Renewable Energy 146 (2020) 2589–2625

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A survey on smart grid technologies and applications

Dileep G.

Department Electrical & Electronics Engineering, Madanapalle Institute of Technology & Science, Madanapalle, Andhra Pradesh, 517325, India

ARTICLE INFO

Article history:
Received 1 January 2019
Received in revised form
16 August 2019
Accepted 18 August 2019
Available online 23 August 2019

Keywords:
Smart grid
Smart substation
Smart sensor
Smart metering
Home and building automation

ABSTRACT

The Smart Grid is an advanced digital two-way power flow power system capable of self-healing, adaptive, resilient and sustainable with foresight for prediction under different uncertainties. In this paper, a survey on various Smart Grid enabling technologies, Smart Grid metering and communication, cloud computing in Smart Grid and Smart Grid applications are explored in detail. Opportunities and future of Smart Grid is also described in this paper. For Smart grid enabling technologies Smart meters, smart sensors, vehicle to grid, plug in hybrid electric vehicle technology, sensor and actuator networks are explored. Advanced metering infrastructure, intelligent electronic devices, phasor measurement units, wide area measurement systems, local area network, home access network, neighborhood area network, wide area networks and cloud computing are explored for Smart Grid metering and communication. Home and building automation, smart substation, feeder automation is explored for smart grid applications. Associations of initial studies for the next step in smart grid applications will provide an economic benefit for the authorities in the long term, and will help to establish standards to be compatible with every application so that all smart grid applications can be coordinated under the control of the same authorities. Therefore, this study is expected to be an important guiding source for researchers and engineers studying the smart grid. It also helps transmission and distribution system operators to follow the right path as they are transforming their classical grids to smart grids.

1. Introduction

Majority of the world's electricity distribution system or 'grid network' was built when energy was reasonably low cost. Minor upgrading has been made to the primitive grid network to meet up with the rising demand of energy. Still the utility grid operates in the way it did almost 100 years ago, energy flows from central power plants to consumers through utility grid and by preserving surplus capacity reliability is ensured. Such a system is environmentally extravagant and incompetent and consumer of fossil fuels, that is a principal emitter of particulates and greenhouse gases, and not well suited to distributed energy resources (DERs). In addition, the utility grid may not have sufficient capacity to meet demand in future. Revolutionary changes in communication systems, mainly inspired by the Internet, presents greater control and monitoring possibility all over the power system and hence more low cost, flexible and effective operation. The Smart Grid [1–10] is a chance to utilize the new communication technologies and information to revolutionize the conventional electrical power system. However, any significant change made in conventional power system requires careful justification and expensive due to the scale of investment that has been made in it over the years and the huge size of the power system. The consent among climate scientists is clear that the man-made greenhouse gases are leading to dangerous climate change. With regards to climate change, Smart Grid is capable of facilitating climate change mitigation (CCM) and climate change adaptation (CCA) from both a behavioral and institutional perspective (energy conservation and demand management) as well as from a technological standpoint (i.e., the integration of renewable energy sources). Integration of renewable energy through Smart Grid help to reduce the emission of carbon particulate and greenhouse gases, thereby helps in CCM. Energy conservation and demand management programs included in Smart Grid helps in reducing energy consumption. Integrating climate change considerations into Smart Grid planning and deployment, electricity stakeholders can ensure that the implemented Smart Grid technology does not contribute to greenhouse gas emissions and does not result in a grid that is vulnerable to climate change-related damage. Reduction in wasted energy, losses and effective management of loads needs accurate information. State of utility grid becomes observable and different possibilities for control

E-mail address: dileepmon2@gmail.com.

https://doi.org/10.1016/j.renene.2019.08.092
0960-1481/

Abbreviation

ADC	Analog to digital converter
AMI	Advanced metering infrastructure
AMR	Automatic meter reading
BAS	Building automation system
BIPV	Building integrated photovoltaic
CBM	Circuit breaker monitor
CCA	Climate change adaptation
CCM	Climate change mitigation
CHP	Combined heat and power
CS	Compressive sensing
DA	Distribution automation
DERs	Distributed energy resources
DERMS	Distributed energy resource management systems
DFR	Digital fault recorder
DFRA	Digital fault recorder assistant
DG	Distributed generation
DMS	Distribution management system
DPR	Digital protective relays
DPRA	Digital protective relay analysis
DSM	Demand side management
DULRs	Dual-use line relays
EM	Electromagnetic
EMS	Energy management system
ESI	Energy services interface
FA	Feeder automation
FAN	Field area networks
FACTS	Flexible AC transmission systems
FERC	Federal energy regulatory commission
FLISR	Fault location, isolation and service restoration
HAN	Home area network
HMI	Human machine interface
IADS	Integrated automated dispatch systems
IEDs	Intelligent electronic devices
IHD	In-home display
GD	Generation dispatch
GFR	Grid frequency regulation
GMC	Grid monitoring and control
GPS	Global positioning system
GUI	Graphical user interface
LAN	Local area network
MUs	Merging units
NAN	Neighborhood area network
NCAP	network capable application processor
NCIT	Non-conventional instrument transformers
NIC	Network interface card
NIST	National institute of standards and technology
OMS	Outage management system
PARs	Phase angle regulating transformers
PCUs	Power conditioning units
PDCs	Phasor data concentrators
PHEV	Plug in hybrid electric vehicle
PLC	Programmable logic controllers
PMU	Phasor measurement unit
PV	Photovoltaic
RESs	Renewable energy sources
RFEH	Radio frequency energy harvesting
RTP	Real time pricing
RTUs	Remote terminal units
R&D	Research and development
SA	Substation automation
SANETs	Sensor and actuator networks
SGCC	Smart Grid control center
SNTP	Simple network time protocol
SPV	Solar photovoltaic
STIM	Smart transducer interface module
TEG	Thermoelectric generator
TOU	Time-of-use
T&D	Transmission and distribution
VTC	Video teleconferencing
V2G	Vehicle to Grid
WAMS	Wide area measurement systems
WAN	Wide area networks

Nomenclature

Hz	Hertz
kVAR	kilovolt-ampere reactive
kW	kilowatt
kWh	kilowatt hour
s	Seconds

emerge once monitoring of all the parts of the power system is done. Future de-carbonized electrical power system is likely to rely on generation from a combination of renewable DERs, nuclear power plants and fossil-fuelled plants with carbon capture and storage [11–22]. Combination of different generator modules increases the difficulty to manage the power system to run at constant output for commercial and technical reasons. It is hard to control and monitoring cost-effective and synchronized operation such a power system without the help a smarter grid. Hence, Smart Grid is essential for future power system [23–28].

The choice of Smart Grid has been evolved into a goal from a vision and it is being realized slowly all around the globe. Smart Grid initiatives across the globe are facilitated by concrete energy policies, audit and management [29–37]. Many developed countries have already installed Smart Grid technologies in the electricity network. But there are many other countries which are lagging in Smart Grid technology implementation. This paper traces the emergence of Smart Grid as a need to modernize the conventional utility grid [38–51]. Large number of research papers have been reviewed to included best basic knowledge of Smart Grid fundamentals, technologies, functionalities, characteristics, needs, challenges and future scope. Each components of Smart Grid technologies like smart meters, smart sensors, and its application in Smart Grid has also been explained in detail. The role of Smart Grid metering and communication technologies for real time measurement and monitoring purpose, with the challenge of data privacy and security, has also been explored.

2. Smart grid: the definitions

The concept of Smart Grid unites a number of technologies, consumer solutions and addresses several policy and regulatory drivers. Smart Grid does not have any single obvious definition. Definition of Smart Grid by European technology platform is,

> "*A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it-generators, consumers and those that do both-in order to efficiently deliver sustainable, economic and secure electricity supplies.*"

In smarter grids the Smart Grid is defined as,

"*A Smart Grid uses sensing, embedded processing and digital communications to enable the electricity grid to be observable (able to be measured and visualized), controllable (able to manipulated and optimized), automated (able to adapt and self-heal), fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources).*"

Definition of Smart Grid by U.S. department of energy is,

"*A Smart Grid uses digital technology to improve reliability, security and efficiency (both economic and energy) of the electrical system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.*"

IEC definition for Smart Grid is,

"*The Smart Grid is a developing network of transmission lines, equipment, controls and new technologies working together to respond immediately to our 21st Century demand for electricity.*"

IEEE definition for Smart Grid is,

"*The smart grid is a revolutionary undertaking-entailing new communications-and control capabilities, energy sources, generation models and adherence to cross jurisdictional regulatory structures.*"

From the aforementioned definitions, the Smart Grid can be described as a transparent, seamless and instantaneous two-way delivery of energy, information and enabling the electricity industry to better manage energy delivery and transmission and empowering consumers to have more control over energy decisions. A Smart Grid incorporates the benefits of information technologies and advanced communications to deliver real-time information and enable the near-instantaneous balance of supply and demand on the electrical grid. Two-way exchange of information between the utility grid and consumer is one significant difference between Smart Grid and today's utility grid. For example, under the Smart Grid concept, a smart thermostat might receive a signal about electricity prices and respond to higher demand (and higher prices) on the utility grid by adjusting temperatures, saving the consumer money while maintaining comfort. Fig. 1shows a snapshot of the deliverance of the Smart Grid.

Thus, the working definition becomes:

"The Smart Grid is an advanced digital two-way power flow power system capable of self- healing, adaptive, resilient and sustainable with foresight for prediction under different uncertainties. It is equipped for interoperability with present and future standards of components, devices and systems that are cyber-secured against malicious attack."

Need for Smart Grid.

(1) Opportunities to take advantage of improvements in electronic communication technology to resolve the limitations and costs of the electrical grid have become apparent.
(2) Concerns over environmental damage from fossil-fired power stations.
(3) The rapidly falling costs of renewable based sources point to a major change from the centralized grid topology to one that is highly distributed.

Introducing Smart Grid to the electrical power utility grid infrastructure will,

(1) Improves the reliability of utility grid by reducing power quality disturbances and reducing consequences and probability of widespread blackouts.
(2) Allows for the advancements and efficiencies yet to be envisioned.
(3) Reduces electricity prices paid by consumers by exerting downward pressure.
(4) Better affordability is maintained for energy consumers.
(5) Greater choice of supply and information is provided to consumer.
(6) Integrates renewable/nonconventional DERs.
(7) Improves security by reducing the consequences and probability of natural disasters and manmade attacks.
(8) Facilitate higher penetration of alternating power generation sources.
(9) Reduces loss of life and injuries from utility grid related events, thereby reduces safety issues.
(10) Integrates electrical vehicles as generating and storing devices, thereby revolutionize the transportation sector.
(11) Improves the overall efficiency by reducing loses and wastage of energy.
(12) Smart Grid reduces environmental pollution by reducing emission of greenhouse gases and carbon particulates and provides cleaner power by promoting deployment of more renewable DERs.

3. Characteristics of smart grid

Smart Grid employs innovative products and services along with intelligent control, communication, monitoring and self-healing technologies. The literature suggests the following attributes of the Smart Grid.

(1) Smart Grid provides consumers better choice of supply and information also permits consumers to play a part in optimizing operation of the system. It enables demand side management (DSM) and demand response (DR) through the incorporation of smart appliances, smart meters, micro-generation, electricity storage and consumer loads and by providing consumers the information regarding energy use and prices. Information and incentives will be provided to consumers for revising their consumption pattern to overcome few constraints in the power system and improving the efficiency.
(2) It allows the connection and operation of generators of all technologies and sizes and accommodates storage devices and intermittent generation. It accommodates and assists all types of residential micro-generation, renewable DERs, DGs and storage options, thereby considerably reduces the environmental impact of the whole electricity supply system. It allows 'plug-and-play' operation of microgenerators, thereby improves the flexibility.
(3) It optimizes and operates assets efficiently by pursuing efficient asset management and operating delivery system (working autonomously, re-routing power) according to the need. This includes the utilizing of assets depending on when it is needed and what is needed.

(4) It operates durably during cyber or physical attacks, disasters and delivers energy to consumers with enhanced levels of security and reliability. It improves and promises security and reliability of supply by predicting and reacting in a self-healing manner.
(5) It provides quality in power supply to house sensitive equipment that enhances with the digital economy.
(6) It opens access to the markets through increased aggregated supply, transmission paths, auxiliary service provisions and DR initiatives.

4. Functions of Smart Grid

Functions of Smart Grid includes,

(1) Exchange data on electricity generators, consumers and grids over the Internet and process this data by means of information technology
(2) Integrate numerous new smaller electricity generation facilities.
(3) Balance out fluctuations in electricity yields that arise as a result of the use of renewable energies.
(4) Through sensors, communications, information processing, and actuators that allow the utility to use a higher degree of network coordination to reconfigure the system to prevent fault currents from exceeding damaging levels.
(5) Using time synchronized sensors, communications, and information processing.
(6) Real-time determination of an element's (e.g., line, transformer etc.) ability to carry load based on electrical and environmental conditions.
(7) Using flexible AC transmission systems (FACTS), phase angle regulating transformers (PARs), series capacitors, and very low impedance superconductors.
(8) Adjustable protective relay settings (e.g., current, voltage, feeders, and equipment) that can change in real time based on signals from local sensors or a central control system
(9) Automatic isolation and reconfiguration of faulted segments of distribution feeders or transmission lines via sensors, controls, switches, and communications systems
(10) Automated separation and subsequent reconnection of an independently operated portion of the transmission and distribution (T&D) system
(11) By coordinated operation of reactive power resources such as capacitor banks, voltage regulators, transformer load-tap changers, and distributed generation (DG) with sensors, controls, and communications systems
(12) On-line monitoring and analysis of equipment, its performance, and operating environment in order to detect abnormal conditions.
(13) Higher precision and greater discrimination of fault location and type with coordinated measurement among multiple devices.
(14) Real-time measurement of customer consumption and management of load through Advanced Metering Infrastructure (AMI) systems and embedded appliance controllers that help customers make informed energy use decisions via real-time price signals, time-of-use (TOU) rates, and service options.
(15) Real-time feeder reconfiguration and optimization to relieve load on equipment, improve asset utilization, improve distribution system efficiency, and enhance system performance.
(16) Customers are provided with information to make educated decisions about their electricity use.

5. Evolution of smart grid

The existing electricity utility grid is a product of rapid urbanization and infrastructure developments in different parts of the world in the past century. Utility companies adopt similar technology even though they exist in several differing geographies. Political, economic and geographic factors also have an influence on erection and development of electrical power system. Regardless of such differences, the fundamental topology of the existing electrical power system has stayed unchanged. Power industry has operated with clear differentiation between its generation, transmission and distribution subsystems with the inception of Smart Grid. Hence, different levels of automation, transformation and evolution have been shaped in each step. As shown in Fig. 1, the existing electricity utility grid is a hierarchical system in which power delivery to consumers at the bottom of the chain is guaranteed by power plants at the top of the chain. The source has no real-time information about the termination point's service parameters, system is a one-way pipeline. So, in order to withstand maximum estimated peak demand across its total load, utility grid is therefore over-engineered. Peak demand doesn't occur frequently; hence, a system designed based on peak demand is inefficient. Moreover, the system stability has decreased due huge rise in demand of power and low investments in infrastructure. With the safe margins fatigued, any irregularity across the distribution network or any unexpected surge in demand causing component failures can trigger catastrophic blackouts. Various levels of control and command functions have been introduced by the utility companies to ease troubleshooting and maintenance of the expensive upstream assets. SCADA is a typical example which is widely deployed. About 90% of all disturbances and power outages have their roots in the distribution network; from bottom of the chain, i.e. from distribution system, move towards Smart Grid has to start. Moreover, the inability of utilities (utility companies) to expand their generation capacity in line with the increasing electricity demand and brisk increase in the cost of fossil fuels has hasten the requirement to modernize the distribution network by introducing new technologies that can help with revenue protection and DSM. As shown in Fig. 2, most recent infrastructure investments have been the focused on the metering side of the distribution system. Introduction of automatic meter reading

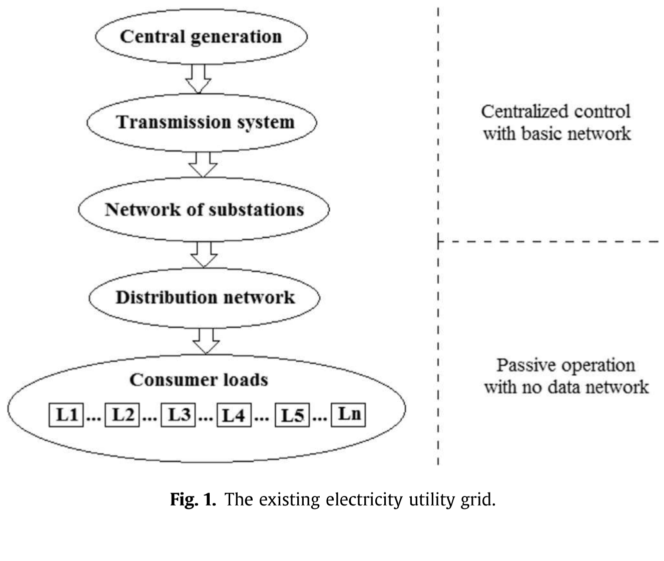

Fig. 1. The existing electricity utility grid.

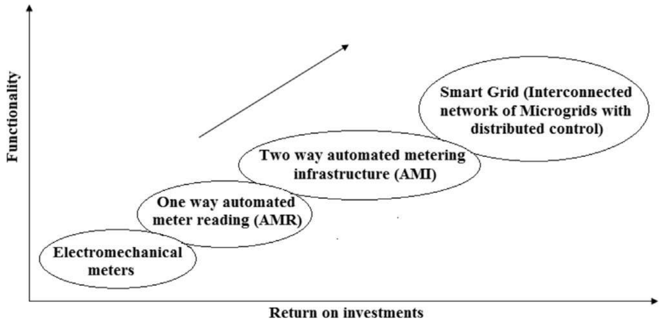

Fig. 2. The evolution of the Smart Grid.

(AMR) systems is an example for this. AMR in the distribution network allows utilities to read the status from consumers' premises, alarms and consumption records remotely. As shown in Fig. 3, the major drawback of AMR technology is that it does not does not address DSM. Capability of AMR is restricted to reading meter data due to its one-way communication system. Based on the information received from the meters it does not allow utilities take corrective action. In other words, transition to the Smart Grid is not possible with AMR systems, since pervasive control at all levels is not possible with AMR alone. Utilities across the world have been moved to AMI, rather than investing on AMR. AMI presents utilities with the ability to modify service level parameters of consumers. Through AMI, utilities can congregate their fundamental targets for revenue protection and load management. AMI gathers instantaneous information about individual and aggregated demand, put caps on consumption and performs various revenue models to control their costs. The coming out of AMI heralded a determined move by stakeholders to further improve the ever-changing concepts around the Smart Grid. In reality, one of the main criteria that the utilities consider in choosing among AMI technologies is whether or not they will be compatible with their yet-to-be-realized Smart Grid's technologies and topologies. Hence, evolution of electric grid can be summarized as, (i) adding nerves, (ii) adding brains, (iii) adding muscles and (iv) adding bones. Adding nerves involves the addition of sensory devices at utility grid level and consumer level. The primary motive of this is to provide data from the smart choice to entire system. Smart meters and AMI are consumer level nerve system of Smart Grid. Advanced visualization technologies are employed at the transmission and distribution level to provide utility grid operators more real-time, wide-area awareness of grid status. This capability will allow for enhanced optimization of power generation, transmission and distribution, as well as more rapid response to problems. Synchrophasors deployed for measuring voltage and current readings in transmission lines is an example for advanced visualization technology. Adding brains refers to processing and using the information sensed by Smart Grid nerves effectively. DR is primary form of this at consumer level. DR is a change in consumer energy consumption in response to a signal from utilities. Adding muscles involves the addition of DERs, combined heat and power (CHP) plants and storage devices into the utility grid thereby making the grid more reliable and secure. Adding bones refer to the improvement that is made in the transmission and distribution lines to facilitate power line communication and integration of DERs. Components of Smart Grid are listed in Table 1 and comparison of traditional grid with the Smart Grid is listed in Table 2.

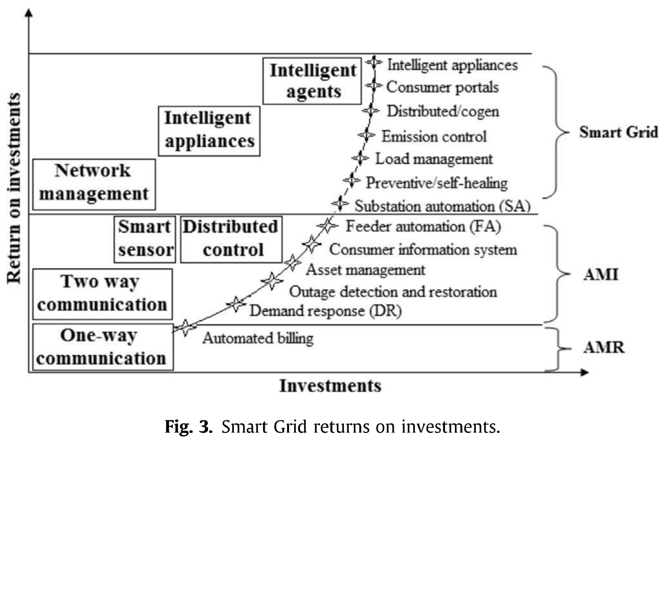

Fig. 3. Smart Grid returns on investments.

6. Smart grid reference architecture

The national institute of standards and technology (NIST) Smart Grid reference architecture consists of several domains and its sub-domains, each of which contains many actors and applications [52]. Actors comprises of devices, computer systems or software programs, etc. Actors have the facility to formulate decisions and information exchange with other actors through network interfaces. The tasks that performed by the actors within the domainare termed as applications. Applications are carried by a single actor or by several actors working together. The actors cluster domains to discover the commonalities which will define the interfaces. Usually, actors in the same domain have similar objectives. Communications within the same domain may have similar necessities and characteristics. Domains may contain other domains. Flows represent the flow of information or energy through the utility grid. The point of access between a system and domain is represented by interfaces. There exist both communications and electrical interfaces. Communications interfaces will be bidirectional and represent the access point for information to enter and exit a system or domain. They represent logical connections rather than physical connections. The Smart Grid domains are listed briefly in Table 3 and discussed in more detail in the sections that follow.

The actors in a particular domain frequently interact with actors in other domains to enable Smart Grid functionality. Fig. 4 shows the domains in Smart Grid. The conceptual model is a legal and regulatory framework which includes policies and necessities that apply to various actors and applications and to their interactions. Regulations, adopted by the federal energy regulatory commission (FERC) at the federal level and by public utility commissions at the state and local levels, govern many aspects of the Smart Grid. Such regulations are intended to ensure that electric rates are fair and reasonable and that security, reliability, safety, privacy and other public policy requirements are met. The transition to the Smart Grid introduces new regulatory considerations, which may transcend jurisdictional boundaries and require increased coordination among federal, state and local lawmakers and regulators. The

Table 1
Major components of the Smart Grid.

Nerves	- AMI (network and meters) - Advanced visualization and grid sensing technology
Brains	- DR (via. dynamic pricing) - Building energy management systems (EMS) - Data management systems (DMS) - End-use energy efficiency
Muscle	- DGs from CHP, renewable and other sources - Energy storage technologies (including PHEVs)
Bones	- New transmission lines (superconducting and HVDC) - New substation equipments and transformers

Table 2
Comparison of conventional utility grid and Smart Grid.

Characteristics	Conventional utility grid	Smart Grid
Active participation consumer	Consumers are uninformed and they do not participate	Consumers are involved, informed and participate actively
Provision of power quality for the digital economy	Response to power quality issues are slow	Rapid resolution of power quality issues with priority
Accommodation of all generation	Many obstacles exist for integration of DERs	Many DERs with plug- and- play option can be integrated at any time
Optimization of assets	Little incorporation of operational data with asset management- business process silos	Greatly expanded data acquisition of grid parameters; focus on prevention, minimizing impact to consumers
New products, services and markets	Limited and poorly integrated wholesale markets; limited opportunities for consumers	Mature and well-integrated wholesale markets; growth of new electricity markets for consumers
Resiliency against cyber attack and natural disasters	Vulnerable to malicious acts of terror and natural disasters; slow response	Resilient to cyber attack and natural disasters; rapid restoration capabilities
Anticipating responses to system disturbances (self-healing)	Responds to prevent further damage; focus on protecting assets following a fault	Automatically detects and responds to problems; focus on prevention, minimizing impact to consumers
Topology	Mainly radial	Network
Restoration	Manual	Decentralized control
Reliability	Based on static, offline models and simulations	Proactive, real-time predictions, more actual system data
Power flow control	Limited	More extensive
Generation	Centralized	Centralized and distributed, substantial RES and energy storage
Operation & maintenance	Manual and dispatching	Distributed monitoring, diagnostics and predictive
Interaction with energy users	Limited to large energy users	Extensive two-way communications
System communications	Limited to power companies	Expanded and real-time
Reaction time	Slow Reaction time	Extremely quick reaction time

Table 3
Smart Grid domains in conceptual model.

Domain	Actors in the domain
Consumer	End users of electricity, may also generate, store and manage the energy usage
Markets	The participants and operators exchange
Utilities	The organization that provides service to the consumer
Operations	The managers in movement of electricity
Bulk generation	The bulk quantity generator of electricity, can be also stored for future use
Transmission	The transporter of electricity over long distance
Distribution	The distributor of energy to consumer

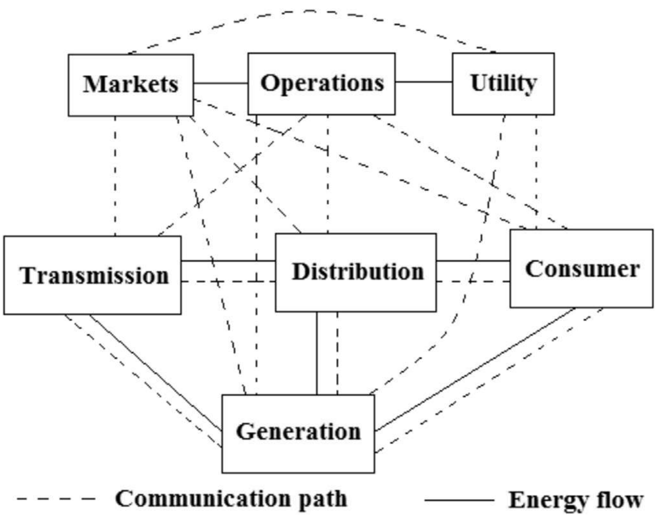

Fig. 4. Smart Grid conceptual model.

conceptual model must be consistent with the legal and regulatory framework and support its evolution over time. The standards and protocols identified in the framework also must align with existing and emerging regulatory objectives and responsibilities. The conceptual model is intended to be a useful tool for regulators at all levels to assess how best to achieve public policy goals that, along with business objectives, motivate investments in modernizing the nation's electric power infrastructure and building a clean energy economy. Various domains of Smart Grid conceptual model are explained below.

(1) Consumer domain

The consumer is finally the stakeholder that the whole utility grid was created to support. Actors in the consumer domain allow the consumers to manage their energy consumption and generation. Some actors also offer control and information flow between the consumer and the other domains. The boundaries of the consumer domain are usually considered to be the utility meter and the energy services interface (ESI). The ESI provides a safe interface for utility-to- consumer interactions. The ESI in turn can act as a bridge to facility-based systems such as a building automation system (BAS) or a consumer's energy management system (EMS). The consumer domain is generally segmented into sub-domains for home, building/commercial and industrial. The energy requirements of these sub-domains are usually set at less than 20 kW of demand for home, 20–200 kW for building/commercial and over 200 kW for industrial. Every sub-domain has several actors and applications, which may also be there in the other sub-domains. Each sub-domain has an ESI and a meter actor that may be located on the EMS or in the meter or in an independent gateway. The ESI is the primary service interface to the consumer domains. Through AMI infrastructure or via another means, such as the Internet ESI communicate with other domains. The ESI communicates to devices and systems within the consumer premises across a local area network (LAN) or home area network (HAN). There may

Table 4
Typical application within the consumer domain.

Application	Description
Home/building automation	System which is able of monitoring and controlling a range of functions within a building such as lighting and temperature control.
Industrial automation	System which controls industrial processes such as warehousing or manufacturing.
Micro-generation	Comprises of all types of DGs including; solar, wind and hydro generators. May be monitored, dispatched or controlled via communications.
Storage	Means to store energy that may be converted directly or through a process to electricity. Thermal storage units and batteries are examples.

be more than one EMS and hence more than one communications path per consumer. The EMS is the doorway for applications like in-home display (IHD) of consumer usage, monitoring and control of DG, remote load control, reading of non-energy meters and integration with building management systems and enterprise. The EMS may provide logging/auditing for cyber security purposes. The consumer domain is electrically connected to the distribution domain. It communicates with the market, operations, distribution and utility domains. Typical application within the consumer domain is listed in Table 4.

(2) Markets domain

The utility grid assets are bought and sold in markets. Actors in the markets domain exchange price, and balance supply and demand within the power system. The boundaries of the market domain include the edge of consumer domain, the operations domain where controls happen, the domains supplying assets (e.g. generation, transmission, etc). Communication among the markets domain and the energy supplying domains are vital because efficient matching of consumption with production is reliant on markets. Energy supply domains comprises of bulk generation domain and DERs. DER is located in the transmission, distribution and consumer domains. To some extent DERs participate in markets today and will contribute to a larger extent as the Smart Grid becomes more interactive. Communications for markets domain interactions must be auditable, reliable and traceable. They must support e-commerce standards for non-repudiation and integrity. The permitted latency in communications with these resources must be reduced as the percentage of energy supplied by small DER increases. The burning challenges in the markets domain are extension of DER signals and price to each of the consumer sub-domains, expanding abilities of the aggregators, interoperability across all utilities and consumers of market information, simplifying the market rules, evolving communication mechanisms for prices and energy characteristics between and throughout the markets and consumer domains and managing the growth and regulation of retail and wholesale energy sales. Typical application within the market domain is listed in Table 5.

(3) Utility domain

Actors in the utility domain perform services to support the business processes of power producers, distributors and consumers. These business processes range from conventional utility services such as billing and consumer account management to enhanced consumer services such as management of energy use and home energy generation. The utility must not compromise the stability, reliability, integrity, cyber security and safety of the electrical power network when delivering existing or emerging services. The utility domain shares interfaces with the operations, markets and consumer domains. Communications with the operations domain are vital for situational awareness and system control, communications with the consumer and markets domains are vital for enabling economic growth through the development of "smart" services. Utilities will produce new and innovative products and services to meet the new necessities and opportunities presented by the evolving Smart Grid. Services may be performed

Table 5
Typical application within the market domain.

Example	Description
Market management	Market managers include independent system operators (ISOs) for wholesale markets and forward markets in various ISO/regional transmission organizations (RTOs) regions. There are services, transmission and DR markets as well.
Retailing	Retailers trade power to consumers and may aggregate or broker DER between market or consumers in the future. Most are connected to a trading organization to allow participation in the wholesale market.
DER aggregation	Smaller participants are combined together by aggregators (as utilities or consumers or curtailment) to enable DERs to play in the larger markets.
Trading	Traders are participants in markets, which include aggregators for consumption, provision, curtailment and other qualified entities. There are a number of companies whose main business is the selling and buying of energy.
Market operations	Helps in smooth functioning of market. Functions include price quotation streams, balancing, audit, financial and goods sold clearing and more.
Auxiliary operations	Provide a market to provide spinning reserve, voltage support, frequency support and other auxiliary services as defined by FERC and various ISO. These markets function are on basis of regional or ISO usually.

Table 6
Typical application within utility domain.

Example	Description
Consumer management	Managing consumer relationships by giving point-of-contact and solving consumer issues and problems effectively.
Home management	Monitoring and controlling home energy and responding to Smart Grid signals while minimizing impact on home occupants.
Building management	Monitoring and controlling building energy and responding to Smart Grid signals while minimizing impact on building occupants.
Account management	Managing the utility and consumer business accounts.
Billing	Managing consumer billing information, sending billing statements and processing received payments.
Emerging services	All of the services and innovations that have yet to be created. These will be instrumental in defining the Smart Grid of the future.
Installation & maintenance	Installing and maintaining premises equipment that interacts with the Smart Grid.

by the utilities, by existing third parties or by new participants drawn by the new business models. The major challenge in the utility domain is to develop the key interfaces and standards that will enable a dynamic market-driven ecosystem while protecting the critical power infrastructure. These interfaces must be capable to operate over a variety of networking technologies while maintaining consistent messaging semantics. Typical application within utility domain is listed in Table 6. Few benefits to the utility domain from the employment of the Smart Grid include,

(4) Operations domain

The responsibility for smooth operation of power system is with actors in the operations domain. Today, a regulated utility is responsible for bulk of these functions. The Smart Grid enables more of them to be outsourced to utilities, others may evolve over time. No matter how the markets and utility domains evolve, still there will be basic functions required for planning and operating the service delivery points of a “wires” company. In transmission operations, EMS is employed to analyze and operate the transmission power system efficiently and reliably, whereas in distribution operations, similar DMS are employed for analyzing and operating the distribution system. Typical application within operations domain is listed in Table 7.

(5) Generation domain

Generation domain is responsible for generating electricity for delivery to consumers. The transmission domain is usually the boundary of the generation domain. The bulk generation domain is connected to the transmission domains electrically and shares interfaces with the markets, operations and transmission domains. Communications with the transmission domain is most important because without transmission, consumers cannot be served. The bulk generation domain should communicate main performance and quality of service issues such as scarcity and generator failure. These communications may cause the routing of electricity onto the transmission system from other sources. A lack of sufficient supply may be addressed directly (via operations) or indirectly (via markets). New necessities for the bulk generation domain comprises of greenhouse gas emissions controls, increases in renewable energy sources (RESs), provision of storage to manage the variability of RESs. Actors in the bulk generation domain consist of various devices such as equipment monitors, protection relays, fault recorders, remote terminal units (RTUs), programmable logic controllers (PLC) and user interfaces. Typical application within generation domain is listed in Table 8.

(6) Transmission domain

Transmission domain is responsible for the bulk transfer of electrical power from generation station to distribution system through multiple substations. A transmission network is normally operated by an RTO or ISO whose primary responsibility is to maintain stability on the utility grid by balancing supply (generation) with demand (load) across the transmission network. The transmission domain includes actors such as RTUs, power quality monitors, protection relays, substation meters, phasor measurement unit (PMU), fault recorders, sag monitors and substation user interfaces. The transmission domain might contain DER such as

Table 7
Typical application within operations domain.

Application	Description
Monitoring	Supervises network topology, connectivity and loading conditions, including breaker and switch states, as well as control equipment status. They locate consumer telephone complaints and field crews.
Control	Supervise wide area, substation and local; carry out automatic or manual control.
Fault management	Enhance the speed at which faults can be identified, located and sectionalized, and the speed at which service can be restored. They provide information for consumers, coordinate workforce dispatch and compile information statistics.
Analysis	Operation feedback analysis roles compare records taken from real-time operation related with information on network incidents, connectivity and loading to optimize periodic maintenance.
Reporting & statistics	Operational statistics and reporting roles archive online data and perform feedback analysis about system efficiency and reliability.
Network calculations	Real-time network calculations provide system operators the capability to assess the reliability and security of the power system.
Training	Dispatcher training roles provide facilities for dispatchers that simulate the actual system they will be using.
Records & assets	Track and report on the substation and network equipment inventory, provide geospatial data and geographic displays, maintain records on non-electrical assets and perform asset-investment planning.
Operation planning	Perform simulation of network operations, schedule switching actions, load shedding, switching, dispatch repair crews, inform affected consumers and schedule importing of power. They keep the cost of imported power low via peak generation, DER or DR.
Maintenance & construction	Coordinate inspection, cleaning and adjustment of equipment; organize design and construction; schedule and dispatch maintenance and construction work; and capture records gathered by field technicians to view necessary information to perform their tasks.
Extension planning	Develop long-term plans for power system reliability; monitor performance, cost and schedule of construction and define projects to expand the network, such as new feeders, lines or switchgear.
Consumer support	Help consumers to purchase, install and troubleshoot power system services. They also relay and record consumer trouble reports.

Table 8
Typical application within generation domain.

Application	Description
Control	Allow the operations domain to handle the power flow and the reliability of system. A phase-angle regulator within a substation to control power flow between two adjacent power systems is an example.
Measure	Provides visibility into power flow and condition of systems. Digital and analog measurements collected through the SCADA system from an RTU and provided to a grid control center in operations domain.
Protect	React quickly to faults and other events in the system that might cause brownouts, power outages or the destruction of equipment. Performed to maintain high levels of reliability and power quality.
Record	Permit other domains to review what happened on the grid for engineering, financial, operational and forecasting purposes.
Asset Management	Works to find out when equipment must have maintenance, compute the life expectancy of the device and record its history of operations and maintenance, so it can be reviewed in the future for operational and engineering decisions.

Table 9
Typical applications in the transmission domain.

Application	Description
Substation	The control and monitoring systems within a substation.
Storage	A system that controls the charging and discharging of an energy storage unit.
Measurement & control	Includes all types of measurement and control systems to measure, record, and control, with the intent of protecting and optimizing grid operation.

electrical storage or peaking generation units. Energy and supporting auxiliary services are acquired through the markets domain, scheduled and operated from the operations domain and finally delivered through the transmission domain to the distribution system and finally to the consumer domain. The major activity in the transmission domain is in a substation. The transmission network is usually monitored and controlled through a SCADA system composed of a communication network, monitoring devices and control devices. Typical applications in the transmission domain are listed in Table 9.

(7) Distribution domain

Distribution domain comprises of components which provides electrical interconnection between the transmission domain, the consumer domain and the metering points for consumption, distributed storage and DG. The distribution system can be arranged in a variety of structures, including looped, radial or meshed. Reliability of distribution system depends on the types of actors that are deployed, its structure and the degree to which they communicate with each other and with the actors in other domains. Formerly distribution systems have been radial configurations, with little telemetry and almost all communications within the domain was performed by humans. Consumer with a telephone was the first installed sensor base in this domain, whose call initiates the dispatch of a field crew to restore power. Traditionally, various communications interfaces within this domain were hierarchical and unidirectional, though they now normally can be considered to work in both directions, even as the electrical connections are beginning to do. In the Smart Grid, the distribution domain communicates more closely with the operations domain in real-time to handle the power flows related with more dynamic markets domain and other environmental and security-based factors. The markets domain communicates with distribution domain in such a way that it will effect localized consumption and generation. Consecutively, changes in behavior due to market forces may have structural and electrical impacts on the distribution domain and larger utility grid. In several models, third party consumer utility might communicate with the consumer domain using the infrastructure of the distribution domain; such a change would change the communications infrastructure selected for use within the domain. Actors in distribution domain comprise of protection relays, capacitor banks, sectionalizers, storage devices, reclosers and DGs. Typical applications in transmission domain are listed in Table 10.

7. Components of Smart Grid

Fig. 5 shows an architectural framework which is partitioned into subsystems with layers of technology, intelligence, innovations and new tools. It involves bulk power generation, transmission, distribution and consumer level of the electric power system. The functions of each component are,

7.1. Smart devices interface component

Electronic devices usually connected to other devices or networks via different wireless protocols and, which can operate interactively and autonomously are termed as smart devices. Smart devices for monitoring and control forms a part of the generation components real time information processes. These resources must be effortlessly included in the operation of both DERs and centrally distributed. Several notable types of smart devices are smart cars, smart doorbells, smart refrigerators, smart bands, smart thermostats, smart locks, phablets and tablets, smartwatches, smart key chains, smartphones, smart speakers and others.

7.2. Storage component

Due to the inconsistency of RES and mismatch between peak consumption and peak availability, it is significant to find methods to store the energy for future use. Storage component improves reliability and resiliency for the utility grid and electricity consumers. Energy storage technologies include flow batteries, ultracapacitors, flywheels, pumped-hydro, super-conducting magnetic energy storage and compressed air.

7.3. Transmission subsystem component

The transmission system that connects all main substation and load centers is backbone of an integrated power system. Reliability and efficiency at a reasonable cost is the ultimate aim of transmission operators and planners. Transmission lines should bear contingency and dynamic changes in load with no service interruption. To guarantee performance, quality of supply and reliability certain standards are preferred. Strategies to realize Smart Grid performance at the transmission level consist of the design of advanced technology and analytical tools. Advanced technologies with included intelligence are used for performance analysis such as real-time stability assessment, reliability and market simulation tools, robust state estimation and dynamic optimal power flow.

Table 10
Typical applications in the transmission domain.

Application	Description
Substation	The control and monitoring systems within a substation.
Storage	A system that controls the charging and discharging of an energy storage unit.
DG	A power source located on the distribution side of the grid.
DER	Energy resources that are usually situated at a consumer or owned by the distribution grid operator.
Measurement & control	Includes all types of measurement and control systems to measure, record and control, with the intent of protecting and optimizing grid operation.

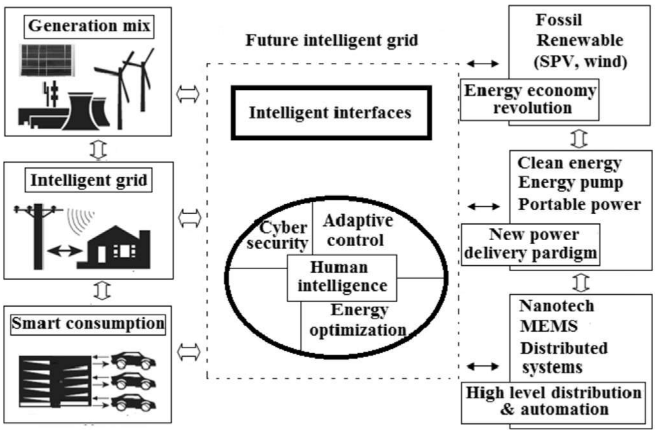

Fig. 5. The intelligent grid.

Real time monitoring based on PMU, state estimators, communication technologies and sensors are transmission subsystems intelligent enabling tools for developing smart transmission functionality.

7.4. Monitoring and control technology component

Monitoring and control technology component consist of devices for self-monitoring, self -healing, predictability and adaptability of generation, smart intelligent network and devices enough to handle reliability issues, instability and congestion. This new flexible grid has to resist shock (reliability and durability) and be dependable to provide real-time changes in its use. Smart energy efficient use devices and smart distributed DERs has inbuilt monitoring and control capability. Such devices are self-aware and can make actions independently based on the situational awareness.

7.5. Intelligent grid distribution subsystem component

The distribution network is last stage in transmission of power to consumers. Primary and secondary distribution feeders supply to small industrial, commercial and residential consumers. At distribution level, intelligent support schemes will have monitoring capabilities for automation using communication links between utility control and consumers, smart meters, AMI and energy management components. The automation function will be prepared with self - learning capability, including modules for automatic billing, fault detection, restoration and feeder reconfiguration, voltage optimization and load transfer and real time pricing (RTP).

7.6. Demand side management component

DSM and energy efficiency options are developed for modifying the consumer demand to cut down operating cost by reducing the use of expensive generators and postpone capacity addition. DSM options contribute to reliability of generation and reduce emissions. These options have an overall impact on the utility load curve. A standard protocol for consumer delivery with two-way information highway technologies is essential. Smart energy buildings and smart homes, plug-and-play, clean air requirements, demand-side meters and consumer interfaces for better energy efficiency will be in place.

8. Smart grid technologies

By incorporating few technologies, the transition of the conventional electric grid to Smart Grid is possible. The Smart Grid technologies that helps in the transition are discussed in next sections.

8.1. Smart meters

Smart meter is an electricity or gas meter that has metering as well as communication abilities [53–68]. It measures energy consumption data and permits it to read remotely and displayed on a device within the home or transmitted securely. The meter can also receive information remotely, e.g., switch from credit to prepayment mode or to update tariff information. It has two key functions to perform: (i) for providing data on energy usage to consumers to help control over consumption and cost and (ii) for sending data to the utility for peak-load requirements, load factor control and to develop pricing strategies on the basis of consumption information. Key feature of smart meters are automated data reading and two-way communication between utilities and consumers. Smart meters are developed to measure electricity, gas and water consumption data's. In Smart Grid, smart meters provide consumers with knowledge about how and when they use energy and how much they pay for per kilowatt hour of energy. This will result in better pricing information and more accurate bills and it will guarantee faster outage detection and restoration by the utility. Additional features of smart meters include tariff options, tax credits, DR rates, smart thermostat, prepaid metering, switching, enhanced grid monitoring, remote connect/disconnect of users, appliance control and monitoring and participation in voluntary rewards programs for reduced consumption. Smart meter outputs can be used for voltage stability and security assessment also. Fig. 6 shows a smart meter front view.

8.2. Automated meter reading

AMR devices let utilities to read meters remotely, removing the requirement to send a worker to read each meter separately [69]. While they do represent a certain amount of two-way communication, this functionality is limited and does not increase the efficiency or reliability of the utility grid. They do not have any inbuilt home displays to show the energy consumption pattern to the consumer, hence consumer remains unaware of their energy consumption. Due to this, the utilities cannot communicate to the consumers about their energy consumption, thus consumers cannot adjunct their consumption during peak hours and save

Fig. 6. Smart meter.

energy. AMR in the distribution network lets utilities read the status from consumers' premises, alarms and consumption records remotely. Capability of AMR is restricted to reading meter data due to its one-way communication system [70]. Based on the information received from the meters it does not let utilities take corrective action. In other words, transition to the Smart Grid is not possible with AMR systems, since pervasive control at all levels is not possible with AMR alone [71]. AMR is the collection of consumption data from consumer's like electric meters and smart meters remotely using telephony, radio frequency, power-line or satellite communications technologies and process the data to generate the bill. Fig. 7 shows block diagram of an AMR system. Functions of each block are explained below.

Reading unit carry out two important jobs basically. Initially, the reading from analog meters is converted into digital. Subsequently the data are processed to communication unit for transmission.

(2) Communication unit

This is one of the most challenging and important part of this system. Data is the most important part for meter reading and billing system, hence this part is challenging. Data transmission should be in an efficient manner without any loss of data.

(3) Data receiving and processing unit

Data receiving and processing unit receives the data transmitted from the communication unit and processes it for future purpose.

(4) Billing system

Billing system is the final stage of AMR which takes the meter number and can generate bill for that meter. It uses the data of the database those are collected from the meter reading through all the unit of our system. Analysis on electricity usage for each meter can be also carried out using this system.

8.3. *Vehicle to grid (V2G)*

The incorporation of electric vehicles and Plug in hybrid electric vehicle (PHEV) is an additional part of the Smart Grid system. V2G power employs electric-drive vehicles to provide power to particular electric markets [72–82]. Fuel cells, battery or hybrid of these two is employed to store energy in vehicles. There are three main different versions of the V2G concept (i) a hybrid or fuel cell vehicle, (ii) a battery-powered or plug-in hybrid vehicle or (iii) a solar vehicle, all of which involve an onboard battery. The major advantages of V2G are (i) it provides storage space for renewable energy generation and (ii) it stabilizes large scale wind generation via regulation. PHEV significantly cut down the local air pollution problems. Hybridization of electric vehicles and associations to the utility grid conquers the limitations of their use including battery weight/size, cost and short range of application. PHEV offers an alternative to substitute the use of petroleum based energy sources and to reduce overall emissions by using a mix of energy resources. The use of PHEVs potentially has a significant positive impact on the electric power system from the point of view of increasing

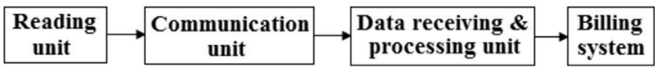

Fig. 7. Block diagram of an AMR system.

(1) Reading unit

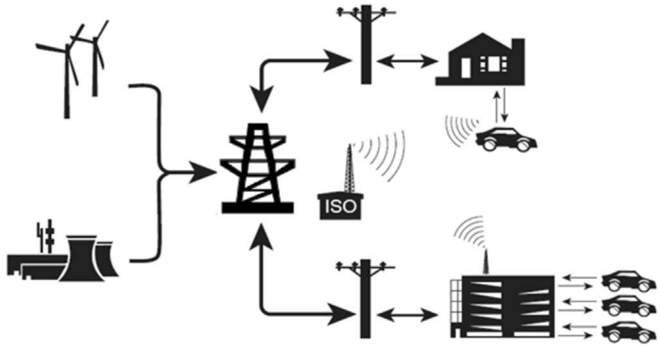

Fig. 8. The connections between vehicles and the utility grid.

electric energy consumption, substituting petroleum fuels with unconventional sources of energy. The associations between vehicles and the utility grid are illustrated in Fig. 8. The connections between vehicles and utility grid are illustrated in Fig. 8. Electricity flows one-way from generators through the grid to electricity users. The flow is two ways from electric vehicles. A control signal is needed in order to communicate with the electric vehicles when the grid needs energy. In Fig. 8, the grid operator is labeled ISO, for independent system operator. The control signal from the ISO could be a broadcast radio signal, or through a cell phone network, direct Internet connection, or power line carrier. In any case, the grid operator sends requests for power to a large number of vehicles. It may do so directly to individual cars, or it may communicate with parking lot operators for example, who in turn would communicate with the fleet of parked cars at their disposal.

Two types of power interactions are possible between the vehicle and utility grid.G2V consists of utility grid supplying energy to the plug-in vehicle through a charge port. A V2G vehicle is capable of providing energy back to the utility grid. V2G presents the potential for the grid system operator to call on the vehicle as a distributed energy source. V2G technology can be employed, turning each vehicle with its 20 to 50 kWh battery pack into a distributed load balancing device or emergency power source. Electricity flows all over the utility grid from generators to consumers whereas unused energy flows back and forth from the electric vehicles as shown in Fig. 8 (the lines with two arrows). During off-peak time, battery electric vehicles can charge and during peak time, battery can discharge through the utility grid.

There are two basic V2G architecture (i) deterministic architecture and (ii) aggregative architecture. In deterministic architecture, services are provided to the plug-in vehicles directly from the grid system operator. A direct line of communication exists between plug-in vehicles and grid system operator, thus each vehicle can be treated as a deterministic resource. The vehicle is permitted to bid and carry out services when it is at the charging station. The contracted payment for the previous full hours is made and the contract is ended when the vehicle leaves the charging station. The availability and reliability achievable by means of the deterministic V2G architecture is about 92% and 95% respectively. Deterministic architecture is simple and easy to implement, but it prevents V2G from providing several services that require high power and energy minimum thresholds.

Fig. 9 shows the connections in deterministic approach. In aggregative architecture, an intermediate aggregator is inserted in between grid system operator and plug-in vehicle. The aggregator can bid to carry out auxiliary services at any time, while the individual vehicles can engage and disengage from the aggregator as they arrive at and leave from charging stations. Fig. 10 shows the connections in aggregative approach. Availability and reliability of

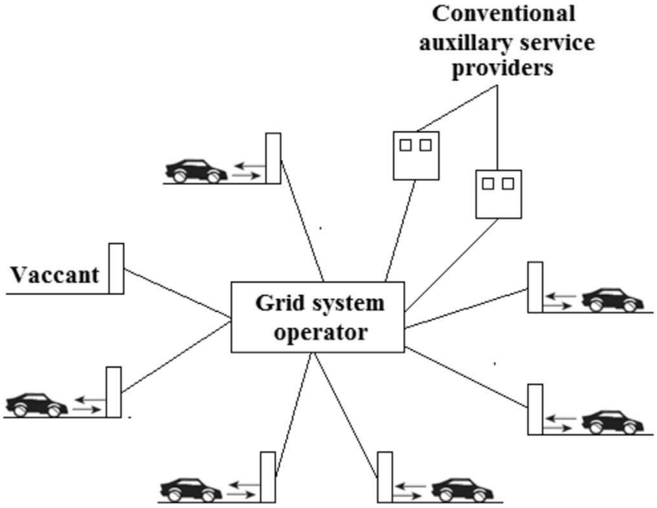

Fig. 9. Deterministic approach of vehicle to utility grid connection.

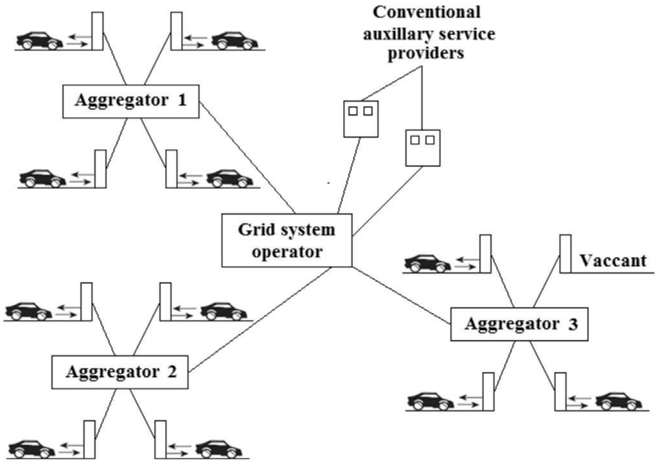

Fig. 10. Aggregative approach of vehicle to utility grid connection.

base load generators is about 93% and 98.9% respectively. An aggregation of PEVs will be needed in order to participate in the energy market. In fact, two different approaches can be followed: cost.

Function-based power drawn scheduling and price-sensitive energy bidding [16]. The first one, which is suitable for the deterministic V2G architecture, consists in establishing the PEV charging profile on the basis of the energy price given by the day-ahead market and in updating it dynamically. As a result, each PEV is responsible for its charging without interference from the system operator: in the hours of cheapest prices, the PEV should recharge at its maximum rate. On the other hand, the price-sensitive energy bidding approach entails that the PEV fleet participates in the day-ahead market and the amount of energy purchased depends on the price the PEV owner is willing to pay. This approach, which is not possible for the V2G deterministic architecture, is particularly suitable for the aggregative one. However, in both cases, PEVs can participate in the services markets. Since the aggregative V2G architecture would appear to be the most promising one, several studies have been carried out aiming to define the role and tasks of this framework, which is also defined aggregator. Its role may be acting as an intermediary between each PEV owner and the system operator, whereas its tasks may consist in grouping a certain number of PEVs, appropriately coordinating their charging, and providing profitable services.

Advantages,

(1) Peak load leveling.
(2) Carbitrage.
(3) Backup power solutions

8.4. Plug in hybrid electric vehicle technology

A PHEV is a hybrid electric vehicle with a larger battery pack [83–102]. So, it runs on electricity when its battery SOC is high or else, the IC engine takes over and the vehicle uses gasoline similar to a hybrid vehicle. The battery pack can be recharged via a plug which provides connection to the utility grid; hence, a PHEV, compared to conventional cars, has an extra equipment to connect to an external electrical source for recharging. PHEVs are characterized by their all-electric range. In cases of extreme emergencies like a sudden increase in oil prices or major decrease in oil supplies, the stored or unused energy that utilities preserve during night time or off-peak time can be utilized to support the vehicles. It must also considered that efficiency of electric drive systems is about 70% only, as an example, a first-generation PHEV can travel about 75 cents per gallon of gas or about 3-4miles per kWh. All PHEV vehicles will be employed with connection to the utility grid for electrical energy flow, a logical connection or control is compulsory for communication with the utility grid operator and onboard metering and controls. Fuel cells can generate power from gaseous and liquid fuels and PHEV can function in either capacity. Fig. 11 shows the major architectures of PHEV.

The architecture of a PHEV is defined based on the connection between their power train components. These components are the IC engines, PEI, battery (B), motor/generator (M/G) and transmission (T/R). Four major architectures are (i) series (electrically coupling), (ii) parallel (mechanically coupling), (iii) series-parallel (mechanical and electrical coupling) and (iv) complex (mechanical and electrical coupling). Fig. 3.8 shows these four architectures. However, series (e.g., Chevrolet Volt) and complex (e.g., Toyota Prius) topologies are the most well-known architectures for PHEVs. The battery charger can be on-board or external to the vehicle. Onboard chargers are limited in capacity by their weight and size, dedicated off-board chargers can be as large and powerful as the user can afford, but require returning to the charger; high-speed chargers may be shared by multiple vehicles. PHEV operates in three modes (i) charge-sustaining (ii) charge-depleting and (iii) blended mode or mixed modes. These vehicles can be designed to drive for an extended range in all-electric mode; either at low speeds only or at all speeds. These modes manage the vehicle's battery discharge strategy and their use has a direct effect on the

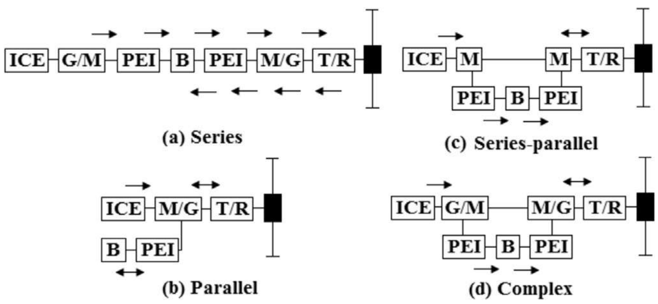

Fig. 11. PHEV architectures (a) Series, (b) parallel, (c) series parallel and (d) complex.

size and type of battery required. In charge-sustaining mode certain amount of charge above battery SOC is sustained for emergency use. Before reaching SOC, vehicle's IC engine or fuel cell will be engaged. Charge-depleting mode permits a fully charged PHEV to operate exclusively on electric power until its battery SOC is depleted to a predetermined level, at which time the vehicle's IC engine or fuel cell will be engaged. This period is the vehicle's all-electric range. This is the only mode that a battery electric vehicle can operate in, hence their limited range. Mixed mode describes a trip using a combination of multiple modes. For example, a car may begin a trip in low speed charge-depleting mode, then enter onto a freeway and operate in blended mode. The driver might exit the freeway and drive without the IC engine until all-electric range is exhausted. The vehicle can revert to a charge sustaining-mode until the final destination is reached. This contrasts with a charge-depleting trip which would be driven within the limits of a PHEV's all-electric range.

Advantages of PHEV,

(1) Operating costs.
(2) Vehicle-to-grid electricity.
(3) Fuel efficiency and petroleum displacement.

Disadvantages of PHEV,

(1) Cost of batteries.
(2) Recharging outside home garages.
(3) Emissions shifted to electric plants.
(4) Tiered rate structure for electric bills.
(5) Lithium availability and supply security.

8.5. Smart sensor

Smart sensors are defined as sensors that provide analog signal processing of recorded signals, digital representation of the analog signal, address and data transfer through a bidirectional digital bus, manipulation, and computation of the sensor-derived data [103–111]. Fig. 12 shows basic architecture of IEEE 1451 standard for smart sensor network. Main components are transducer electronic data sheet (TEDS), transducer independent interface (TII), smart transducer interface module (STIM) and network capable application processor (NCAP). A smart sensor provides additional functions further than those required for generating an accurate demonstration of the sensed quantity. It is composed of many processing components integrated with the sensor on the same chip. Has intelligence of some forms and provide value-added functions beyond passing raw signals, leveraging communications technology for telemetry and remote operation/reporting. Objectives of smart sensors consist of integrating and sustaining the distributed sensor system measuring intelligently and smartly, crafting a general platform for controlling, computing, yielding cost effectiveness and communication toward a common goal and interfacing different type's sensors. The virtual sensor is a component of the smart sensor, which is a physical transducer/sensor, plus a connected digital signal processing (DSP) and signal conditioning necessary for obtaining reliable estimates of the essential sensory information.

Smart sensors enable more accurate and automated collection of environmental data with less erroneous noise amongst the accurately recorded information. It offers functionalities beyond conventional sensors through fusion of embedded intelligence to process raw data into actionable information that can trigger corrective or predictive actions. Smart sensors are extensively employed in monitoring and control mechanisms in variety of fields including Smart Grid, battlefield, exploration and a great number of science applications. For supporting Smart Grid monitoring and diagnostics applications, automated, reliable, online and off-line analysis systems are required in conjunction with smart sensors. Smart sensors enable condition monitoring and diagnosis of main substation and line equipment including transformers, circuit breakers, relays, cables, capacitors, switches and bushings. Fig. 13 shows the basic block diagram of smart sensor. A sensing unit senses the changes in parameters and then it is conditioned and converted to digital signal using a signal conditioning and digitalization unit. An analog to digital converter (ADC) is included in signal conditioning and digitalization unit to convert sensed analog signal to digital. Digital equivalent of the measured analog signals are processed and analyzed by the central processing unit. A copy of processed data is stored in memory of the main processor for future use and made available to local users through local human machine interface (HMI) and remote users through remote HMI. A communication interface is also incorporated with the smart sensor module for transmitting and receiving the sensed signals and commands. Task processing is carried out by main processor and communication interface.

To deliver the best value, the sensor systems might be arranged in three tiers depending upon the available architecture and application necessities. They are (i) local level, (ii) station/feeder level and (iii) centralized control room level. Local level sensor is a stand-alone device with embedded intelligence for local data processing and local/remote communications. Fig. 14 shows the basic structure of a local level sensor. Station/feeder level sensors

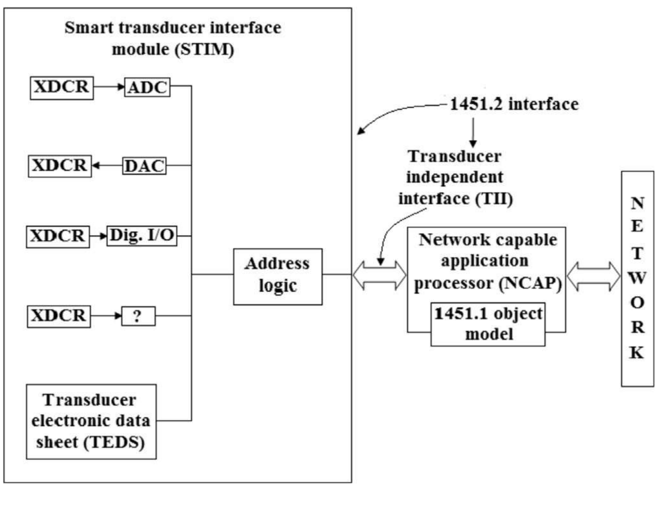

Fig. 12. The IEEE 1451 standard for smart sensor network.

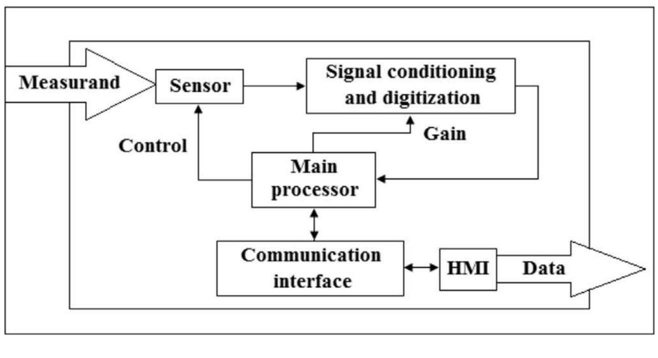

Fig. 13. Basic components of a smart sensor.

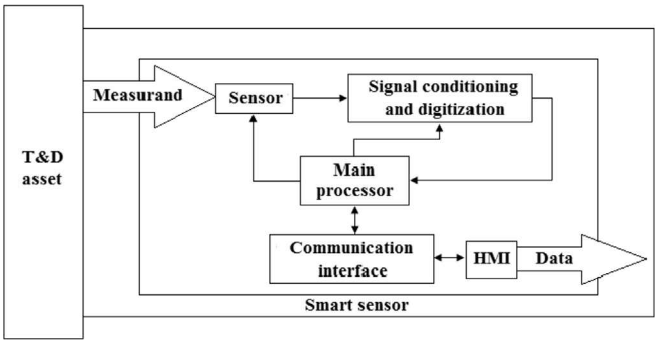

Fig. 14. Basic structure of a local level sensor.

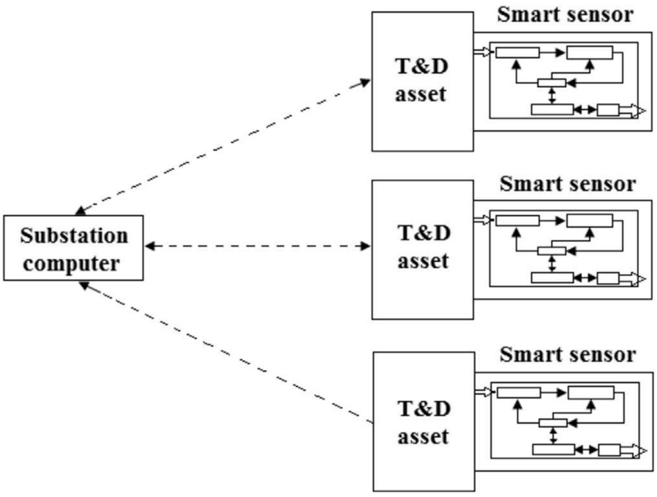

Fig. 15. Basic structure of a station/feeder level sensor (radial topology).

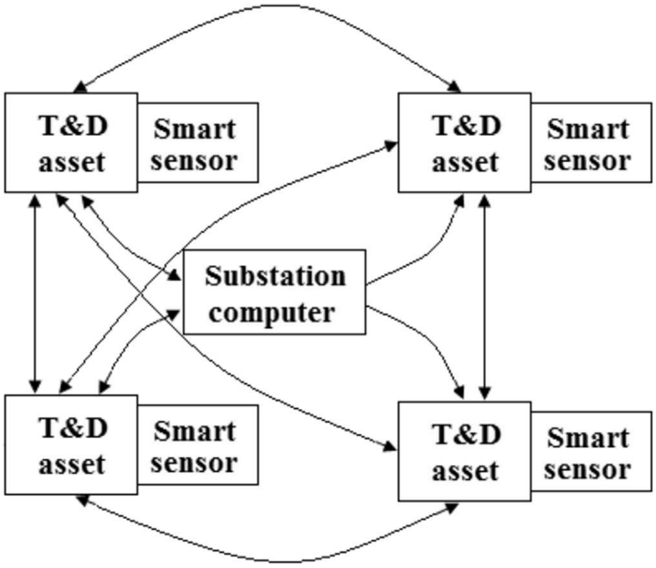

Fig. 16. Basic structure of a station/feeder level sensor (meshed topology).

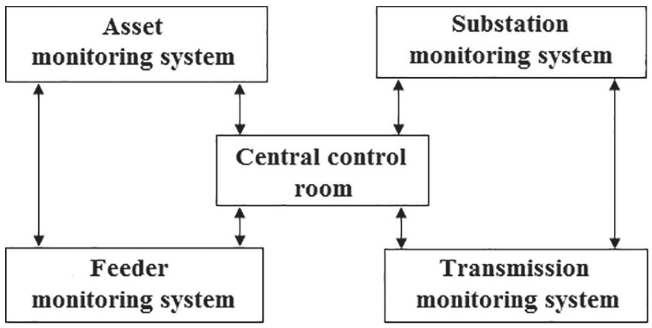

Fig. 17. Basic structure of a centralized control room level sensor.

performs monitoring and diagnostics of distributed systems outside the substation environment. The basic structures of radial and meshed topologies of station/feeder level sensor are shown in Fig. 15 and Fig. 16 respectively. Centralized control room level performs system-wide monitoring and diagnostics applications. Fig. 17 shows the basic structure of a centralized control room level sensor.

8.6. Sensor and actuator networks (SANETs) in smart grid

From information flow and energy flow point of view, Smart Grid applications of SANET can be observed as energy flow management and optimization by making use of the information flow [112]. The facility of physical parameter sensing, physical device control and decision making are necessary for this processing. Fig. 18 shows a high-level description of SANET in Smart Grid. By employing SANET energy flow and its supporting infrastructures are sensed in Smart Grid. The sensed data is then transmitted to controllers through information flow for making decision. Through the information flow, controllers formulate issue control commands and control decisions to the actuators. Actuators execute the control tasks on receiving the control commands. The three main driving forces of Smart Grid include enhancing energy efficiency, improving security and reliability and reducing greenhouse gas emissions. Applications of SANET in three main areas are explained below.

8.6.1. DERs penetration

DERs include variable and non-variable sources. Non-variable DERs have been already employed widely in existing utility grids for decades. But due to discontinuous nature, integration of variable DER sources, such as solar photovoltaic (SPV) system and wind, in large amount might cause severe problems in maintaining the stability of the utility grid. By employing SANET, precise and up-to date atmospheric conditions, such as wind speed and solar insolation can be obtained to forecast the characteristics of the DER generators. Additionally, on the basis of predictions and measurements, compensation mechanisms can be implemented to control the backup generators according to the need, advanced storage devices or even consumer power loads to address the variations of the DER supplies.

8.6.2. Grid monitoring and control (GMC)

GMC is necessary for reliable, secure and high quality electricity services. GMC play a key role in SANET, it continuously monitors and control the entire system efficiently. Preventive and corrective functions are core duties of SANET in GMC. Specially, SANET is required to prevent potential failures, detect and predict disturbances, monitor equipment health, enable self-healing or fast auto-restoration and react rapidly to energy generation, consumption fluctuations and catastrophic events. Different types of SANET have been used for GMC, such as SCADA, WAMS and PMU which provide real-time monitoring on power quality, reliability and in some cases react to them automatically on a regional and even national scale.

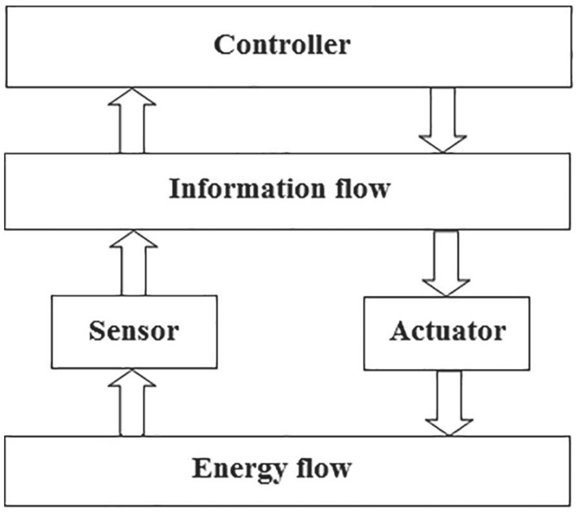

Fig. 18. Relation of SANET and smart grid.

8.6.3. Generation dispatch (GD)

Excellent balance between the supply and demand is required to make a power system effective. GD and DSM are two effectual methods to maintain the balance required and thereby improve the energy efficiency. GD monitors and controls electricity generation so that the quantity of power generated meets the demands at any time. GD has been already employed in conventional utility grid and plays a vital role in it. Though, this function in Smart Grid must overcome extra challenges, since it has to dynamically manage considerable amount of DERs, particularly DERs at the consumer domain. Real-time grid frequency regulation (GFR) and renewable forecasting are two effective mechanisms to deal with the DERs penetration problem in GD. At control centers real-time DERs information has to be sensed and gathered for renewable forecasting; and after quick analysis of the gathered information, suitable commands are issued to generation scheduling and regulation functions. Real-time GFR helps to optimize generation scheduling on the basis of variations of frequency and voltage level, very responsive hardware and high speed data transmission is required for this. DSM is counterpart of GD located in the generation domain, which works mainly in the consumer domain and interacts with the utility, operation domains and market. DSM manages demand side load in response to constraints of power supply. DSM is a significant application of SANET and imposes some particular functional necessities on the underlying SANET, such as facilities of real-time load monitoring, two-way data exchanging between the demand side and utilities, demand side load control and data processing.

8.6.4. Actors of SANET in smart grid

SANET is composed of sensors, controllers, actuators and communication networks. Main sensors and actuators commonly used in Smart Grid are highlighted below. Main needs on controller and communication networks by the various Smart Grid applications are also explained.

8.6.4.1. Sensors in Smart Grid. Fig. 19 shows the commonly used sensors in Smart Grid. The sensors are generally classified into three categories on the basis of type of the physical parameter measurement. They are (i) energy flow sensors, (ii) environment sensors and (iii) working condition sensors. Energy flow sensors are used to sense voltage, current, energy, power factor, frequency and magnetic and electric fields etc. Environment sensors are used to sense humidity, temperature, luminance movement and occupancy, solar intensity, wind speed and smoke and gas. Sensors for working condition usually measures pressure, speed, temperature, acceleration, vibration and position.

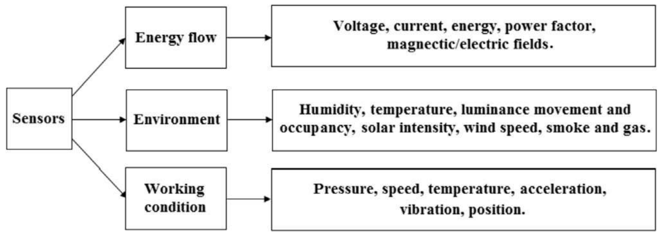

Fig. 19. Sensors in smart grid.

8.6.4.2. Actuators in Smart Grid. Fig. 20 shows the main actuators generally used in Smart Grid. The actuators are also classified into three categories on the basis of type of the physical phenomena or actions. They are (i) energy flow, (ii) working condition and (iii) actuators for user interface. Actuators for energy flow are used for breaker, dimmer and switch etc. Actuators for working condition are employed for valve, break and motor etc. User interface actuators are employed for light, speaker and display etc.

8.6.4.3. Controllers and control logic in smart grid. Based on the application necessities, controllers are reclassified into distributed micro-controllers, centralized control centers, complicated, powerful or simple and less powerful. Usually, two kinds of controller's works together to provide monitor and control function in a SANET application. Due to the large fluctuations in energy generation and consumption, SANET applications in Smart Grid need more powerful controllers with powerful computational control logics, such as AI control and fuzzy control, to handle the dynamics. Additionally, SANET applications in Smart Grid might need a large number of controllers to work together. Hence, each controller must be of low cost to facilitate a large-scale deployment.

8.6.4.4. Communication network. To support the sophisticated features of Smart Grid, the volume of data exchanged between different actors in SANET unavoidably increases to a large number when compared to conventional utility grids. In the meantime, various SANET applications in Smart Grid generally have different communication necessities, in terms of bandwidth and transmission delay, etc. The necessities and characteristics on different SANET actors for the three main Smart Grid applications are summarized in Table 11.

8.6.4.5. Challenges of SANET in smart grid. The major design challenges of SANET in Smart Grid are,

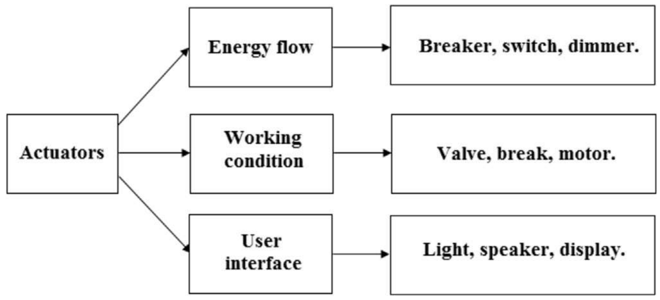

Fig. 20. Actuators in smart grid.

Table 11
Requirements of SANET actors for different Smart Grid applications.

SANET Actors	DERs penetration	GMC	GD & DSM
Sensors	Energy flow Environment	Energy flow Working condition	Energy flow Working condition
Actuators	Energy flow	Energy flow Working condition	Energy flow Working condition User interface
Controllers	Distributed and centralized Dynamic level: High Cost: Medium to high	Distributed and centralized Dynamic level: High Cost: Medium to high	Distributed and centralized Dynamic level: High Cost: Low to medium
Communication networks	Bandwidth: Medium Delay: Medium	Bandwidth: High Delay: Stringent	Bandwidth: Low Delay: Medium

(1) Distributed operation and heterogeneity

Distributed operation and heterogeneity are two main characteristics of information flow in Smart Grid. Since, SANET depends on the information flow, the distributed operation and heterogeneity, which provide the configuration of a connected and efficient information flow, become the two main challenges of SANET in Smart Grid.

(2) Dynamics

The dynamic behavior of utility grid is due to the variation of demands and supplies, continuously varying environmental conditions, dynamic user behaviors and other random events. In a Smart Grid, due to increased usage of DERs, such as solar and wind, makes the problem even more challenging.

(3) Scalability

A usual SANET application in Smart Grid might cover hundreds of kilometers, and engages in control and monitoring of thousands of pieces of devices and equipments. Scalability is a main challenge. It is essential to make use of protocols with low overhead and algorithms with linear complexity.

(4) Flexibility

Since, Smart Grid is still developing, new policies, technologies and consumer demands keep emerging and SANET must offer the flexibility to house all the diversities and growing factors.

(5) Energy efficiency and cost efficiency

One of the driving forces of Smart Grid is to improve the efficiency of the utility grid, and SANET itself must be energy efficient. Additionally, it must be cost effective to lower the deployment barrier.

8.6.5. SANET applications

The service reusability and interoperability offered by SANET helps to develop diverse kinds of applications.

(1) Context aware intelligent control

To address the challenges of dynamics, context-aware intelligent control is proposed. The fundamental idea is to develop context-aware and proactive control logics to optimize performance of the system under dynamic environment.

(i) Atmospheric conditions, such as humidity and temperature.
(ii) Energy flow readings, such as demand level and power supply.
(iii) Human behaviors, such as movement, preference on environment.
(iv) Economic incentives, such as tiered electricity rates.
(v) Regulation schemes, such as DERs penetration and DSM.

Occupancy-based light control is a simple example of context-awareness, where the context is whether the room is occupied or not and light is turned on or off, based on it. The context-aware intelligent algorithms make use of the contexts, obtained by exploiting the services of person, to optimize the overall performance of a SANET application.

(2) Compressive sensing (CS)

CS is proposed to address the challenges of economy, energy efficiency and scalability. The fundamental idea of CS is to utilize data correlation in the space and time domains to decrease the communication cost and the hardware cost.

8.6.6. Device technologies

Advanced device technologies help to improve the energy efficiency and economy and make a SANET more flexible and scalable for Smart Grid applications. SANET itself consumes certain power. Low power consumption design is essential to reduce the total power consumption. In SANET, all the main functions, such as sensing, control, data transmission and calculating consumes power. Lists of possible mechanisms to reduce power consumption are listed in Table 12. Employing a mechanism on one actor has an impact on others. As an example, data aggregation and data compression can reduce the power requirement for data transmission, but increase the consumption of power for regenerating the data. Hence, optimization of power required to be considered from a system point of view. The process by which energy is derived from external sources, captured and stored is known as power harvesting. The major power harvesting mechanisms applicable to SANET in Smart Grid are listed in Table 13.

Solar energy is the cleanest and most available renewable energy source. The Modern technology can harness this energy for a variety of uses, including producing electricity, providing light and heating water for domestic, commercial or industrial application. Solar energy can also be used to meet our electricity requirements. Through solar photovoltaic (SPV) cells, solar radiation gets converted into DC electricity directly. This electricity can either be used as it is or can be stored in the battery. Basic component of photovoltaic (PV) panel is solar cell, which is mainly made from pure silicon wafer. Solar cells work on the principle of photovoltaic effect, the phenomenon by which incident solar radiations are converted into electrical energy directly. Following three conditions are to be satisfied for obtaining useful power from solar cell,

Table 12
Power conserving mechanism.

SANET Actor	Power conserving mechanism
Sensing	CS to exploit correlations in time and space domains
	Sensing on demand to avoid continuous and unnecessary sensing
Control	Event based control
Calculating	Low complexity algorithm
Data transmission	CS
	Distributed data processing and control instead of centralized control
	Data compression and data aggregation
	Low power data transmission technologies

Table 13
Power harvesting mechanism.

Type of energy	Power harvesting device
Ambient radiation	SPV panel (solar energy)
	Antenna and transducer (RF energy)
Kinetic	Piezoelectric devices (mechanical strain, motion, vibration, noise)
	Micro-wind turbine (wind power)
Thermal	Thermoelectric generator (thermal gradient)

(1) Incident photons must be absorbed into the active part of semiconductor material and potential energy of the incident photons must be transferred to valence shell electrons. Further with this particular energy, electrons must be dislodged from the bond and freed.
(2) The dislodged electrons having extra energy must be carried to the edge of semiconductor material so that it will be available for carrying to the load. This particular provision is fulfilled by creating an internal field in the material by forming p-n junction by a process known as doping.
(3) The charged particles available at the edge of material must be carried to the load through an external circuitry.

In order to create a p-n junction, two different layers of silicon wafer are doped with agents known as impurity atoms. Top layer of the wafer is doped with n-type dopant such as phosphorus. Outer most shell of phosphorus atoms contains five electrons, out of these five electrons, four combines with the silicon atom and remaining one move freely in the crystal lattice. Base layer of the silicon wafer is doped with p type dopant such as boron. Outer layer shell of boron atoms contains three free electrons, these three free electrons combines with the silicon atom leaving a hole, a positive charge. Electron from the neighboring bond jumps into the hole, leaving behind a positive charge; hence a positive charge moves freely in the crystal lattice. Atomic structure of dopant atom is similar to that of silicon atom. Base of the wafer, which is doped with boron is 1000 times thicker than top of the wafer which is doped with phosphorus. When p type and n type layers join together, electrons diffuse across the junction and create a barrier which prevents further electron flow. The junction formed at the point of contact of p type and n type material is known as p-n junction. An electric field is produced at p-n junction due to imbalance in electric charge, which in turn restricts further diffusion of the charges. Then the silicon cell is coated with antireflective coating to enhance the absorption of solar irradiation. Grid lines are drawn across the cell to collect electrons, which are released from the valence shell absorbing solar irradiation. These grid lines are then connected to metallic contacts provided at both ends of the solar cell. Metallic contacts act as the end terminal for external connection to load. When solar irradiation falls on the surface of panel, few of the photons get reflected from grid lines and surface of the cell. Remaining photons will penetrate into the substrate; those with less energy will pass the substrate without having an impact. Those photons with energy greater than the band gap dislodge electrons from the valence band and create electron hole pairs. On both sides of p-n junction electron hole pairs are created. Electron-hole pairs diffuse across the junction and swept away in the opposite direction by electric field across the junction and are fed to the load. If the incident solar radiation is more, more number of electron hole pairs will be created; hence more current will be generated by the panel.

Radio frequency energy harvesting (RFEH) is an energy conversion technique employed for converting energy from the electromagnetic (EM) field into the electrical domain (i.e., into voltages and currents). In particular, RFEH is a very appealing solution for use in body area networks as it allows low-power sensors and systems to be wirelessly powered in various application scenarios. Extracting energy from RF sources sets a challenging task to designers and researchers as they find themselves at the interface between the electromagnetic fields and the electronic circuitry. Piezoelectric energy harvesting methods convert oscillatory mechanical energy into electrical energy. This technology, together with innovative mechanical coupling designs, can form the basis for harvesting energy from mechanical motion. The wind energy conversion systems convert wind energy into electrical energy by employing wind turbine and induction generator. Through a multiple-ratio gearbox wind turbine is coupled with the induction generator. The major parts of a wind turbine are the rotor, the nacelle and the tower. The generator and the transmission mechanisms are housed in nacelle. Rotor may have two or more blades. The kinetic energy of wind flow is captured by rotor blades in wind turbine and then through a gearbox it is transferred to the induction generator side. The mechanical power developed by wind turbine is used to drive generator shaft to generate electric power. The slower rotational speed of wind turbine is converted to higher rotational speeds on the induction generator side by gearbox. A thermoelectric generator (TEG), also called a Seebeck generator, is a solid state device that converts heat flux (temperature differences) directly into electrical energy through a phenomenon called the Seebeck effect (a form of thermoelectric effect). Thermoelectric generators function like heat engines, but are less bulky and have no moving parts.

9. Smart grid metering and communication

Communication plays a vital role in real-time operation of power system. Initially, telephone was employed to communicate line loadings back to the control center as well as to dispatch operators to execute switching operations at substations. But, with the increase in the DG penetration, network connections for individual DERs in Smart Grid network are becoming difficult day by day due to a number of network constraints, e.g., thermal overloads and voltage limits as well as hardwired connection complexities. Hence, the success of Smart Grid depends on the application of efficient and cost effective communication system for measuring, monitoring and controlling purpose [113-130], [131-150], [151-158]. High-speed, fully integrated, two-way communication technologies will permit the Smart Grid to be a dynamic, interactive mega infrastructure for real -time information and power exchange. This technology plays a crucial role in the performance of the Smart Grid by monitoring, measuring and transferring real time data for control purpose. For the secured transmission of highly sensitive data within the communication network, formalized standards and protocols are necessary. Apparently, existing monitoring, measuring and control technology plays a role in Smart Grid network too. Setting up suitable standards, interoperability and cyber security needs careful study, for example, formalizing the protocols and standards for the secure transmission of highly sensitive and critical information within the proposed communication system. Furthermore, open architecture's plug-and-play environment will provide secure network smart sensors and control devices, protection systems, control centers and users.

9.1. Advanced Metering Infrastructure

AMI is not a single technology; it is an incorporation of several technologies which provides an intelligent connection between utilities and consumers [159–165]. As shown in Fig. 21, AMI is the convergence of utility grid, the communication infrastructure and the supporting information infrastructure. The primary motivation for developing a network centric AMI is industry security requirements and implementation guidance. The telecom, cable and defense industries present numerous examples of standards, necessities and best practices that are directly applicable to AMI implementations. Deploying an AMI is a basic step in modernization of utility grid. AMI provides information to the consumers which are required to make intelligent decisions, the capability to implement those decisions and a variety of choices leading to significant benefits. Additionally, utilities are able to improve consumer service greatly by asset management processes and refining utility operating based on AMI data. Through the incorporation of many technologies (such as integrated communications, HANs, smart metering, standardized software interfaces and data management applications) with asset management processes and existing utility operations, AMI gives an important link between the

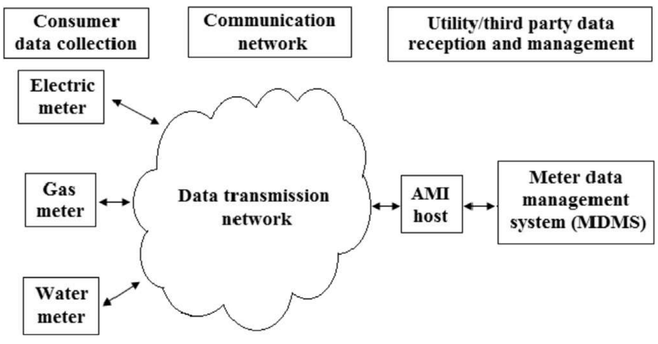

Fig. 21. Building blocks of AMI.

generation, utility grid, consumers, storage and their loads. Initially, AMR technologies were employed to improve the accuracy of meter reading and to reduce costs. The benefits of two-way interactions between utilities, consumers and their loads led to the evolution of AMI from AMR.

Following are principal characteristics of AMI,

(i) AMI technologies provide the basic link between the utility grid and the consumer.
(ii) Generation and storage options distributed at consumer site can be monitored and controlled via AMI technologies.
(iii) Markets are enabled by connecting the utility grid and the consumer through AMI and allowing them to participate actively, either as load that is responsive directly to price signals, or as part of load that can be bid into various types of markets.
(iv) Smart meters employed with power quality monitoring abilities which facilitate quick detection, diagnosis and resolution of power quality problems.
(v) Remote connection and disconnection of individual supply.
(vi) Facilitates more distributed operating model that decreases the vulnerability of the utility grid to terrorist attacks.
(vii) Automatically send the consumption data to the utility at pre-defined intervals.
(viii) Helps in self-healing by detecting and locating failures, serving in outage management system (OMS) more accurately and quickly.
(ix) Provides an ever-present distributed communications infrastructure having excess capacity that can be used to accelerate the deployment of advanced distribution operations equipment and applications.
(x) AMI data provides the granularity and timeliness of information required to improve asset management and operations.

AMI infrastructure comprises of HANs, including communicating thermostats, communication networks from the meters to local data concentrators, smart meters and back-haul communications networks to corporate data centers, meter data management systems (MDMS) and at last, data addition into existing and new software platforms. In addition to this, AMI provides a very “intelligent” step toward modernizing the entire power system. AMI technology and interference is shown in Fig. 22.

At consumer level, smart meters communicate data on energy consumption to both utilities and consumers. To make consumers more aware of their energy usage, smart meters communicate with IHDs also. Smart meters incorporated to AMI performs time-based pricing, net metering, consumption data for utility and consumer, loss of power (and restoration) notification, power quality monitoring, remote turn on/turn off operations, energy prepayment, tamper and energy theft detection, load limiting for “bad pay” or DR purposes, communications with other intelligent devices in home. Additionally, electric pricing information provided by the utility allows load control devices like smart thermostats to modulate electric demand, based on pre-established consumer price preferences. Based on these economic signals more advanced consumers employ DERs. Consumer portals access the AMI data in ways that facilitate more intelligent energy consumption decisions, even providing interactive services like prepayment. The utility employs enhanced office systems that collect and analyze AMI data to help optimizing economics, operations and consumer service. For example, AMI gives instant feedback on power quality and consumer outages, enabling the utility to address utility grid deficiencies rapidly. AMI's two-way communication infrastructure also supports utility grid automation at the circuit and station level.

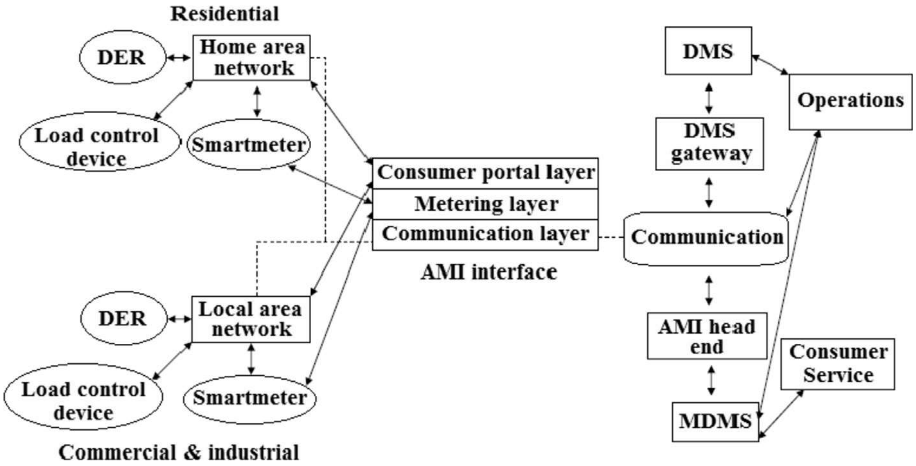

Fig. 22. Overview of AMI.

Huge amount of data flowing from AMI allows better planning of asset maintenance, improved management, additions and replacements. The resulting more reliable and efficient utility grid is one of AMI's many benefits. AMI communications infrastructure supports continuous interaction between the consumer, the utility and the controllable electrical load. It has the potential to serve as the foundation for a multitude of modern utility grid functions beyond AMI. A range of architectures can be employed for data collection and communication, the most common being local concentrators that gather data from groups of meters and transmit that data to a central server through a backhaul channel. Various media like power line carrier, broadband over power lines, copper or optical fiber, Internet, wireless or combinations of these can be considered to provide part or all of this architecture. A HAN interfaces with a consumer portal to link smart meters to controllable electrical devices. Its energy management functions may include in IHDs to inform the consumer about energy cost and usage, responsiveness to price signals on the basis of consumer-entered preferences, set points that limit utility or local control actions to a consumer specified band, control of loads without continuing consumer involvement, consumer over-ride capability. The HAN/consumer portal provides a smart interface to the market by acting as the consumer's "agent." New value added services like security monitoring is also supported by HAN. A HAN can be implemented in a number of ways, with the consumer portal situated in any of several possible devices including the meter itself, the neighborhood collector, a stand-alone utility-supplied gateway or even within consumer supplied equipment. MDMS database with analytical tools facilitates interaction with other information systems such as OMS, consumer information system, billing systems, enterprise resource planning, power quality management and load forecasting systems, mobile workforce management, geographic information system, transformer load management and utility's web site. One of the main functions of an MDMS is to perform validation, editing and estimation on the AMI data to guarantee that despite disruptions in the communications network or at consumer premises, the data flowing to the systems described above is whole and accurate.

AMI provides benefits to consumers, utilities and society as a whole and are explained below,

(i) Consumer benefits

Consumer will have more choices about price and service, less interruption and more information with which to manage cost, consumption and other decisions. It also means better power quality, higher reliability and more accurate billing. A key benefit of AMI is its facilitation of DR and innovative energy tariffs. AMI helps the consumer to adjust their energy consumption in according to the present market prices.

(ii) Utility benefits

Utility benefits fall into two main categories, operations and billing. AMI helps the utility to avoid anticipated readings, provide timely and accurate bills, operate more reliably and efficiently and offer considerably better consumer service. AMI eliminates the training, health insurance, vehicle and other fixed cost expenses of manual meter reading. With AMI the utility can instantly point out the outage location, thus it can send the repair crews in a more efficient and timely way. Using AMI various maintenance and consumer service issues can be resolved cost-effectively and more quickly through remote diagnostics.

(iii) Societal benefits

. AMI improves energy efficiency in delivery and use, producing a positive environmental impact. It can accelerate the use of DGs, which can in turn encourage the use of DERs. And it is likely that emissions trading will be enabled by AMI's detailed measurement and recording capabilities.

The challenges of AMI include,

(i) High capital costs

A full scale deployment of AMI involves expenditures on software and all hardware components, including meters, network infrastructure and network management software, along with cost associated with the installation and maintenance of meters and information technology systems.

(ii) Standardization

Interoperability standards need to be defined, which set uniform requirements for AMI technology, deployment and general operations and are the keys to successfully connecting and maintaining an AMI-based grid system.

(iii) Integration

AMI is a complex system of technologies that must be integrated with utilities' information technology systems, including consumer information systems, geographical information systems, work management system, mobile workforce management, SCADA/DMS, OMS, feeder automation system, etc.

9.2. Intelligent electronic devices

Power system monitoring and control is basically carried out by SCADA systems primarily based on the data that collected and fed from RTUs situated in substations. In substation switchyard, RTUs are wired to the CB links and each change in the CB status contact is provoked in form of alarm to the operators. The RTUs also collects analog measurement data's obtained through instrument transformers (CTs and VTs) and connecting transducers. If the measured analog value is above the threshold value, it is reported either as an operator measurement or an alarm. The data recorded by RTU cannot be accessed locally by the consumer; it will be only accessible after it has been sent to a centralized location. In addition to this, the SCADA system design is not the most robust one; there is a possibility of errors in the readings because of malfunctioning of transducers, CB contacts, RTUs or SCADA communication equipment. Comparatively slow scanning rate of SCADA for measurements (1–10s) is another performance concern. The SCADA systems fail to track dynamic changes occurring for intervals shorter than the SCADA scan time. The limitations in capabilities of SCADA can be overturned by inclusion of IEDs. IEDs are microprocessor based devices with ability to exchange data and control signals with another device over communication link. This new unit provides real-time synchronization for event reporting [166–172]. IEDs can be regarded as the eyes and ears of any remote power management systems. IEDs are installed to improve monitoring, control, protection and data acquisition capabilities of the power system. Besides their main function, IEDs are capable to record various types of data. Redundancy and amount of data coming from a substation can be improved in this way. If designing of IEDs are with interface to global positioning system (GPS), further improvement in data usage can be achieved with automating system disturbance analysis. IEDs receive data from power equipment and sensors and can issue control commands, such as tripping CBs, if they sense any abnormality in current, voltage or frequency or lower/raise voltage levels in order to maintain the desired level. Common types of IEDs consist of CB controllers, capacitor bank switches, voltage regulators, protective relaying devices, recloser, controllers, LTC controllers etc. By a setting file this is normally controlled. Usually one of the most time consuming roles of a protection tester is the testing of setting files. Fig. 23 shows functional architecture of IED.

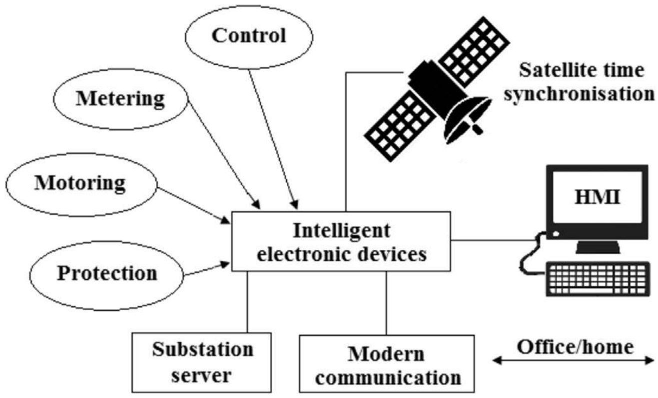

Fig. 23. Functional architecture of IED.

Digital protective relays (DPR) are primarily IEDs, using a microprocessor to perform several monitoring, control and protective functions. A usual IED can contain around 5–8 control functions controlling separate devices, an auto-reclose function, 5–12 protection functions, communication functions, self-monitoring function etc. Thus, they are appropriately named as intelligent electronic devices. Three types of IEDs have been considered in this section, circuit breaker monitor (CBM), digital fault recorder (DFR) and DPR. These devices can measure internal CB control signals, relay trip signal, phase currents and voltages, internal relay logic operands and oscillography data. The CBM is designed to monitor condition of CBs and control circuit signals during opening and closing process. The DPR is designed to monitor transmission line when a fault is detected and operating conditions on trip CBs. The DPR responds to sudden change in current, voltage, impedance, frequency and power flow and it will trip substation CBs for faults up to a certain distance away from the substation. The DFR is a device which is primarily designed to capture and store short duration transient events, trends of input quantities such as power, harmonics, frequency, RMS and power factor and longer-term disturbances. After being triggered by a pre-set trigger value, the device records large amount of data. Automated analysis application can be developed for each type of devices. Data recorded by each device is converted to a standard format using the application and reports are generated per each IED type. Those reports are small in size and can be sent easily out of substation through communication infrastructure (in case of multiple events). All extracted data and information are available instantly after event occurrence.

9.2.1. Circuit breakers monitor analysis (CBMA)

CBMA carries out analysis of waveform taken from the CB control circuit using a CBM and produces an event report and suggests repair actions. The solution is executed using an expert system for making decision and advanced wavelet transforms for extracting waveform feature. It facilitates maintenance crews, operators and protection engineers to consistently and quickly estimate CB performance, recognize performance shortages and outline probable causes for formal functioning. Fig. 24 shows software modules of CBMA.

9.2.2. Digital protective relay analysis (DPRA)

DPRA is an expert system which automates diagnosis and validation of relay operation. Different relay reports and files are taken as inputs and it generates reports by analyzing taken inputs using embedded expert system. Diagnosis and validation of relay operation is based on comparison of expected and actual relay behavior in terms of the status and timing of logic operands. Fig. 25 shows software modules of DPRA.

9.2.3. Digital fault recorder assistant (DFRA)

DFRA carry out automated analysis and DFR event records data integration. It converts various DFR native file formats to COMTRADE. Additionally, DFRA carry out signal processing to find out

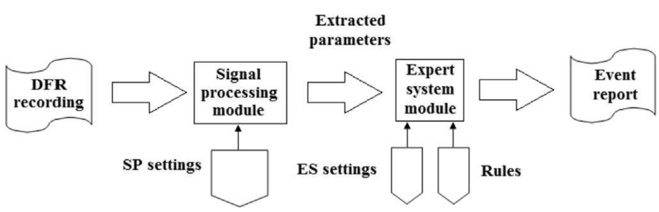

Fig. 24. Circuit breakers monitor analysis architecture.

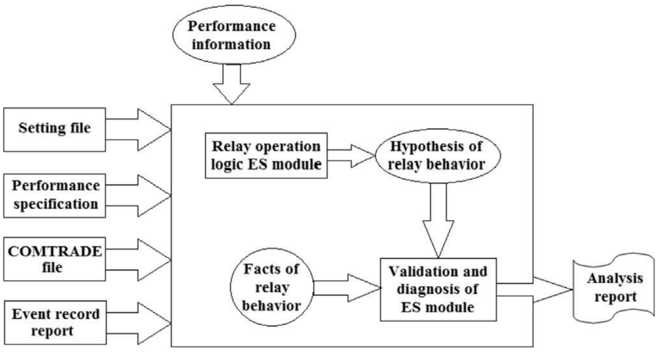

Fig. 25. Digital protective relay analysis architecture.

pre- and post-fault analog values, statuses of the digital channels (related to auxiliary breaker, communication signals and relay trip), faulted phases and fault type. It also checks and evaluates fault location, system protection, etc. Fig. 26 shows software modules of DFRA.

DPRA and DFRA can carry out thorough disturbance event analysis. Though, DFRA cannot carry out complete analysis on operation of protective relays, since the internal states of a protective relay cannot be recorded using DFR device. In contrast, DPRA can diagnose and validate the relay operations totally, but disturbance information might not be complete, because DPR collects data from single transmission line only. DFRA cannot execute the CB tripping operation analysis because CB control circuit signals are not monitored by DFR device, but CBMA provide this information in detail. Data incorporation across the whole substation is necessary to accomplish full IED data utilization. To realize full event explanation, the results of various analyses have to be merged. The whole idea is to collect and incorporate data automatically from all substation IEDs, examine it and extract information needed for different type of users such as system operators, protection engineers, maintenance staff, etc. Data can be examined at the substation level and conclusion can be sent to the maintenance and protection group directly. Another approach is to preprocess data then extract and send it to the control center, where the information is merged with data from SCADA, processed by centralized applications and the results prepared for various user groups. By combining data from CBMA, DPRA and DFRA comprehensive reports are generated.

9.2.4. Information for system operators

Responsibility of decision making on system operation and restoration are with system operators. When an event occurs in the system, they are interested to know that the fault is permanent or not, location of the fault and whether CB and relays operated correctly. IED devices collect more data than RTUs, hence, the extra data can be used to verify and complement with the SCADA reading. Normally right conclusion is only being made by using IED data. To improve the accuracy of the analysis data obtained from SCADA through RTUs can be combined with data obtained from IEDs; this will provide better results to the operator.

9.2.5. Information for protection engineers

Responsibility on the final assessment on rightness of any system response to a given fault condition is with protection engineers. They have to check operation of each device using the information gathered by IED and in case of misoperation they need to find out the cause for device misoperation or failure. Generally, they are involved in DPR operation during the event. Major information needed for protection engineers, are name of substation, fault type, duration and range, affected circuit, triggered time and date, event outcome and devices operation with major focus on relay operation. If the fault was removed within the specified time and all devices operate properly, there is no need for any supplementary data and second level of report that have further information will not be generated. Second level of the report explains displays signal waveforms and internal logic operation of relay. It lists series of the relay signals status and recommends remedial actions.

9.2.6. Information for maintenance staff

Maintenance staffs are responsible for system repair and restoration. Responsibility for monitoring CB operation is also with this group. Report will be generated for maintenance staff which consisting of information about signals affected by tripping operation, pre-, during and post-fault analog signals values, waveforms display and suggestion for remedial actions.

9.3. Phasor measurement units

PMU is a device that measures the electrical waves on a utility grid by employing a general time source for synchronization [173–179]. The PMUs consist of branch current phasors and bus voltage phasors, as well as locations information and other network parameters. Time synchronization permits synchronized instantaneous measurements of various remote measurement points on the utility grid. The resulting measurement is known as a synchrophasor. PMU is the metering device whereas a synchrophasor is the metered value. PMUs are considered to be one of the most important measuring devices in the future of power systems. PMU can be a devoted device, or the PMU role can be integrated into a protective relay or other device. PMU can measure 50 Hz AC waveforms (currents and voltages) usually at a rate of 48 samples per cycle. Fig. 27 shows basic components of a PMU. The current and voltage signals are converted to voltages with appropriate instrument transformers or shunts (usually within the range of ±10 V), so that they are matched with the requirements of the

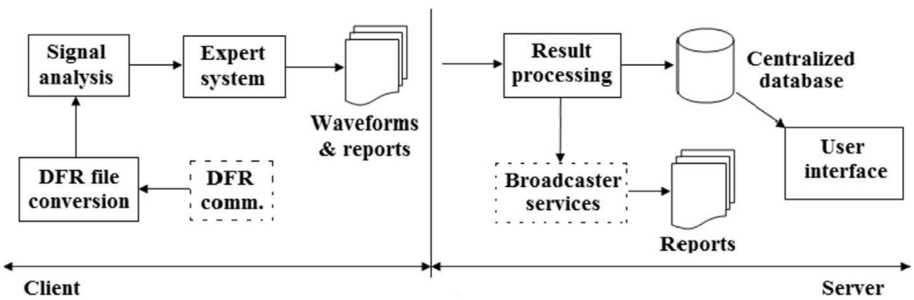

Fig. 26. Digital fault recorder analysis architecture.

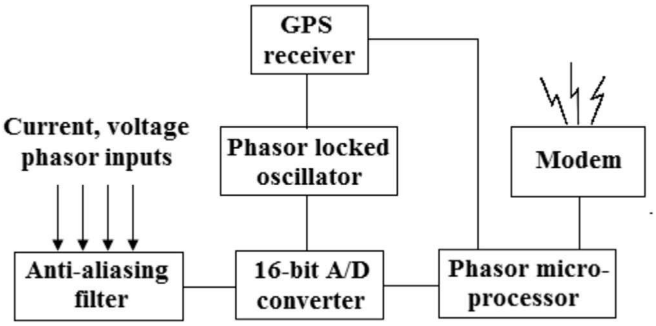

Fig. 27. Basic components of a phasor measurement unit.

ADCs. By using an ADC for each phase the analog AC waveforms are then digitized. A phase-locked oscillator along with a GPS provides the required high-speed synchronized sampling with 1 μs precision. Though, PMUs might receive in multiple time sources including non-GPS references which is calibrated and working synchronously. The resultant time-stamped phasors can be transmitted to a local or remote receiver at rates up to 120 samples per second. Phasor measurements are taken with high accuracy from various points of the power system at the same instant, permitting the operator to visualize the precise angular difference between various locations. Microprocessor based instrumentation such as disturbance fault recorders (DFRs) and protection relays integrate the PMU module with other existing functionalities as an extended feature.

PMUs are appropriate for monitoring and control of voltage stability. Offering wide area situational awareness, mitigate or even prevent blackouts and phasor measurement work to ease congestion. When incorporated with Smart Grid communications technologies, the taken measurements will provide dynamic visibility into the power system. Implementation of Smart Grid with real time measurement will improve every aspect of the power delivery system including generation, transmission, distribution and consumption. It will increase the potential of DGs integration, bringing generation closer to the pocket loads. Additional utility monitoring systems include electronic instrument transformers, dynamic line rating technology, temperature, batteries, conductor sensors, backscatter radios technology, cables, insulation contamination leakage current and monitors for CB and current frequency. PMU measurement system is shown in Fig. 28.

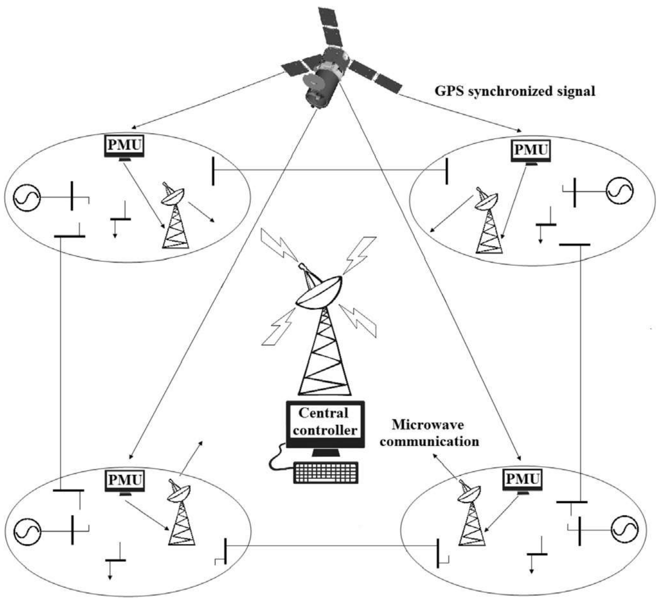

Fig. 28. Conceptual diagram of a synchronized phasor measuring system.

By employing phasor data concentrators (PDCs) technologies, the phasor data is collected either at centralized locations or onsite. The data is then transmitted to a regional monitoring system which is maintained by the local ISO. These ISO's will monitor phasor data from individual PMU's or from as many as 150 PMU's, this monitoring provides an exact means of establishing controls for power flow from multiple energy generation sources. Fig. 29 shows hierarchy of phasor measurement system and levels of PDCs.

9.4. Wide area measurement systems (WAMS)

WAMS is one of the most important components in Smart Grid [180–189]. In comparison to the present SCADA system, measurements of the system states are carried out at a comparatively higher rate (5–60 samples per second versus one per 2–6 s). Additionally, all system phasors are developed continuously and simultaneously, rendering real-time information of power system parameters. Thus, WAMS can improve the performance of utility grids significantly by stability assessment, fault detection, remedial control actions and supporting more accurate state estimation. Fig. 30 shows components of a typical WAMS. It comprises of PDCs for aggregating and relaying measured data. Whereas PMUs are employed widely in WAMS, the currently available dual-use line relays (DULRs) introduce variability to modern WAMS construction. DULRs are the protection digital relays for transformers and transmission lines while providing system protection it can report synchrophasor data. DULR is also called “branch PMU”, since it is installed at transformers and along transmission lines. Even though DULR can only monitor the current phasor of the branch and the voltage phasor of its adjacent bus, still it is promising due to its low construction cost. PMU and DULR interface WAMS with the power system and they consist of CTs, VTs, synchronous GPS clocks and instrumentation cables. Data measured by these devices are transmitted to one or multiple layers of PDCs located at selected locations in the system, where the data are aggregated, compressed and sorted into a time-stamped measurement stream. Usually, the data stream is then fed into application software at the central controller for system state monitoring and control decision generation with various control objectives.

9.5. Local area network (LAN)

LAN is a packet data communication network system which offers high-bandwidth communication over a comparatively

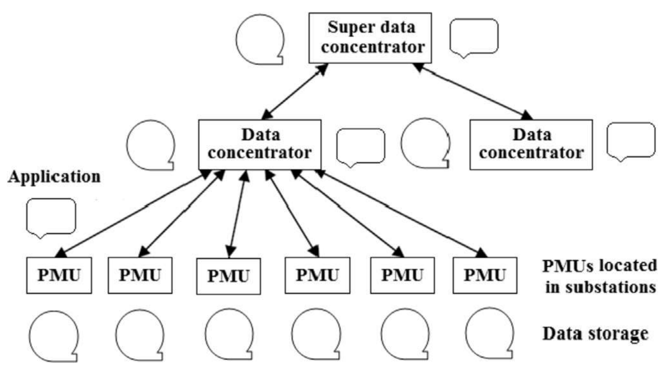

Fig. 29. Hierarchy of phasor measurement system.

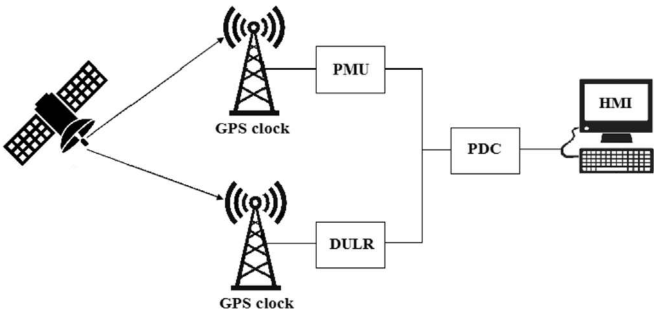

Fig. 30. Components of WAMS.

restricted geographic area through an inexpensive transmission media [190,191]. LAN is composed of two or more components and disk storage with high capacity, which permits all computers in the network to access a general set of rules. LAN has operating system software which instructs network devices, interprets input and permits the users to communicate with each other. In LAN each hardware device is termed as a node. The LAN can incorporate several hundred computers within a geographical stretch of 1–10 km. LAN can also interconnected together to form WAN. LAN with similar architectures act as bridges which are transfer points, whereas LAN with dissimilar architectures act as gateways which converts data as it passes through it. LAN is a shared access technology, in which all connected devices share a common medium of communication such as fiber optics, twisted pair, or coaxial cable. The network interface card (NIC), a physical connection device, connects LAN to the network. Communication between stations in a system is managed by network software.

The advantages and special attributes of LAN include,

(1) Resource sharing: Permits intelligent devices (programs, data files, printers and storage devices) to share resources. Hence, installed software and database can be shared by multiple users in LAN.
(2) Area covered: LAN is usually limited to a restricted geographical area, for example, campus, office building etc.
(3) Cost and availability: Interface devices and application software are reasonably priced and easily available.
(4) High channel speed: Capability to transfer data at rates between 1 and 10 million bits per second.
(5) Flexibility: Easy to maintain and operate and it grow/expand with low chance of error.

Data transmission categories in LAN include, (i) unicast transmission: Single packet of data is sent from the source node to the destination node in the network. (ii) multicast transmission: Single packet of data is copied and sent to specific subset of nodes in the network; by using the multicast addresses the source node addresses the packet. (iii) broadcast transmission: Single packet of data is copied and sent to all nodes in the network; source node addresses the packet by using the broadcast address.

Topologies in LAN include, (i) bus topology: It is a linear LAN topology in which the data transmitted from network station propagates throughout the length of transmission medium and is received by all other stations connected to it. (ii) ring bus topology: A single closed loop is formed by connecting a series of devices one another by unidirectional transmission link. (iii) star topology: The end points in a network are connected to a switch by dedicated links or common central hub. (iv) tree topology: It is similar to the bus topology except that branches with multiple nodes are also possible.

9.6. Home access network (HAN)

LAN limited to an individual home is called as HAN [192,193]. It permits remote control of automated appliances and digital devices all over the house. It facilitates the communication and sharing of resources between computers, mobile and other devices over network connections. HAN may be wired or wireless. It consists of broad band internet connection that is shared between multiple users through a vendor/third party wired or wireless modem. HAN is subsystem within the Smart Grid dedicated to DSM and includes DR and energy efficiency which are the main components in realizing value in a Smart Grid deployment. Smart meters, smart appliances and web based monitoring can be included into this level.

The advantages of HAN include,

(1) Asserting the utility in managing peak electric demand.
(2) Centralized asses to multiple appliances and devices.
(3) Effectively manage utility grid load by automatically controlling high energy consuming systems with HAN and Smart Grid infrastructure.
(4) HANs provide energy monitoring, controlling and energy consumption information about appliances and devices and hence support energy usage optimization by allowing the consumers to receive price alert from the utility.

The main challenges of HAN are,

(1) Integration of various technology solutions is a major challenge, so that smart services, such as comfort, automation, security, energy management and health can be offered seamlessly.
(2) Interoperability is another key concern among the technology solutions that needs to be resolved.
(3) Consumer privacy and security is an issue that needs to be addressed.

The HAN include can be either wired or wireless. There are many advantages associated with installing a wireless network compared to a wired network such as mobility, cost-effectiveness and adaptability. Wireless networking is relatively cheaper than wired Networks since they require no cables between the computers as well as lower long term costs due to less maintenance since there is less equipment. The reduction of cables also reduces the trip hazard caused by cables running along the floor in most homes. Most wireless network equipment is plug-and-play, which helps reduce the total cost such as vendor installation and eliminates redundancy is case of a system crash. Wireless Networking is also very mobile and versatile; it is adaptable to most situations and requirements. Wireless networks can easily be set up and dissembled, which is perfect for many people who are on temporary worksites/homes or leased space. It can also provide networking in places where regular wire cannot reach such as the backyard in a home situation. Access points can be used to boost the wireless signal range if required. Since portable workstations such as laptops have become popular, wireless networks can provide quick and easy access to the internet and workspaces for students and teachers in universities etc. It is also extremely easy to add other components onto this type of network such as easy installation of VoIP and printers etc without the need to configure one's computer. Since wireless networking is a relatively new and contingent form of networking, it is filled with its own hazards and problems such as unreliability and security. Wireless networks have limited bandwidth; hence they cannot support video teleconferencing (VTC). It is also limited in its expandability due to the lack of available wireless spectrum for it to occupy. Wireless network can also be a security risk if not installed and maintained properly. Wireless networks don't require any physical components to connect up to it such as wires, only a wireless adapter is required which significantly increases the accessibility of the network to potential hackers. This scenario is worsened if the network doesn't contain a password since it can then be accessed by anyone with ease. Wireless networks also have an increased chance of jamming and interference due to external factors such as fog and dust storms or when a flying object such as an aeroplane passes over the field. When too many people in the same area use wireless networks, the band of air that they transmit signals on can become overloaded.

Wired networks have existed for a long time, therefore have developed exponentially over the recent years. Improvements have been made in the fields of speed, security and reliability. Wired networks offer the fastest transfer speed of all the networks. Gigabit Ethernet is currently the best choice for wired networks and provides speeds of up to one gigabit per second. This is almost three times faster than the best wireless connection available and almost ninety times faster than a regular connection. Wired networks consist of physical, fixed connects which are not prone to interference and fluctuations in available bandwidth caused by factors such as walls. Features such as shielding (adding an aluminium foil around the wires) and twisting at different strengths help reduce interference. Wired networks also have a better security system than wireless networks. The network itself is harder to connect to since it has to be physically connected to through wires which can become a hassle when trying to hack into it. It cannot be accessed from anywhere since the signals are not broadcasted. Wired networks mainly suffer the inverse of the advantages of a wireless network system such as lack of mobility and greater cost. Wireless network requires greater resources such as cabling, switch/hub and network cards to install and to maintain therefore the initial and long term costs are much higher. It can also be a large loss when it has to be disassembled and reinstalled since they wiring has to be completely overhauled and is normally unusable after because of damage. Wired networks can also be a hassle to install new components into because of all the hardware required to do this. Cables and network cards are required to install new computers to the system and wires need to be drawn from the switch to the computers. The wiring can become messy and indistinguishable very quickly and can become a potential safety hazard due to the risk of triping.

9.7. Neighborhood area network (NAN)

NAN is a wireless community presently employed for wireless local communication applications; it covers an area bigger than a LAN [194–199]. A few architectural structures will focus on the interoperability and integration of the different domains within the Smart Grid. Domains consist of groups of individuals, devices, systems or buildings having similar communications characteristics. Bulk generation includes generators, plant control system and market services interface; this domain interact with the transmission domains and market operations through the Internet, substation LANs and WANs. Transmission includes electric storage, data collectors, controllers and substation devices; this domain interacts with bulk generation and operations through substation LANs and WANs; integrated with the distribution domain. Distribution interacts with operations and consumers through field area networks (FAN-provides connectivity to a large number of devices spread throughout a given geographic area). Consumer includes PHEVs, metering, consumer equipment, electric storage, energy management systems (EMS), appliances and so on. Utilities domain interacts with operations and consumers primarily through the Internet. Utility and third party providers, which handle billing consumer services, are included in this. Operations include SCADA, web access management system and EMS; this domain can be subdivided into transmission, distribution and ISO/RTO.

9.8. Wide area networks (WAN)

WAN is a network that spans large geographical locations, usually to interconnect multiple LANs [200].

WANs are usually classified into three separate connection types,

(1) Point-to-point technologies.
(2) Circuit-switched technologies.
(3) Packet-switched technologies.

Point-to-point technologies (often termed as leased or dedicated lines) are generally the costliest form of WAN technology. Point-to-point technologies are generally leased from a utility and offer assured bandwidth from one location to another. On the basis of allocated bandwidth and distance of connection cost is determined. Normally, point-to-point links doesn't need any call-setup, the connection is generally always on. Circuit switched technologies need call-setup to make connection on and transfer information. Once data transfer is complete, the session will be torn down (hence it is termed as on-demand circuit). Circuit switched lines are normally low-speed as compared to point-to-point lines. Packet-switched technologies share a common infrastructure between all subscribers. Hence, bandwidth is not assured, but is allocated on a best effort basis. Packet-switched technologies are not suited for applications that need bandwidth consistently, but are noticeably less expensive than devoted point-to-point lines.

9.9. Cloud architecture of smart grid

Cloud computing is an excellent method for Smart Grids due to its flexible and scalable characteristics and its ability to handle large volumes of data. In order to cope with the storage and communication of vast transferable data large-scale real-time computing capabilities is necessary in construction of a Smart Grid [201–208]. But once the expended entities are in place, cloud computing will unload the Smart Grid by presenting remote data storage, automatic updates, reduced maintenance of IT systems by saving energy, money and manpower. Fig. 31 shows cloud architecture of Smart Grid.

Fig. 32 shows data and energy flow in Smart Grid. It is a wide multi-port system network node. Cloud architecture in Smart Grid is distributed and dynamic. Different component has different characteristics and its characteristics determine specific ways to control it; hence, the system cannot employ a combined control strategy. DGs and load may cut out or access at any time which causes some problems to combined management. Microgrid and the conventional network constitute a layered topology, various subsystems creates layered information. Hence, multi-agent technology is introduced in Smart Grid, which constructs a platform that can reflect capacity and status of each node as well as coordinate the control of each node. The cloud architecture is a dynamic and distributed. The different attributes of every component determine that they must be controlled in specific ways; the system can't utilize a unified control procedure.

The application brings a number of benefits to the consumers, environment and the electricity company, in terms of its functionality,

(1) Details of the consumers (associations, households and buildings).

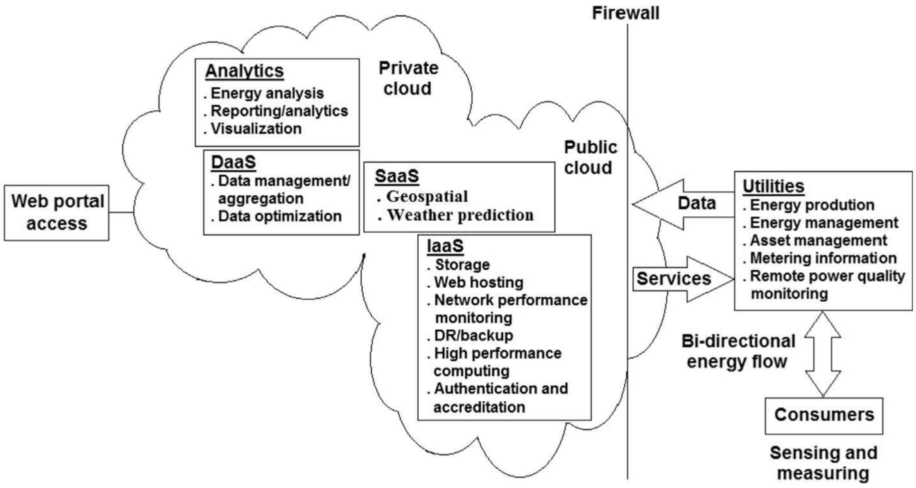

Fig. 31. Smart Grid cloud architecture.

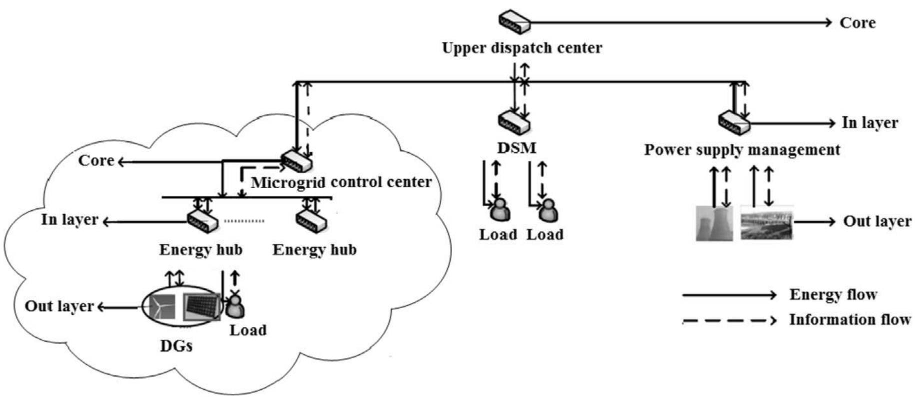

Fig. 32. Data and energy flow in Smart Grid.

(2) Follow electricity consumption indicators and temperature in real-time.
(3) Reading electricity consumption indicators at fixed intervals.
(4) Consumer recommendations on the best tariff plans according to each user profile.
(5) Presenting consumption of electricity (through dynamic analysis, reports and graphs).
(6) Outbreak alerts based on measurable factors and notifying approved persons by desktop alerts and emails.
(7) Calculation and application of penalties.
(8) Issuing invoices each month automatically.
(9) Disconnecting bad-payers and notifying them by email.
(10) Presentation of financial statements (issuing and paying billing, invoices, debt).
(11) Identifying abnormal power consumption caused.

The web presence of cloud platforms helps to share the information on real-time energy usage and cost of energy with consumers. Knowing in real-time their energy consumption, homeowners can organize their energy consumption and reduce their bills. Also this application recommends optimal tariff plan according to consumer profile. Smart Grid cloud also provides tools such as Verde via the Web to all applicable stakeholders, provides services as such a Google earth to state, local entities to assess their data in a standardized format, provides other measurement/analytical services to all applicable stakeholders (enabling interoperability and standardization), facilitate an incorporated data sharing environment that will allow state and national level analysis using the same information on demand.

10. Smart grid applications

Smart Grid technologies are equipped for home and building automation, substation automation and feeder automation. Smart Grid technologies enables the effective use of devices, detects faults and isolate faulty devices and equipment's if necessary. Application of Smart Grid technologies for home and building automation, substation automation and feeder automation are described below.

10.1. Home and building automation

Home and building automation is part of Smart Grid network; an automated home or building is termed as a smart home [209–218]. In smart homes sources of energy and appliances are coordinated and controlled in such manner that the Smart Grid objectives are met optimally. Building smarter home needs smart energy controllers which also having smart metering capabilities. Fig. 33 shows the architecture of a typical smart home.

10.1.1. Main controller or the smart controller

The main controller is an intelligent, programmable device capable of performing numerical processing, computations, running optimization subroutines, metering, setting up a two-way communication with the Smart Grid control center (SGCC) and taking decisions on the basis of specified real time constraints. It also has the capability to control the electrical appliances directly.

10.1.2. Smart grid control center

SGCC is the gateway of smart controller's to the energy world; a computer performs the function of energy database and energy exchange. It is owned and functioned by a regulatory body on behalf of utilities. Depending upon the features offered to the consumers, the scope of information in the energy database of SGCC varies. Normally, the information contained in the exchange consists of past, present and the future prices of energy from various utilities and other related costs, like discounts, offers, lock in period etc. If more than one rate is valid, then the time at which each rate is applicable should be displayed. Information about traded volumes and information and profiles of different connected members/users of the SGCC.

Fig. 34 shows typical information in SGCC. The main controller and the optimization algorithms running in it need lot of inputs from SGCC. The controller has to depend on the stored information, if present information is not available from SGCC. The optimization algorithms will not be capable to make the actions on the basis of latest energy information. An SGCC must be there in each geographical area and all the consumers and utilities in that region must be connected to the SGCC. Every consumer must have an account in SGCC and they can access this account to gather the information associated with them. Consumers can forecast their energy consumption and through SGCC they can inform to utility about the forecasts. The utility can choose to reward the consumer based on the accuracy of the forecasts. It must act as a database for storing the information about energy system. A significant feature of SGCC is that it acts as a backup information storage system. The main controller accesses the SGCC periodically and gathers data like utilities details, applicable rates, energy consumed, information related to power quality, etc. Thus, any information which has contractual or financial importance will be stored in SGCC and the local controller database. Utilities access SGCC to place in their latest offers, to know the total number of consumers availing their service, update the present and future prices and to know about their consumer's consumption patterns. This information is not available to the consumers. SGCC also keeps the consumers credit reports, which is only accessible to the utilities. Through internet (through their PC), connected to controller, consumers access the SGCC to check the present and future energy prices to know about

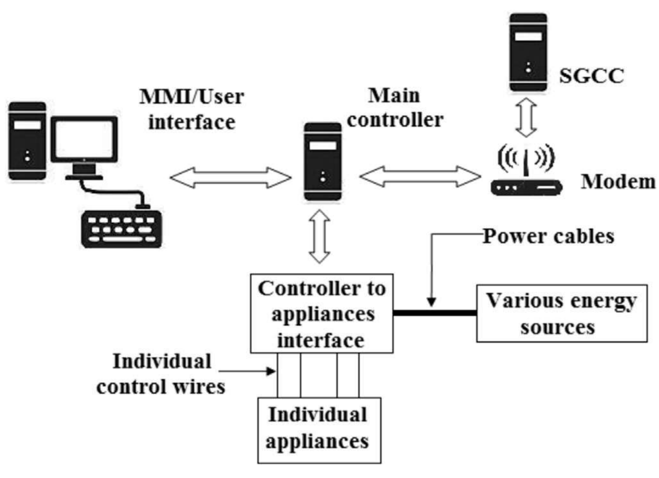

Fig. 33. Architecture for smarter homes.

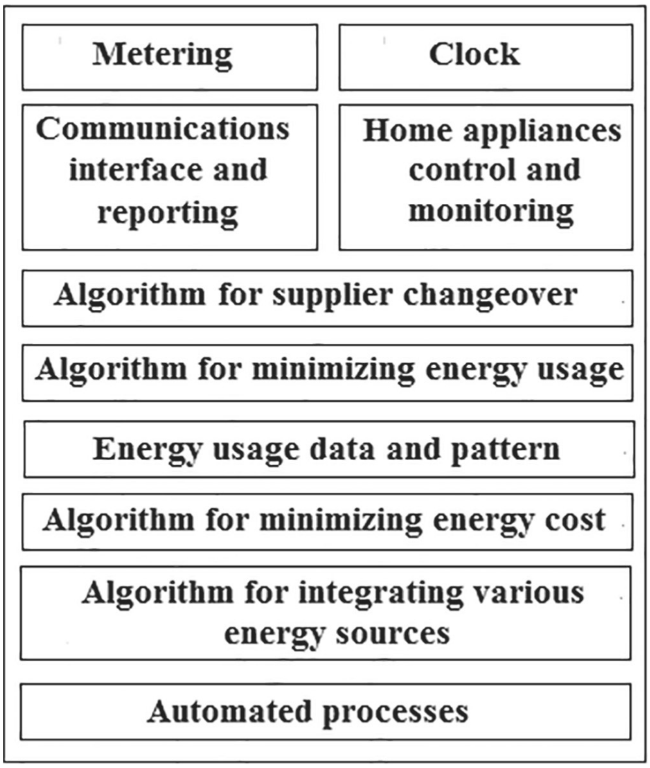

Fig. 34. Typical information in SGCC.

their consumption patterns and to initiate the changeover to a different utility when needed. Information regarding the service levels of each utility will be also available in SGCC. SGCC also acts as a gateway for the consumer complaints. In the complaint database of SGCC, information about the complaints for each utility will be stored and will be published periodically to let consumers to choose the utility they would like. It will be also a center of information for the consumers to inform their energy related restoration activities, blackouts and outages, present and future shortages. This will permit the consumers to plan accordingly. SGCC also houses information for each utility according to the source of energy i.e., from the non-renewable, renewable, nuclear etc. The changes in energy policy, initiated by the utility or by the government, will be published on SGCC and will be accessed by the consumers.

10.1.3. Sources of energy

Normally, sources of energy can be any one or combination of following (i) supply from the utility grid (ii) supply of gas and (ii) other locally offered DGs like wind energy, building integrated photovoltaic (BIPV), small-hydro, bio-mass with output of few kilowatt and storage devices.

10.1.4. Controlled appliances

Various energy consuming devices in the home are controlled appliances. The controlled appliances/loads are generally classified into Type-A, Type-B and Type-C. The loads which do not permit much flexibility in switching are termed as Type-A loads. Their switching operation cannot be timed according to the requirement, i.e., switching cannot be much advanced or delayed and are either intermittent or continuous following a specific pattern. The examples are domestic entertainment appliances, lighting loads, refrigerator and appliances needed during the cooking etc. The loads which offer switching flexibility is termed as Type-B loads, their switching can be timed. The examples are dish washers, dryers, washing machine etc. They switch off automatically when the process is complete. The loads which do offer flexibility in terms of switching but need human intervention are termed as Type-C loads. Examples of this type of load are vacuum cleaners, electric iron etc. Numbers of Type-C loads are decreasing day by day due to rapid growth of automation industry.

10.1.5. Network interfaces

The main controller interacts with the SGCC through network interfaces. The network interface can be an optical interface or electrical or combination of these. Moreover, the interface can be built in the controller also.

10.1.6. MMI console or the user interface

MMI console permits access to the information on SGCC, house owner to interact with the controller, configure the controller, update the software, change the settings etc.

10.1.7. The controller to appliances interface

This interface usually consists of relays. The relays will switch on or switch off the power supply to individual appliances on the basis of commands from the controller. This interface can be a separate module or can be incorporated with the main controller. Modern day multifunction relays employed in the control and protection applications permits seamless integration of switching interface and controller.

10.1.8. The main controller

The main controller is a computer in which the software needed to build the intelligence related to energy in the house is stored. Enormous functionalities can be built in the controller depending upon sources of energy available in the controlled area, diversity and variety of the loads etc. Main controller receives the clocks signal from SGCC and hence works in synchronized with it. Features of main controller in different control areas are,

(1) Features of controller in a simple residential area

The main controller periodically contacts the SGCC and downloads the energy updates. Main controller downloads the newest energy prices from SGCC and uses the information to work out the energy usage charges with the present utility. On the basis of switching costs, present and future prices of energy, compulsory lock in period of present utility and the projected energy consumption will decide whether to continue with the present utility or initiate a switch over process. User will initiate utility switch over process. On the basis of previous energy trends controller can forecast the future energy consumption. When the rate of energy is lowest, Type-B loads like water pumps, dryers and washing machines etc., which offer flexibility in switching and are not continuous, should be switched. The controller must be programmed to supply these loads only when the rate of energy is low. It records the daily, weekly and monthly energy consumption and will provide the details to the house owner on request. Data related to power quality would be also recorded for legal and contractual purpose. Depending upon the power factor in the controlled area, controller could switch on or switch off the reactive power equipment for power factor correction. Based on the availability of solar radiations the controller will be also programmed to switch off the lights in some parts of controlled area, so that lighting loads are switched on only when needed. After certain time, supply to Type-C loads must be automatically cut off to save energy; the controller must be programmed for the same. Loads like electric iron etc. are not often used for an hour. The controller must assume that the load has been left on accidently, if it senses that the load is on for more than an hour, it must switch off the supplies. This will avoid energy wastage and more significantly a chance of fire.

(2) Features of controller with BIPV in the controlled area

BIPV is an unconventional source of energy employed in areas receiving high density of solar irradiation and it is the most common energy producing source in homes. Since, there is no land cost involved, BIPV is cheapest than all other SPV systems. Additionally, BIPV reduces the cooling load by converting part of the incident radiations into electrical energy. The controller algorithm must be customized to optimize the energy bills when BIPV is incorporated as one of the sources. In such a case the controller must also do the following,

(3) Features of controller with energy storage

To overcome the peak load demand, Microgrid networks employs energy storage devices. The surplus energy is pumped into the storage devices when the demand is low and it is retrieved when the demand is high. The cost of electrical energy during the peaking times are higher than the off peak times. The controller algorithms must be designed to extract profit from stretch between peak and off peak rates when the storage device is part domestic energy system. The controller considers the storage system as an additional Type-B load, activating PCU and permitting energy storage when the energy cost is low and it is retrieved when the rates are high. It also keeps proof of full cycle efficiency of the storage system. The full cycle losses in the storage system and its related auxiliary system must be lower than the spread between the peak and the off peak rates, else the energy cost will increase.

(4) Features of controller with heating systems in controlled area

During off-peak hours, at times cost of electricity might become cheaper than the cost of gas. In such cases the controller can reduce the energy bills by switching the heating system sources between electricity and gas. On the basis of spot prices of electricity and gas and efficiency of electricity and gas based heating system, the switching over is decided. Each load cannot be designed to have dual energy sources, only heating loads can be switched over to electricity and gas. The controller must have the intelligence to take decision on switchover of the source. The efficiencies of electricity based and gas based heating system should have considered by the algorithm while switching.

(5) Remote access features

One of the foremost advantages of smart controller is its ability to permit remote access to the owner. Through the SGCC consumer can access the controller from a remote site on Internet through a secured password based system. The consumer can turn on or turn off the main energy inputs and appliances according to his wish. This characteristic of a smart controller helps to decrease the accidents caused by the appliances left on by the consumer during the vacations. On the other hand, the main controller can be programmed to turn off few appliances i.e. Type-B and Type-C loads, when it detects idleness in the house for a certain period. Fig. 35 shows typical information's stored in a smart home controller.

10.1.9. Automated processes

Smart Grid provides the chance of setting up automatic processes that are advantageous to all the consumers. These processes help the consumers to decrease the amount spent on energy by

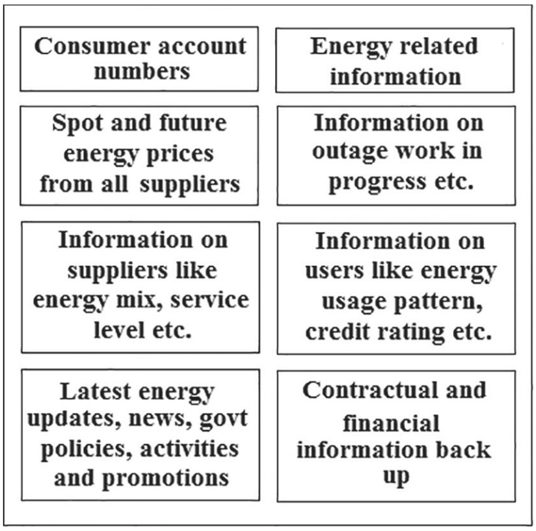

Fig. 35. Typical information's in a smart home controller.

choosing cheaper source or by decreasing the energy consumption and helps to improve level of services. Three such processes are discussed below,

(1) The utility changeover process

The utility changeover process will be initiated by the main controller or manually by the consumer based on present and future prices of energy, the forecasted future energy consumption and the changeover costs. The controller periodically assesses the information regarding the energy prices and works out the economics in automatic changeover process. The controller will be asked to initiate the changeover process on receiving the instruction from the consumer in the manual change over process. Once the controller is manually instructed by the consumer, the controller sends a message to the SGCC requesting it officially to make the changeover. Details of the consumer will be forwarded to the new utility and if the new utility accepts the credentials of the consumer, a confirmation is issued to the consumer for the official change over. The utility issues the terms and conditions or the contract also at same time. Under the user profile, the terms and conditions must be also displayed on SGCC, as these would influence the changeover decision. Though for an extra security, the contract is sent to the consumer in digital format. The consumer can accept or reject the contract, if not rejected within certain time it would be deemed to be accepted. An acceptance letter is sent back to the utility and also one copy of the acceptance letter is stored in the SGCC, once the contract is accepted or deemed to have been accepted. A unique number is assigned to the contract and this number is communicated to the consumer and the utility. The consumer and utility can also assign their own contract numbers internally. Though, in the energy market, the contract will identified by the number given by SGCC. SGCC sends the request of changeover to the existing utility and after receiving the confirmation from the utility it forwards the confirmation to the consumer or the controller. SGCC will debits the account of the consumer on the basis of total energy consumed until the changeover process with the changeover costs. The debits made from the account of the consumer are then credited to the particular utility (outgoing utility) accounts. The changeover process will be formally completed after resetting the meter and storing new tariff in the controller which will work out the energy consumption of the consumer.

(2) Complaint addressing mechanism

In Smart Grid, consumers can monitor their energy consumption pattern and the rate at which the consume energy. Hence, the complaints related with billing will be substantially low in Smart Grids. As these details will be available online as well as locally, hence, the chances of complaints and error will be reduced. The Smart Grid can assist fair and impartial investigation against the complaints. The steps involved in complaint mechanism are, the consumer registers a complaint in SGCC. The complaint can be either quality of power supply related or billing related. An investigation is carried out based on the details of complaint in SGCC. The data from main controller is demanded in case of any doubts. The data stored in the consumer's account of SGCC has a backup in the hard disk of controller. The investigation reports are forwarded to the consumer and necessary action is taken by the utility. The consumer can be effectively compensated if the investigation proves that the utility is at fault. A database for complaint is also maintained and if the complaints are proved to be real then it is moved to database for public view and it helps the other consumers for proper selection of utility. Unsolved complaints which remain for a particular period of time will be moved to another database for public view. The complaint database will record the name of the utility and it will help the consumers to determine the quality of the services provided by the utility.

(3) Automated billing and collection mechanism

Automated billing mechanism helps the utility by reducing the collection efforts and consumer by reducing the work concerned with periodic payments. Following are the steps involved in an automated billing and collection mechanism. The utilities set up payment mode like payment when the energy consumption goes beyond a particular amount or payment every month based on actual energy consumption. The consumer selects a particular payment mode from the options offered by the utility. The payment conditions are decided jointly and it is stored in SGCC and controller. Details of payment are also stored in main controller. Details of energy consumption are also sent to SGCC by main controller daily, which then transfers these details to the related utility. The utility fixes the bill on the basis of payment options selected by the consumer and sends it to SGCC for sending to the consumer. The bill includes the total amount and the date in which the amount is likely to be deducted from the account. Using the data available in the controller, consumer can validate the details. Once the payment has been credited, utility sends a confirmation to the consumer. For certain period the records will be stored in SGCC. Records of payment will be also stored in the main controller.

Finally, the main advantages home and building automation are,

(1) Improved energy prices due to competition in energy market.
(2) Improved services due to increased service monitoring.
(3) Switch over from one utility to another is easier and the process is also faster.
(4) For the poor quality of supply consumers will get compensation.
(5) Integration of home based DERs with the home energy system become much easier.
(6) Automated load controlling helps in distributing load over time which is beneficial to the consumer and utility grid.

10.2. Smart substation

Conventionally a substation employs CBs, protection relays, VTs and CTs all, which are wired collectively using, copper cables [219–230]. With advances in digital technology, communications and standards, this is now changing to what is known as the smart substation in which, the workstations, protection devices and low level transducers are connected together on an optical fiber communications backbone. The substation system architecture is divided into three levels; (i) the station level where operations, engineering functions and reporting take place, (ii) the bay level where system protection and control functions are implemented and (iii) the process level where signals from VTs, CTs and other transducers are transmitted. Fig. 36 shows the basic architecture of smart substation.

Smart substation consists of several key components and elements as follows,

(1) Protection, monitoring and control devices (IED)

Primary devices (tap-changers, protection relays, VTs, CTs, etc.) in the smart substation are implemented as IEDs. IED is a key component of substation integration and automation. These devices can communication with each other and with higher level smart substation control via the IEC 61850 optical network. Implemented to meet compliance necessities and save money. IEDs control CBs, voltage regulators and capacitor bank switches. Typical applications of IEDs in smart substation includes (i) DR, (ii) power fault reporting in the event of failures, (iii) low-voltage stabilization, (iv) asset management, (v) record load curves for future planning, (vi) integrated automatic transformer monitoring and (vi) automatically reconfigure the network in case of a fault.

(2) Sensors

Sensors are used to collect data from power equipment at the substation yard such as CBs, transformers and power lines. Conventional copper-wired analog apparatus are replaced by optical apparatus with fiber-based sensors in smart substation for monitoring and metering. Single sensor might serve different types of IEDs through a process bus. Advantages of fiber-based sensors includes (i) higher accuracy, (ii) reduced size and weight, (iii) higher performance, (iv) high bandwidth, (v) wide dynamic range, (vi) safe and environment friendly, (vii) no saturation and (viii) low maintenance.

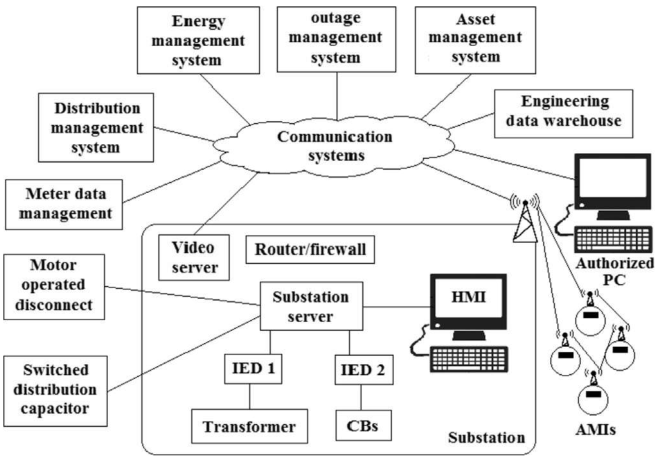

Fig. 36. Basic architecture of smart substation.

(3) Station and process bus

Exchange of signals between the bay level IED and station control, the bay level IED and transducers, devices and system equipment are carried by station bus and process bus respectively. This provides a better reliability for main substations as compared to a single bus. The station and process bus systems are usually implemented using Ethernet switches (external or built into the IED), connected together in a ring configuration.

(4) Supervisory control and data acquisition

SCADA is a system or a combination of systems that gathers data from different sensors at a station or in other remote locations and then sends these data to a central computer system, which then manages and controls the data and controls devices in the field remotely. Control and data acquisition equipment comprises of a system with at least one master station, a communications system and one or more RTUs. SCADA system has operator graphical user interface (GUI), engineering applications that act on historian software, data and other components.

(5) GPS time clock

The accurate time keeping is an important requirement of smart substation. This guarantee the protection functions operate within the required times and synchronizes smart substation in different locations so that event and operation logs can be compared and trip events analyzed. The preferred approach to achieving this is by the use of a GPS clock to transmit time synchronization signals to the IED, using simple network time protocol (SNTP).

(6) Electronic fiber optic CTs and VTs

A growing trend in the smart substation is the use of optical current and voltage transducers (sometimes called non-conventional instrument transformers-NCIT). These devices operate by measuring changes in the optical performance of fibers in the presence of electric and magnetic fields. The transducers are able to measure both current and voltage. As the signals are generated and transmitted using optical fiber, transducer signals are not subject to voltage drop issues and electromagnetic interference which can affect conventional equipment. Optical transducers also tend to be smaller, have improved linear characteristics and more accurately reproduce the primary signal.

(7) Master stations

A master station comprises of a computer system which is responsible for communicating with the field equipment and includes an HMI in the control room or elsewhere. The major components of a master station are (i) data acquisition servers that interface with the field devices through the communications system, (ii) real-time data servers, (iii) application server, (iv) historical server and (v) operator workstations with an HMI. Hardware components in a master station are connected through one or more LANs. Different types of master stations are (i) SCADA master station, (ii) SCADA master station with AGC, (iii) EMS, (iv) DMS and (vi) FA system. The primary functions of SCADA master station are (i) data acquisition, (ii) user interface, (iii) remote control, (iv) report writer and historical data analysis. The primary functions of SCADA master station with AGC are (i) economic dispatch, (ii) AGC and (iii) interchange transaction scheduling. The primary functions of EMS are (i) state estimation, (ii) optimal power flow, (iii) contingency analysis, (iv) three phase balanced operator power flow, (v) dispatcher training simulator and (vi) network configuration/topology processor. The primary functions of DMS are (i) interface to consumer information system, (ii) three phase unbalanced operator power flow, (iii) interface to outage management, (iv) interface to automate mapping/facilities management and (v) map series graphics. The primary functions of FA system are (i) two-way distribution communications, (ii) load management, (iii) voltage reduction, (iv) fault identification/fault isolation/service restoration, (v) short-term load forecasting and (vi) power factor control.

(8) Remote terminal unit

RTUs are microprocessor-based device that interfaces with a SCADA system. Provides data to the master station and enables the master station to issue controls to the field equipment. RTUs have physical hardware inputs to interface with field equipment and one or more communication ports. When compared to conventional substations, RTUs are smaller and more flexible in smart substation. In smart substations, one smaller RTU (capable of accepting higher level ac analog inputs) with distributed architecture approach is employed for one or more substation equipment. Additional functionalities include DFR and power quality monitoring and advances in communications capabilities, with extra ports available to communicate with IEDs.

(9) Merging units (MUs)

MUs collect signals from various equipment's and transducers. These signals are then transmitted to other devices via the process bus. MU is the interface between the traditional analog signals and the bay controllers and protection relays.

(10) Data types and data flow

Two types of data sets are there in smart substation, they are (i) operational or real-time data, which is for operating utility systems and performing EMS software applications such as AGC and (ii) nonoperational data, which is for historical, real-time and file type data used for analysis, maintenance, planning, and other utility applications. Operational data and nonoperational data have independent data collection mechanisms. Hence, two separate logical data paths must also exist to transfer these data. One logical data path connects the substation with the EMS and second data path transfers nonoperational data from the substation to various utility information technology systems.

Implementation of IEDs, smart sensor, electronic fiber optic CTs, and VTs and high-speed communication techniques improves overall performance of substation. The sensors in substation improves measuring accuracy, thereby faults can be cleared easily to maintain reliability. The digital substation offers numerous advantages over a conventional arrangement. These include,

(i) Better EMC performance and isolation of circuits.
(ii) Improved measurement accuracy and recording of information.
(iii) Easy incorporation of modern electronic CT and VT sensors.
(iv) Interoperability between devices made by different manufacturers.
(v) Improved reliability.
(vi) Easier and simpler installation.
(vii) Improved commissioning and operations.

10.3. Feeder automation (FA)

FA is the ability to monitor and control the distribution network remotely, to collect and provide information to consumers in a useful manner [231–243]. Some utilities refer to FA as distribution automation (DA), while others may refer to it as SA. FA uses digital sensors and switches with advanced communication and control technologies to automate feeder switching, voltage and reactive power management, equipment health monitoring and outage. FA provides a building block for monitoring, control and protection of the distribution system. From utility to utility the definition for FA varies. FA products are designed for interoperability and rapid automation implementation. These products offer SCADA interface and facilitate FA with or without communications. FA products aid to strengthen existing distribution systems and present a strong foundation for building a totally implemented feeder scheme in the future. FA products are a powerful tool for reducing operation costs and improving consumer service. Solutions not only have to be justified based on hard benefits, which are measurable to the bottom-line (e.g., increased kWh sales, reduced operating and maintenance costs, deferred or eliminated capital expenditures), they must also satisfy the need of less tangible benefits. FA products and system solutions can be incrementally incorporated and scaled within existing utility feeder infrastructures. Fig. 37 shows the basic FA architecture.

FA consists of several key components and elements as follows,

FA is achieved by employing number of field devices along the distribution network. Few of the field devices employed for FA is explained,

(1) Remote fault indicators

Remote fault indicators are sensors that detect current and voltage levels on feeders outside usual operating boundaries. Operators can utilize this information to determine the location of a fault rapidly or distinguish between temporary high loads and a fault, such as high motor starting current. Visual displays are equipped with fault indicators to assist field crews and connected to communications networks that are incorporated with SCADA or distribution management system (DMS) for providing greater accuracy in locating and identifying faults.

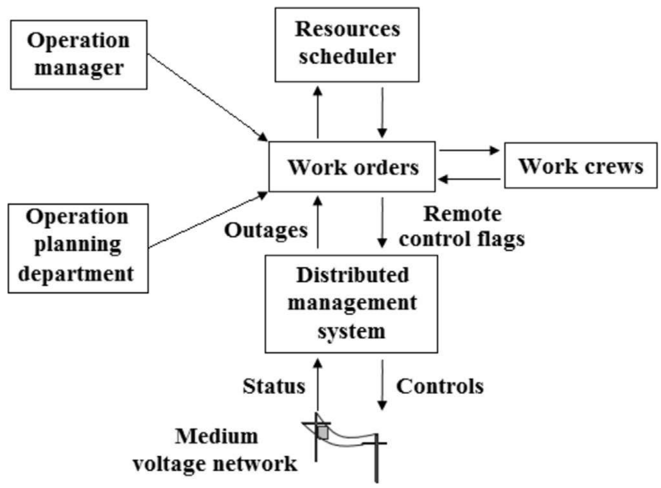

Fig. 37. Basic feeder automation architecture.

(2) Smart relays

Smart relays apply sophisticated software to accurately detect, isolate and diagnose the cause of faults. They may be installed on devices in automated switching schemes or in utility substations for feeder protection. Device controls are activated according to algorithms and equipment settings. The relays also store and process data to send back to grid operators and back office systems for further analysis. Advances in relay and sensor technologies have enhanced the detection of high impedance faults difficult to detect with conventional relays, that occur when energized power lines contact a foreign object, but such contact only produces a low-fault current.

(3) Automated feeder switches and reclosers

Automated feeder switches open and close to isolate faults and reconfigure faulted segments of the distribution feeder to restore power to consumers on line segments without a fault. They are normally configured to work with smart relays to operate in response to signals from utilities, distribution management systems or control commands from autonomous control packages. Switches can be also configured to open and close at programmed sequences and intervals when fault currents are detected. This action, known as reclosing, is used to stop power flow to a feeder that has been impacted by a hindrance and re-energize after the obstruction has cleared itself from the line. Reclosing reduces the probability of continuous outages when trees and other objects temporarily contact power lines during high winds and storms.

(4) Automated capacitors

Utilities employ capacitors for reactive power compensation requirements caused by inductive loads from overhead lines, consumer equipment or transformers. Reactive power compensation reduces the total amount of power that need to be provided by power plants, resulting in a flatter voltage profile along the feeder and less energy wasted from electrical losses in the feeder. A distribution capacitor bank consists of a group of capacitors connected together. The capacity of the banks installed on distribution feeders depends on the number of capacitors, and usually ranges from 300 to 1800 kV-ampere reactive (kVAR). Capacitor banks are mounted on substation structures, distribution poles or “pad-mounted” in enclosures.

(5) Automated voltage regulators and LTCs

Transformers that make small adjustments to voltage levels in response to changes in load are termed as voltage regulators. They are installed along distribution feeders and in substations to regulate downstream voltage. Multiple “raise” and “lower” positions are available with voltage regulators and can automatically adjust according to loads, feeder configurations and device settings.

(6) Automated feeder monitors

Feeder monitors measure load on distribution lines and equipment and can trigger alarms when equipment or line loadings reach potentially damaging levels. Monitors deliver data in near-real time to office systems and analysis tools so that grid operators can successfully assess loading trends and take corrective switching actions, such as repairing equipment when necessary, transferring load or taking equipment offline. These field devices are employed in coordination with information and control systems to avoid outages from occurring due to overload conditions or equipment failure.

(7) Transformer monitors

Transformer monitors are equipment health sensors for measuring parameters, such as insulation oil temperatures of power transformer, which can reveal possibilities for abnormal operating conditions and premature failures. To measure various parameters of different types of devices these devices can be configured. Usually, these devices are applied on substation transformers and other equipment whose breakdown would result in considerable cost and reliability impacts for utilities and consumers.

Performance of FA technology in four main areas are described below,

(1) Reliability and outage management

FA technologies provided highly developed ability for operators to locate, detect and diagnose faults. In particular fault location, isolation and service restoration (FLISR) technologies can automate power restoration within seconds by isolating faults automatically and switching a few consumers to adjacent feeders. FLISR can decrease the number of affected consumers and consumer minutes of disruption by half during a feeder outage for certain feeders. Fully automated validation and switching normally improves reliability than operator initiated switching with manual validation. Accurate fault location allows the operators to send repair crews precisely and inform consumers on outage status, which in turn reduces repair costs and outage length, reduces the load on consumers to report outages and guarantees satisfaction of consumer.

(2) Voltage and reactive power management

Automated power factor correction and voltage regulation enables utilities to reduce peak demands; more efficiently utilize existing assets, improve power quality and defer capital investments for the growing digital economy. Utilities use CVR to reduce energy consumption, reduce feeder voltage levels and improve the distribution system efficiency particularly during peak demand times. Automated power factor correction provides new ability to utilities for boosting power quality and managing reactive power flows.

(3) Equipment health monitoring

Installing sensors on main components (e.g., transformer banks and power lines) to assess equipment health parameters can provide real-time alerts for abnormal conditions of equipment as well as analytics that help utilities to plan preventative equipment maintenance, repair and replacement.

(4) Integration of DERs

Grid integration of DERs needs highly developed tools to monitor and dispatch DERs, and to address new control and power flow issues, such as reactive power management, voltage fluctuations, harmonic injection and low-voltage ride through. Few Smart Grid networks have been tested distributed energy resource management systems (DERMS) and integrated automated dispatch systems (IADS) on small DER installments.

11. Benefits of Smart Grid

Benefits of Smart Grid are,

(1) Self-Healing: detects and responds to routine problems and quickly recovers if they occur, minimizing downtime and financial loss.
(2) Motivates and includes the consumer: visibility into real-time pricing, and affords them the opportunity to choose the volume of consumption and price that best suits their needs.
(3) Provides Power Quality for 21st Century Needs: provides power free of sags, spikes, disturbances and interruptions.
(4) Accommodates all generation and storage options: "plug-and-play" interconnection to multiple and distributed sources.
(5) Enables markets: supports energy markets that encourage both investment and innovation.
(6) Optimizes assets and operates efficiently: build less new infrastructure, transmit more power through existing systems, and thereby spend less to operate and maintain the grid.

For consumers,

(1) Offer up-to-the-moment information on their energy usage
(2) Enable electric cars, smart appliances, and other smart devices to be charged and programmed to run during off-peak hours to lower energy bills.
(3) Open up a wider range of electricity pricing options.

For utilities and other stakeholders,

(1) Reduce inefficiencies in energy delivery.
(2) Quickly restore power after outages.
(3) Improve management of distributed energy resources, including Microgrid operations and storage management.
(4) Integrate the sustainable resources of wind and solar energy more fully into the grid.
(5) Increase grid reliability and reduce the frequency of power blackouts and brownouts.
(6) Increase grid resiliency.

12. Opportunities of smart grid

Smart Grid technologies help in,

(1) Upgrading and expanding infrastructure to improve interconnectivity and communications.
(2) Build up smart tools and technologies to exploit DR, demand load control and energy efficiency.
(3) Helps in educating the consumers.
(4) Creating models to promote Smart Grid investment and inform regulatory frameworks.
(5) Build up infrastructure to guarantee cyber security and resilience.
(6) Regulations in communication, price and cyber security.

Local,
The local opportunities of Smart Grid include,

(1) Integrated communications
  (i) Data acquisition, protection and control and allow consumers to interact with intelligent electronic devices in an integrated system.
  (ii) To connect components to open architecture for real-time information and control, information and data exchange to optimize system reliability, asset utilization and security.
  (iii) Areas for improvement include: Substation automation (SA),DR, feeder automation (FA), SCADA, EMSs, wireless mesh networks and other technologies, power-line carrier communications and fiber optics.
(2) Sensing and measurement
  (i) Support acquiring data to evaluate the health and integrity of the grid and support automatic meter reading, elimination of billing estimates and prevent energy theft.
  (ii) To support faster and more accurate responses.
(3) Advanced components
  (i) Used to determine the electrical behavior of the grid and can be applied in either standalone applications or connected together to create complex systems such as Microgrids.
  (ii) To apply the latest research in superconductivity, storage, power electronics, and diagnostics.
  (iii) The success, availability and affordability of these components will be based on fundamental research and development (R&D) gains in power electronics, superconductivity, materials, chemistry, and microelectronics.
(4) Advanced control methods
  (i) To monitor essential components that enable rapid diagnostics and precise solutions appropriate for any event.
  (ii) Using the devices and algorithms that will analyze, diagnose, and predict grid conditions and autonomously take appropriate corrective actions to eliminate, mitigate, and prevent outages and power quality disturbances.
(5) Improved interfaces and decision support.

Convert complex power-system data into information that can be easily understood by grid operators.

Regional and national opportunities of Smart Grid include,

(1) Provide higher quality power that will save money lost on outages.
(2) Accommodate all generation and energy storage options.
(3) Motivate consumers to actively participate in grid operations.
(4) Be self-healing.
(5) Resist attack.

Global opportunities of Smart Grid are,

(1) Run the grid more efficiently.
(2) Enable higher penetration of intermittent power generation's sources.
(3) Enable electricity markets to flourish.

13. The future: the key challenges of smart grid

The major challenges that Smart Grid facing are,

(1) Strengthening the utility grid: It must be ensured that the utility grid has sufficient transmission capacity to accommodate more energy resources, especially renewable resources.
(2) Moving offshore: Most effective and efficient connections for offshore wind farms and for other marine technologies (tidal

and wave energy) which is stochastic in nature, must be developed.

(3) Developing decentralized architectures: Decentralized architectures must be developed to enable harmonious operation of small-scale electricity supply systems with the total system.

(4) Communications: Developing a communication infrastructure which allows the operation and trade of potentially millions parties in a single market.

(5) Active demand side: Enabling all consumers to play an active role in the operation of the system, with or without their own generation.

(6) Integrating intermittent generation: Finding the best ways for integrating intermittent generation like residential micro-generation.

(7) Enhanced intelligence of generations: The problems associated with enhanced intelligence generation schemes (like FREEDM) system must be resolved to revolutionize the utility grid.

(8) Advanced power system monitoring, protection and control: Advanced measurement schemes like synchronized phasor measurements must be common to achieve synchronization by same time.

(9) Capturing the benefits of DG and storage: Advanced technologies must be developed to capture DERs more effectively. Hybrid energy system, such as, SPV-Wind, SPV-fuel cells e. t. c are necessary to maintain reliability and to power remote areas.

(10) Preparing for electrical vehicles: Electrical vehicles are mostly emphasized due to their mobile and highly dispersed character and possible massive employment in the next years, which would yield a key challenge.

14. Conclusion

In this paper an overview on evolution of Smart Grid, its functions, components, technologies, advantages, challenges, characteristics, applications, benefits, opportunities and future scope is given. Various Smart Grid technologies like smart meters, smart sensors, V2G and PHEV and its application in Smart Grid has also been explained in detail. The role of Smart Grid metering and communication technologies like AMI, IEDs, PMUs, WAMS, LAN, WAN, NAN and HAN for real time measurement and monitoring purpose, with the challenge of data privacy and security, has also been explored. Smart Grid cloud architecture and advantages are also presented. Applications of Smart Grid technologies for home and building automation, smart substation and feeder automation has also been discussed. It is difficult to predict exact future of the Smart Grid, but current innovations show an active merging of sectors, mechanics and communities for a common goal. At the end future research possibilities in Smart Grid is explained in "The Future: The key challenges of Smart Grid" sections. Smart Grid can be more effective in helping environmental conservation and energy sustainability. There are opportunities for research in the areas of time series forecasting, power quality and reliability studies, battery systems, cloud computing, power flow optimization, and renewable energy integration.

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