Wireless Communication: In RF wireless communication, electromagnetic waves are used to carry the information. So many different communication architecture have been proposed with their advantages such as easy installation, low cost and flexibility and disadvantages such as information security breach, limited available spectrum and interference from other users or devices [120], [121]. In a MIMO communication architecture, band width and power efficiency can be increased by increasing number of antennas at transmitter and/or at receiver side (See Fig. 10). To further improve the system performance large scale or massive MIMO communication systems are also been proposed with large number of antennas [122]. Table 5 is summarizing RF wireless communication technologies. Note the RF band values can be different for various countries or regions.

Applications and Advantages: A scalable MIMO communication system architecture is shown in Fig. 11. This system has a MIMO energy management system (EMS). Table 6 lists the application of RF wireless communication. RF wireless communication technologies will get a place in DERs by using the concept of simultaneous information and power transfer (SWIPT) [70] to reduce energy resources wastage. A super capacitor was used with multi directional power flow to store energy for wireless sensor nodes. WSNs in a DG can be used for information and control signal communication inside DG system or among different set of DG systems [123]. A smart personal WSN was proposed and implemented inside a building for DC powered LED based lightening system. The energy optimization is achieved by controlling the illuminance using WSN [124]. A smart street lightening system was tested by F. Leccese in which each pole has a transceiver to form a Zigbee communication architecture in a mesh topology. Then all the information is transmitted and processed in a central control unit by using a low cost with good computational performance Raspberry-Pi processor [125]. This central control unit is connected to a grid through Wi-Max to overcome the distance limitations of commercially available Wi-Fi networks [126]. By using the motion and light sensors inside the building, 55% energy saving was achieved. LEDs were controlled and illumination was monitored by using Zigbee architecture, keeping in mind the user satisfaction [127]. A public street lightening system performance was evaluated in [128] with WPAN by using digital addressable lightening interface (DALI) to digitally control light bulbs ballasts. Another smart lightening system was proposed with Brute-Force algorithm to optimize the energy consumption. Among the lightening poles, PLC transceivers were used for monitoring and sharing the information, then the Wi-Max architecture was used for segment and supervisor monitoring and control [129]. Industrial WSN was used for information sensing and exchange to do strategy estimation and event-triggered control [130] in a DG system. A wind power farm (WPF) with wireless RF communication architecture was proposed in [131] according to IEC 61400-25 standard [132] for remote monitoring with scalable area coverage and capacity. The network performance was

TABLE 6. RF with applications.

Reference	Application	Technology	Characteristic
[70]	simultaneous information and power transfer	RF wireless communication	Reduce energy resources wastage
[123]	DER system	WSNs	Extract information and control signal communication
[124]	building implementation	WSN	Enhance DC powered LED-based lightening system
[126]	A smart street lightening system	Zig-Bee, WiMAX, Rasberry pi-card	central control unit with variable combination testing
[127]	Building Motion and Light sensors	Zig-Bee	55 % energy saving
[128]	A street lightening system evaluated	WPAN	Digitally control light bulbs ballasts
[129]	A smart lightening system proposed with Brute-Force algorithm	PLC and Wi-Max	DALI protocol
[130]	information sensing and exchange	Industrial WSN	Strategy estimation and event-triggered control
[131]	Wind Energy System	WPF with RF communication	remote monitoring with scalable area coverage

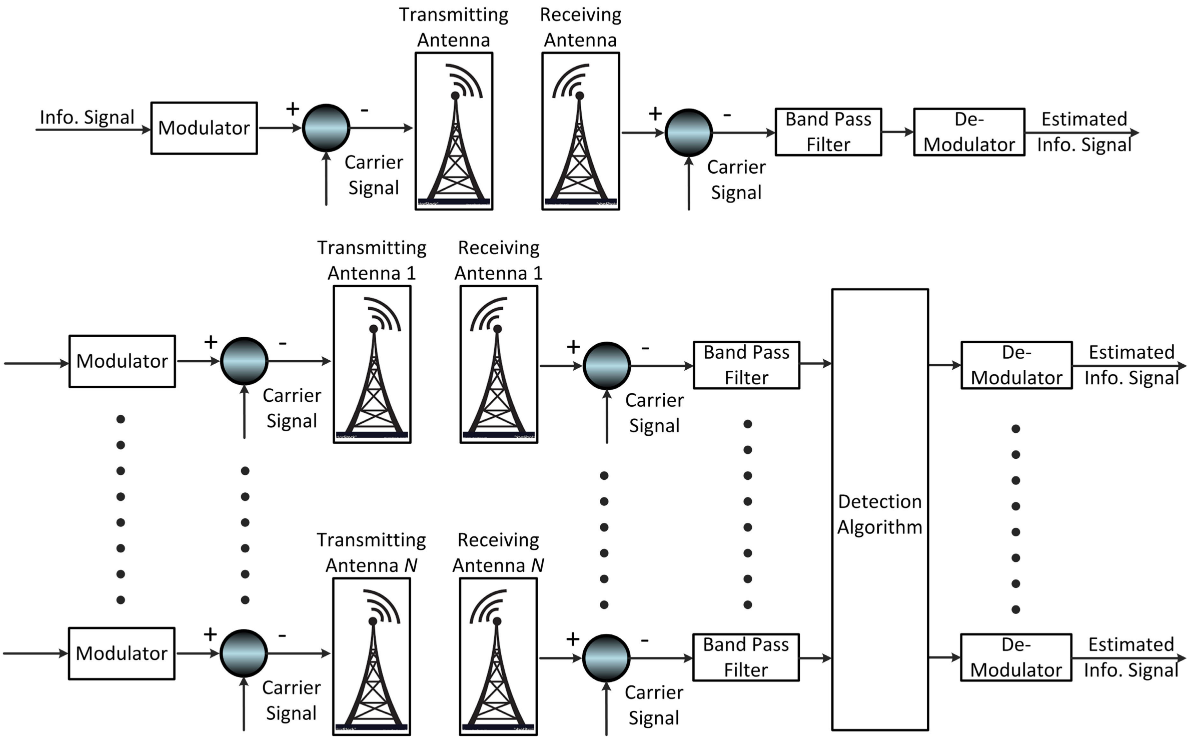

FIGURE 10. A scalable MIMO wireless communication transceiver.

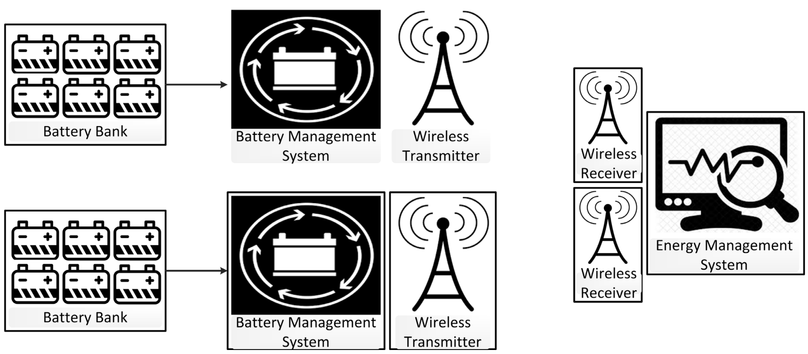

FIGURE 11. EMS with a scalable MIMO wireless communication architecture.

evaluated considering different wireless technologies like ZigBee, WiFi and WiMAX in view of end-to-end delay, wireless channel capacity, and data loss.

C. EXISTING RESEARCH IN COMMUNICATION TECHNOLOGIES – SUMMARY

All the communication technologies discussed in this section are contributing individually or in combination. This is based on the respective technology requirements, such as: 1) cost, 2) data rate, 3) reliability, 4) easy expansion, 5) information security, and 6) interference from other users or devices. In principle, PLC technology has low installation cost with options of flexible expansion. From the perspective of data rates, VLC is significant. It can provide high data rates as compared to conventional RF communication. The massive MIMO communication-based architectures are also

TABLE 7. Future challenges in communication infrastructures.

FEATURES	SEVERAL COMMUNICATION PROTOCOLS/TECHNOLOGIES			
CHALLENGES	Integration	Inter-Operation	Common Protocols	Standardization
FEATURES	SCADA SYSTEMS			
CHALLENGES	Old System	Intelligent Electronic Devices	Protocols Ugrade	Future Grid Requirements
FEATURES	NEW COMMUNICATION TECHNOLOGIES			
CHALLENGES	Optimum Data Rate	Bandwidth	Future Demands	Future Expansions
FEATURES	DIGITAL COMMUNICATION INFRASTRUCTURE			
CHALLENGES	Digital Information	Cyber-Security	Vulnerability of Information	Data Privacy

considered to be a strong candidate for DGs communication networks. This is due to their higher spectral efficiency with low energy consumption.

VI. CONCLUSION AND FUTURE CHALLENGES

The communication system in DGs have gained a lot of attention due to the increasing trend of utilizing renewable energy resources. Currently, the outlook of renewable as a source of energy is too optimistic. This has raised bars with high expectations on the value of technology. This article provided a survey on the utilization of communication technology in DG system while discussing the recent applications and frameworks. It also expressed the advantages of communication infrastructures in DG systems. However, to successfully implement the framework of communication in DGs, significant challenges of integration of various technologies and digital layers will be encountered.

Though the frameworks and review on communication infrastructures show promising achievements in future DG systems, the full deployment of the infrastructure could face numerous number of challenges. This can be seen in Table 7. These challenges are due to the fusion of various protocols and technologies, which could lead to constraints of standardization and optimization [133]–[135].

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ZIMRAN RAFIQUE (Member, IEEE) received the B.Sc. degree in electrical engineering from the University of Engineering and Technology at Lahore, Lahore, Pakistan, in 2002, the M.Sc. degree in electronic engineering from the Ghulam Ishaq Khan Institute of Engineering, Sciences and Technology, Topi, Pakistan, in 2005, and the Ph.D. degree from the Electrical and Electronic Engineering Department, Auckland University of Technology, Auckland, New Zealand, in 2014.

He is currently working as an Assistant Professor with the Department of Electrical Engineering technology, Higher Colleges of Technology, Sharjah, United Arab Emirates. He has more than nine years of industrial, teaching, and research experience. His research interests include smart grid communication and control technologies, alternate energy systems, wireless multimedia sensor networks, and massive MIMO communication systems.

HARIS M. KHALID (Senior Member, IEEE) received the B.S. degree (Hons.) in mechatronics and control systems engineering from the University of Engineering and Technology at Lahore, Lahore, Pakistan, in 2007, and the M.S. and Ph.D. degrees in control systems engineering from the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 2009 and 2012, respectively.

He is currently an Assistant Professor in electrical and electronics engineering with the Higher Colleges of Technology, Sharjah, United Arab Emirates. He is also entitled as an Applied Research Coordinator in Sharjah Campuses. In 2012, he joined the Distributed Control Research Group, King Fahd University of Petroleum and Minerals, as a Research Fellow. From 2013 to 2016, he was a Research Fellow with the Power Systems Research Laboratory, iCenter for Energy, Masdar Institute (MI), Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates, which is an MI-MIT Cooperative Program with the Massachusetts Institute of Technology, Cambridge, MA, USA. During this tenure, he was also a Visiting Scholar with the Energy Systems, Control, and Optimization Laboratory, ADNOC Research and Innovation Center, Khalifa University of Science and Technology. He has authored/coauthored more than 60 peer-reviewed research publications. He has served as an Energy Specialist in United Arab Emirates Space Agency "Tests in Orbit" Competitions, which are partnered with Dream-Up and Nano-Racks. His research interests include power systems, cyber-physical systems, electric vehicles, signal processing, V2G technology, fault diagnostics, filtering, estimation, and condition monitoring. He was the Technical Chair of IEEE-ASET 2018–2020 (seven group of conferences) organized in United Arab Emirates. He is also a Reviewer of the IEEE TRANSACTIONS ON POWER SYSTEMS, IEEE TRANSACTIONS ON NEURAL NETWORKS AND LEARNING SYSTEMS, IEEE TRANSACTIONS ON CONTROL OF NETWORK SYSTEMS, IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, and IEEE SYSTEMS JOURNAL. He is also an Associate Editor of *Frontiers in Energy Research | Smart Grids*.

S. M. MUYEEN (Senior Member, IEEE) received the B.Sc. (Eng.) degree from the Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh, formerly known as the Rajshahi Institute of Technology, in 2000, and the M.Eng. and Ph.D. degrees from the Kitami Institute of Technology, Kitami, Japan, in 2005 and 2008, respectively, all in electrical and electronic engineering.

He is currently an Associate Professor with the Department of Electrical and Computer Engineering, Curtin University, Perth, WA, Australia. He has authored/coauthored more than 175 articles in different journals and international conferences and also six books as the author or an Editor. His research interests include power system stability and control, electrical machine, flexible ac transmission systems, energy storage systems, renewable energy, and HVdc systems.

Dr. Muyeen is a Fellow of Engineers Australia. He is serving as Editor/Associate Editor for many prestigious journals from IEEE, IET, and other publishers, including the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, the IEEE POWER ENGINEERING LETTERS, *IET Renewable Power Generation*, and *IET Generation, Transmission and Distribution*. He has been a Keynote Speaker and an Invited Speaker at many international conferences, workshops, and universities.