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Opportunities and challenges in control of smart grids – Pakistani perspective

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ABSTRACT

With the advancement in technologies, the power requirement around the globe is tremendously increasing, putting extra loads on grids. The existing grids cannot bear that load and also do not provide the interface with Distributed Renewable Energy Sources (DRES). Building new lines and substations alone do not serve the purpose of overcoming energy shortfall. Thus a major transformation in electricity infrastructure is need of the hour to meet the ever growing demands of electricity. Converting current power management system to a smart autonomic system is pertinent to achieve an increasing amount of renewable energy generation. This paper presents a comprehensive review of advances in control of smart grids. Various robust and adaptive strategies are spotlighted with a detailed description of control of overloads and power smart grids. Also, power generation, storage and management techniques and development of operational schedule of sources and loads are elaborated. Recently reported systems and Information and Communication Technologies (ICT) techniques in smart grid are highlighted. Renewable energy has potential to eliminate the current electricity crisis in Pakistan's energy sector. The solar, wind, hydro and biogas/biomass are the alternative energy resources found abundantly in the country, which have tremendous potential to offer environment-friendly energy solutions. This in-depth study reveals that a lot of opportunities and potential of smart grid technology exist in developing countries like Pakistan that need to be exploited so as to cope with energy crisis.

1. Introduction

The traditional power generation systems are normally dependent on hefty power generation units. Owing to their big size, these units need to be placed in feasible geographical location. With the help of heavy transmission lines, the generated power is then supplied to grid stations and from grid stations to end users through medium transmission lines. Like all other technologies, power systems are also evolving and instead of relying on single large power generation unit now there are Dispersed Generation (DG) units. These units can be of renewable or traditional sources like wind, solar, hydro, and fossil fuel based generation systems [1,2]. The great oil crisis of seventies has prominently increased the use of renewable energy sources [3]. Economics was the primary driving factor behind that boost. After half a century, today multi-disciplinary research in renewable energy sector has again caught attention of scientists and engineers but this time environment is the main cause. There is allot of research going on in two main renewable energy technologies; wind and solar.

One of the most evolving renewable energy technology is wind turbine [4,5]. In the beginning, only few kilo Watts can be produced through wind turbines but now many Mega Watt capacity turbines are available. Based on induction generator of squirrel-cage type, the old wind turbines were directly connected to a grid station [6]. So the wind-generated power pulses were directly fed to the station without any advanced control except few capacitor panels which were used for regulation of voltage and frequency. With the increase in power capacity of turbines the control parameters became more important and it became necessity of the system to intelligently control the interface between grid and wind turbine [7]. Wind turbines have become active power source from energy source because of evolution in power electronics. This evolution also offered a cost-effective solution by reducing price per kWh produced [8].

There is also positive progress in development of solar or photovoltaic (PV) systems. With the development of PV-cell material and

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increased efficiency of PV-inverters, the complete PV system is becoming economical day by day. There is a lot of research going on in advanced PV technology but in order to have a commercial end product, heavy investment of time and money is still required. Sophisticated control and intelligent power electronics are key enablers to provide a connection between a grid station and a PV system [9,10].

There are two main advantages of utilizing renewable energy resources. First one is that there is no emission of harmful gases in 'green' energy generation. The second advantage is that we are limiting the use of our primary energy resources which are being utilized inexhaustibly now. The drawbacks are the expensive infrastructure and lack of control over system as it depends entirely on weather. Due to this dependency, the energy generation pattern of renewable energy is daily and seasonal which means weather can make the system unavailable. Given that the energy requirements of users have very different characteristics and there is no real system which can store large amount of energy, it is not feasible to operate a power system dependent only on renewable energy sources. These systems are also not dispatch-able like traditional fossil fuel systems. The way systems with wind turbine and PV are developing, the power grid station is becoming heterogeneous and more uncontrolled.

The situation of power sector is getting worse in Pakistan as the country is going through worse power crises of its history. The power shortfall is above 7000 MW in peak load times of year [11]. In year 2009–2010, line losses in Pakistan were 22% [11] while in 2013–2014, it is around 16% (Fig. 1) [12]. According to the statistics provided by Water and Power Development Authority (WAPDA) of Pakistan, the total power generation capacity is 15,764 MW from renewable as well as from traditional sources [13]. The peak energy demand for year 2014-15 was 25,042 MW and the estimated demands for 2015-16 and 2016-17 are 26,249 MW and 27,572 MW respectively [14]. This leads to the fact that there is an annual increase of 8.77% in peak energy demand in the country. The gap between electricity supply and usage is enhancing due to population increase, expansion of cities, line losses and urban life style. This electricity shortage affects industrial, commercial and domestic sectors equally. Pakistan is still depending upon hydro and fossil fuels for electricity generation. Fossil fuel is imported and results in spending large foreign currency reserves [15] and thus is not a viable solution.

Pakistan has huge potential for solar, wind and biogas energy. The government is taking serious actions to promote renewable energy resources. Therefore, smart grid is a very promising solution and can be used to overcome the current electricity crisis [15].

The aforesaid discussion demands a comprehensive analysis to elaborate the relevant facts. The main objective of this paper is to present a systematic deliberation on the control of smart grids and its potential in the context of Pakistan. This research reviews the state of art production technology and energy resources in Pakistan and highlights the potential of renewable energy to meet forecasted demands. It is anticipated that the present review will help the policy makers and other stakeholders to address the energy crisis in the country and significantly uplift the living standard of people by working on reliable sources of energy. The presented past-future comparison on the subject topic with a critical discussion may also be relevant to other developing countries having similar dynamics as that of Pakistan.

The remaining paper is outlined as follows; Section 2 highlights importance of smart grid and its advantages in contrast with conventional grid system. Section 3 explains advances in control with a viewpoint of smart grid. The control strategies and reported technologies applicable to smart grid are reviewed in Section 4. A case study of smart grids in Pakistani perspective encompassing various initiatives by the government in renewable energy is presented in Section 5. Finally, Section 6 comments on conclusion and highlights the potential benefits of this systematic review.

2. Smart grid

Conventionally, the grid is a non-intelligent entity that simply performs the operations of power distribution and control of transmission links from generation unit to end user [16]. Current energy requirement demands a more resourceful grid. Fig. 2 shows the expected global increase in energy consumption. With this growth in demand, failure rate of the current grid system is expected to rise significantly in peak load hours [17] thus leading to an extra expenditure of 25–180 million USD [18]. The present power grid systems are not suited to fulfil next generation power systems requirements mainly because of high energy demands, non-integration with renewable energy sources, complexity of power grid management and other constraints related with capacity and generation. For that reason, development of decidedly reliable, efficient and self-regulating grid is extremely necessary. Such system will be able to integrate sparsely distributed renewable energy generators which will ultimately decrease the dependency over fossil fuels ultimately resulting in an environment friendly solution.

2.1. Smart grid: a new horizon

Smart grid is a solution through which power systems can be digitally intelligent. It is equipped with digital sensors and smart metering techniques, which can simplify many existing problems. It contains analytical tools of intelligent control systems [19] which can control, automate and monitor the live bidirectional flow of energy from power source to end user plug. 'Energy Internet' is the term often used to refer Smart grids. It is a decentralized system that makes the electric power system a bidirectional network constructed on a typical Internet Protocol (IP) system [20]. Instead of one high power generator, smart grid uses dispersed, distinct and big amount of smaller plants. Such a system is more efficient in case of any natural disaster or terrorist attacks. Even if they are affected, their self-healing capability can rapidly isolate the effected part of systems. With the help of intelligent switching, power supply is redirected, like transformer winding protects itself from short circuit through rapid digital protection [21].

Smart grid system is emerging in parallel to cope up with the operational demands and provide enhanced safety, control and protection [2]. As smart grid systems are still under development in most of the world, there are many technical challenges that need to be resolved in order to supply substantial amount of renewable energy. These challenges, on one hand are related with control and communication aspects, while on the other hand, are linked with real-time management issues like real time billing and pricing, micro-grid management [22], kerb-able loads, charging support of electrical vehicles, connection with fossil fuel and renewable energy sources (solar, wind, hydro) and energy storage [23]. There are many technologies available to cope up with smart grids challenges. As wireless sensor networks, which are vastly deployed in many remote applications like battlefield, wildlife monitoring and medical [24], they can be an excellent choice for low cost smart grid communication. The disturbance and power transmission problems can be solved with the help of enormous advancements in the fields of communication, computing and sensor networks. Fig. 3 shows the conceptual model of a smart grid.

2.2. Incorporation of renewable energy source in smart grid

Smart grid can connect many Distributed Renewable Energy Sources (DRES). It has the capability to interface radially connected generators to the grid [26]. This plug and play integration of generators enables smart grid to cope up with new energy demands. Smart grid is flexible enough to control DG system and also has the capability to regulate voltage for highly penetrated DRES [27]. In order to achieve an enhanced reliability of smart grid, frequency controlled and

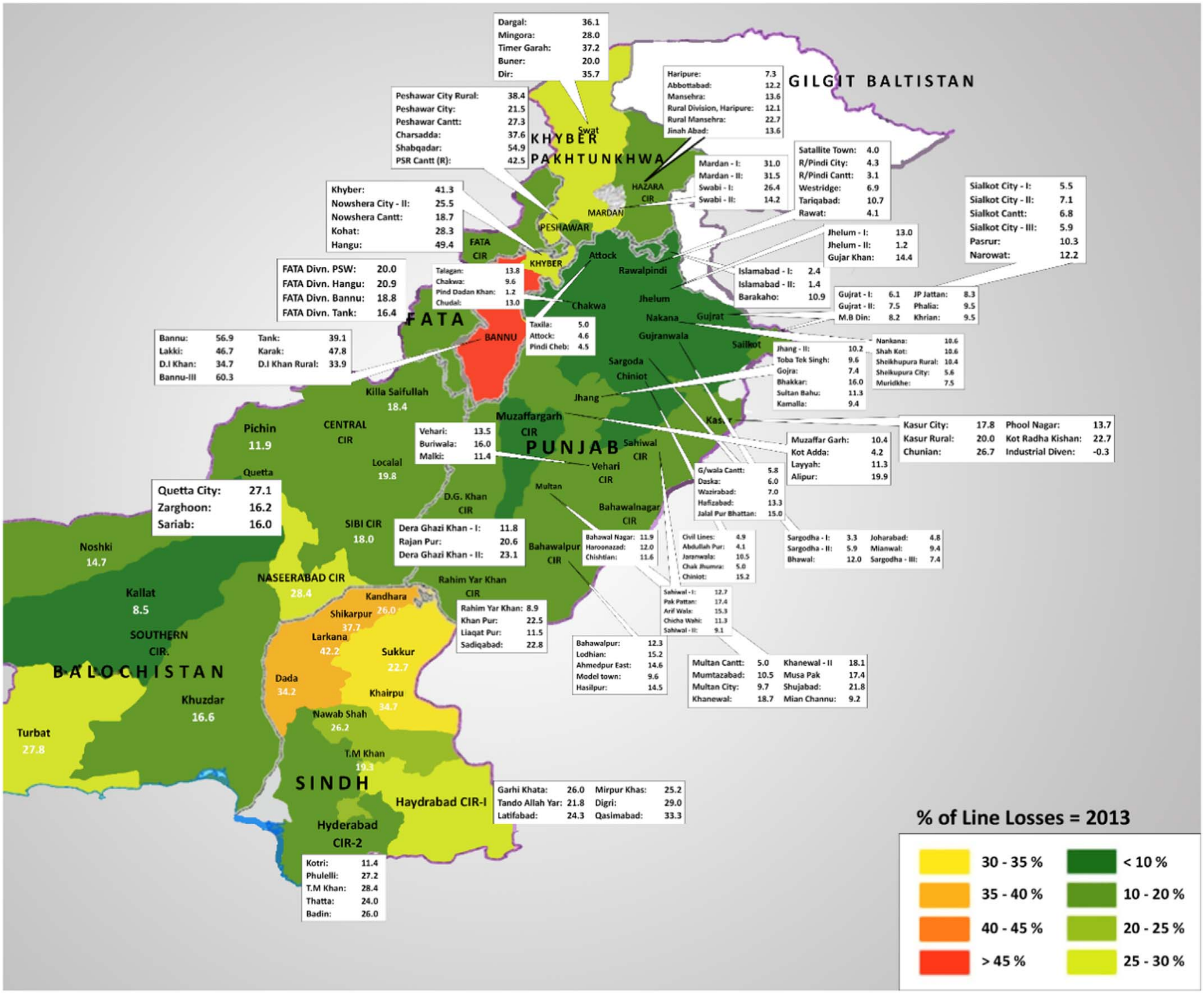

Fig. 1. Line losses in Pakistan up to July 2013 [12].

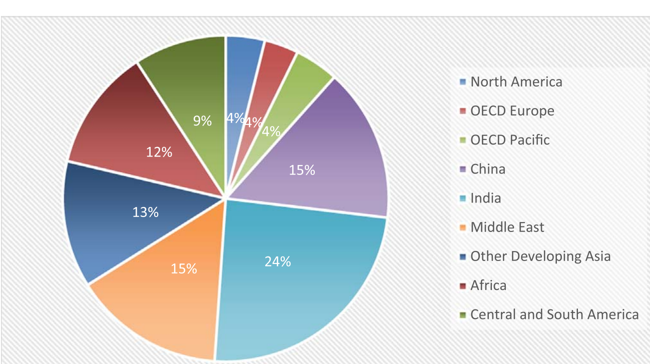

Fig. 2. Global energy consumption growth percentage [17].

responsive loads are introduced. High integration of low and medium sized renewable energy generation units ignite several issues like synchronization between sources and in overall with the grid, removal of harmonics to avoid distortion and smoothing of fluctuation in the generated voltage [28]. Power outage is prevented by smart grid due to its optimization feature which allows end user to efficiently manage the energy utilization. Smart grid has opened many horizons by distributed power generation and storage, and this power can be flexibly added to the system at several levels like transmission and distribution level.

2.3. Smart grid – the future

Practical applications of renewable energy resources have intermittently increased the urge to address energy storage problem. Electric vehicles can be charged through smart grid, so vehicles can store energy by drawing power from smart grid system [29]. Plugin Electric Vehicles (PEVs) / Plugin Hybrid Electric Vehicles (PHEVs) [30] when combined with renewable energy generation system can offer several benefits like bringing a pleasant change in the environment, resulting in low operational cost of vehicles, reducing the consumption of fossil fuel and minimizing the emission of harmful gases [31]. Overall and peak demands can also be reduced by associated technologies like collective heat and power or thermal storage for cooling [32]. In Roqoe island, a distributed approach [33] containing tidal, solar and wind generation system has been implemented. This system uses energy storage which is commercially available and also implements a controller of smart home management system. Fig. 4 shows its schematic diagram.

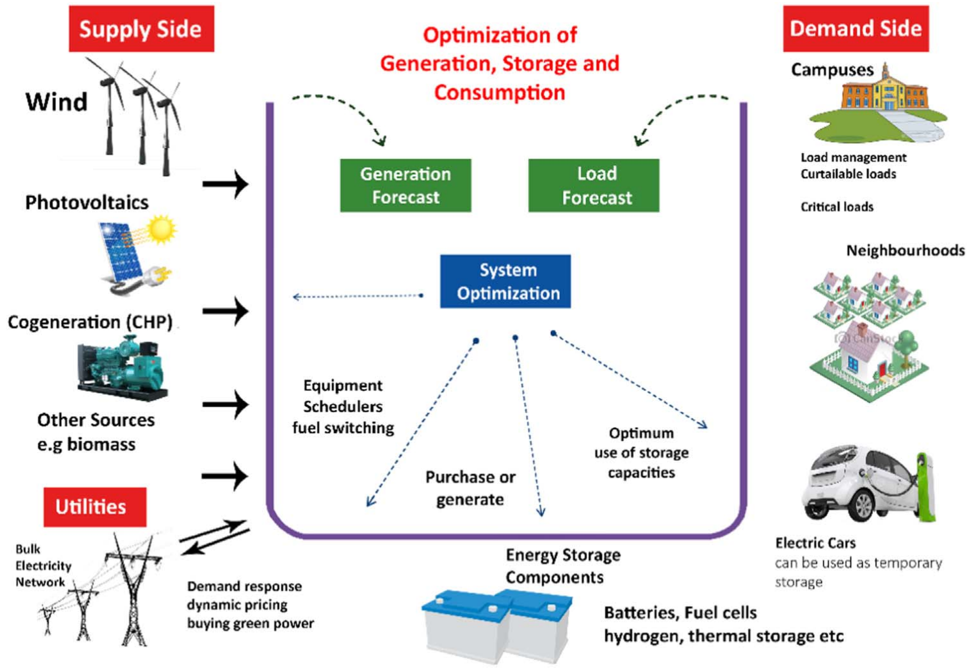

Fig. 3. Conceptual model of a smart grid [25].

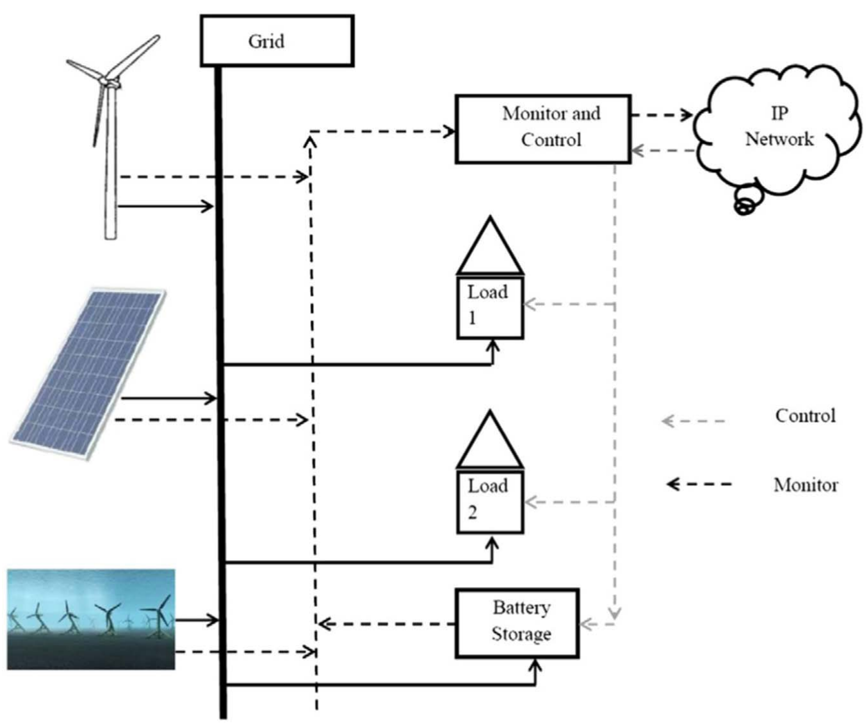

Fig. 4. The Roque system is comprised of renewable energy supply, a smart controller, battery storage, load balancing capabilities and a grid tie connection [33].

The uptime of gasoline based generators is reduced by smart grid with higher penetration of DRES ultimately reducing the CO_2 emission. Pacific Northwest National Laboratory, US assessed that by year 2030, CO_2 emission will be reduced up to 0.525 billion metric tons which is 18% of total CO_2 emission in US [34]. European Technology Platform (ETP) estimated that by 2050, the annual CO_2 emission in Europe will be reduced by 0.7Gt to 2.1Gt [35].

Scientific community has recently highlighted research in various aspects of smart grids. Applications of smart grid technologies in industrial sector have been thoroughly visited by Samad and Sila in [36]. Shafiullah et al. have investigated the challenges of integrating renewable energy resources including wind [37,38] and solar [39] with the grid. Comprehensive reviews of smart grid and the related technologies from DR perspective are reported in [40,41]. A comprehensive state-of-the-art on diverse load classification algorithm for smart grid is presented in [42]. The application of cloud computing in order to develop an advanced smart grid is given in [43]. To achieve efficient low cost communication infrastructure in smart grid, Khan et al. in [44] have proposed implementation of Cognitive Radio Sensor Network (CRSN). IEEE vision for smart grid controls for 2030 and beyond is reported in [45].

Key elements in global modernization and Information and

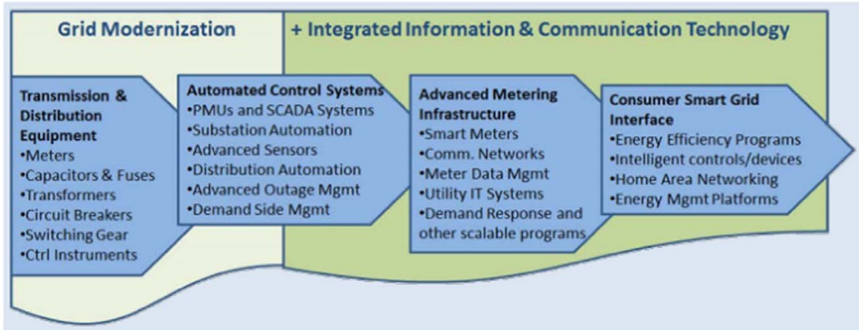

Fig. 5. Smart Grid Technologies Continuum [46].

Communication Technologies (ICT) in the context of smart grid continuum are listed in Fig. 5. These elements range from modern hardware resources to software based supervisory control schemes and consumer interfaces. This multi-disciplinary research on various domains of smart grid witnesses that these grids certainly do have potential to replace the conventional grids in the future [39]. Being a timely review, the present paper is focused on control of smart grid.

3. Advances in control of smart grid

The domain of control and automation is the key enabler of smart grid. With the help of advanced control techniques, electrical grids can be integrated with distributed renewable energy generation systems so as to realize the concept of 'smart electrical grid' [47]. Furthermore, application of advanced control on all levels of smart grid is required for efficient grid management system. Several basic scientific issues [48] related with smart grid occur during its construction and development process which primarily includes prediction, energy storage, control, dispatching, planning and their assessment. The fundamental characteristics of a smart grid [49] include interaction with the power user, adaption to power demands, support of the mature power market, asset optimization, self-healing and prevention from external damages and attacks. Successful implementation of the grid is a function of following features:

- Predictive control of different renewable energy generation systems.
- Coordination and synchronization of generation systems with the central electrical grid and associated loads.
- Cooperation among different control systems.

3.1. Control system hierarchy

On the basis of synchronization and coordination, the control hierarchy of smart grid consists of three control levels, which contains primary, secondary and tertiary level control loops. The control hierarchy of a smart gird is shown in Fig. 6. In the primary control loop, also known as inner control loop, the voltage and current of the distributed energy resource are maintained in the presence of both linear and nonlinear loads. The phase control at this level helps to

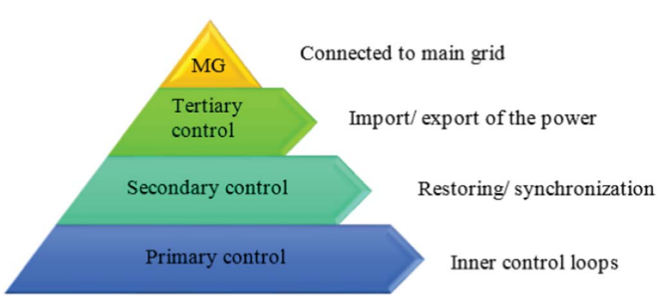

Fig. 6. Hierarchical structure of smart grid [50].

provide independent active and reactive power in the islanded mode [50]. Smart grid can operate in both the islanded as well as Main Grid (MG) connected mode. The principal roles of the smart grid control structure are [51]:

- Voltage and frequency regulation
- Proper load sharing and coordination in the distributed energy resources
- Synchronization of smart grid with the main grid;
- Power flow control between smart grid and the main grid;
- Optimizing the operating cost of smart grid.

In the secondary level regulation voltage and frequency are controlled. For smart grid, its role is to maintain stability under certain tolerance parameter set for main grid operation i.e. ensuring the controlled values of voltage and frequency despite of changes in load and production. Secondary level control can be used in both centralized and decentralized mode [52]. The position of perspective central controller is the main difference between both modes of use. The central control is suitable for a group of resources that are of similar type or certain micro-sources that are manually controlled.

The constant measurement of voltage and frequency is fundamental for connecting smart grid to main grid. These values are provided as reference to the secondary controlled loops and their connection and synchronization is the function of tertiary control.

3.2. Control of hybrid generation systems

The performance of electricity systems can be enhanced by integrating smart grid technologies as they offer better coordination among grid operators. Additionally, smart grid technologies offer grid conditions' dependent control which in turn allows high level integration of renewable energy resources at optimal cost. However, renewable energy resources are reliant on the geographical, economical and regulatory environment conditions, thus needing advanced control of power systems to sustain reliability of the system. The control of smart grid is subjected to the resource information in order to make smart decisions [53]. Wind, solar and tidal energies are natural yet intermittent resources of renewable-energy. Their dependence upon climatic and weather changes makes them unsuitable as a prime energy source for grids and hence inability to retain reliable and continuous supply of energy. This leads to failure for provision of cost effective energy resource, especially in comparison with conventional grid. Consequently, hybrid generation systems evolved as a replacement of conventional energy systems [54]. Hybrid generation systems address the problem by combining two or more systems, thus reducing the dependency of the overall system upon environment parameters resulting in production of reliable and cheap electricity [55–57].

3.3. Forecasting the demand in smart grids

A pre-knowledge of the estimated number of consumers of a smart-grid is required for prediction of direct participation of consumers in demand management. Demand Response (DR) forecasting for single or monolithic load is usually done using Short Term Load Forecasting (STLF) [58]. Multiple STFLs are required when forecasting of various loads is anticipated i.e. one STFL for each load. The scalability problem in forecasting hundreds of thousands of loads is addressed by Short Term Multiple Load Forecasting (STMLF) by combining individual load time-series into a concise model to forecast various loads based on a single model. The accuracy of STMLF has been reported to be 7% higher in comparison with short term forecast for each load individually [59].

3.4. Demand and supply management in smart grid

Electric load for a small area or community requires a small-scale low voltage power supply which are provided by micro grids [60]. On the power supply side, a demand control scheme need to be built so as to achieve the economic consumption scheduling and to fulfil the requirements set by energy users; whereas, on power demand side, there is a need to properly model the randomness of renewable energy generation, which may account for a significant portion of power supply in micro grids. It is pertinent to mention that the load balance constraints act as the connection between power consumption and generation. Given the uncertainties in renewable generation as well as in load consumption, a hierarchical control strategy (e.g. [61]) is required which can ensure regulation of frequency to allocate resources in an optimal way.

Demand control techniques are classified into price based load control techniques which are referred to demand response methods and direct load control which is linked with Demand Side Management (DSM). In price based load control scheme [62], users are encouraged to make energy consumption decisions individually according to the price information. DSM strategies, however, require consumer subscription to an economic incentive program and are usually applied directly by the main controller.

Reported studies also address the renewable energy uncertainties when scheduling the energy generation. Hidden Markov models have also been adopted to characterize renewable energy generation [63–65]. An important task of power demand and supply management in micro grids is to maintain a good match between power generation and consumption at the minimum cost. Since the highly fluctuant renewable energies constitute a significant portion of the power resources in micro grids, the Micro Grid Central Controller (MGCC) faces the challenge of effectively utilizing the renewable energies while fulfilling the requirements of customers. Firstly, a novel uncertainty model is required to capture the randomness of renewable energy generation by introducing a reference distribution according to past observations and empirical knowledge. The model confines the uncertainty of renewable energies permitting these to fluctuate around the reference distribution. An optimization problem is then formulated to determine the optimal power consumption and generation scheduling for minimizing the fuel cost. Finally, a two-stage optimization approach is proposed to transform and solve the prime problem.

3.5. Cyber-physical security of smart grid

Smart grid initiative will result in a grid that is increasingly dependent on its cyber infrastructure in order to support the numerous power applications necessary to provide improved grid monitoring and control capabilities. Cyber security concerns within the communication and computation infrastructure and may allow attackers to manipulate either the power applications or physical system.

Smart grid applications incorporate various individual technologies such as Advanced Metering Infrastructure (AMI) and Wide-Area Monitoring, Protection And Control systems (WAMPAC) [66] that are heavily dependent on the cyber infrastructure since the data is transported through several communication protocols to utility control centres and consumers. AMI is based on the deployment of smart meters at consumer locations to provide two-way communication between the meter and the utility. This provides the utility with the ability to push real-time pricing data to consumers, collect information on current usage, and perform more advanced control analysis of fault detection techniques within the distribution system [67]. WAMPAC can be further subdivided into its constituent components namely, Wide-Area Monitoring Systems (WAMS), Wide-Area Protection Systems (WAPS) and Wide-Area Control (WAC) [68]. Conceptually, three classes of attacks on this control system model for WAMPAC are possible [69]: timing based attacks, integrity attacks and replay attacks. Timing attacks tend to flood the communication network with packets and this slows the network down in several cases and can even shut them down. In data integrity attacks, the data is corrupted in forward or reverse path in the control flow. Replay attacks are similar to data integrity attacks, where the attacker manipulates Phasor Measurement Units (PMU) data or the control messages.

4. State-of-the-art

The control of smart grid power plants has been widely studied from the last four decades, as it emerged that new cheap energy resources are required for home and industrial use, thus making it a well-established scientific domain [70]. When modeling the power plants, many assumptions are made and mathematical models thus obtained are close approximations to the real world plants. Almost all the plants related with smart grids are non-linear in nature. Many processes occurring in the plants are time invariant with respect to the changing environments [71]. When smart grids are designed, it is ensured that stability, reliability and efficiency are met according to design specifications since these parameters play an important role for successful operations of the smart grid. Fig. 7 shows a generalized architecture of smart grids.

Smart grids can fulfil energy requirements of dispersed populations in rural topographies and can additionally provide energy to the national grid. The smart grid also ensures reliable energy supply in case of severe climate conditions due to adaptability, flexibility and robustness [72]. Smart grids also offer a cost effective solution for overcoming limitations which were evident in already existed distributed systems. Limited switching is possible in changing loads of AC and heaters in peak conditions and in emergency situations. With usage of smart grids, active participation of consumers is also possible which results in cost effective and energy efficient utilization of smart grid resources [3]. Several techniques have been developed for the control of smart grid applications ranging from conventional to advanced control design strategies.

4.1. Control strategies for smart grid

The control problem is very challenging since it involves in delivering robustness, effectiveness and optimum performance. The control design personals are also responsible for modeling, simulation and identification of system parameters [70]. Various control design techniques for developing different controllers in smart grid systems can be found in literature including Proportional Integral Derivative (PID), Linear Quadratic Regulator (LQR), Linear Parameter Varying (LPV) control, Sliding Mode Control (SMC), Model Predictive Control (MPC), Fuzzy Logic Control (FLC), Time Delay Compensation (TDC), Neural Network Control (NNC), H- infinity control, Internal Mode Control (IMC) and Phase Locked Looped (PLL) based control.

Use of PID controllers has been reduced because of safer operating constraints and requirements of additional compensators for proper

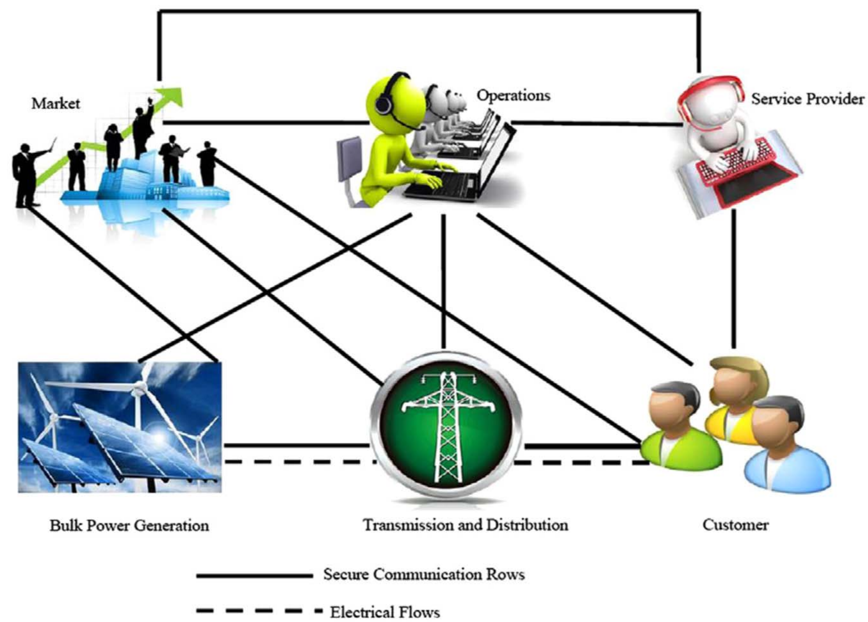

Fig. 7. Architecture of smart grids [19].

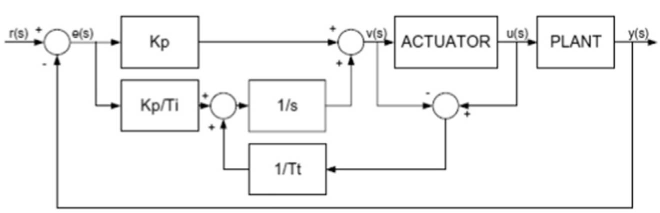

Fig. 8. PID and anti-windup control scheme [70].

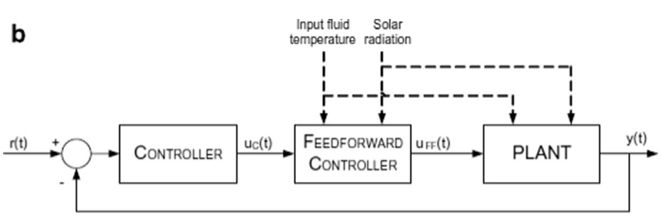

Fig. 9. Basic feed forward control scheme in series configuration [70].

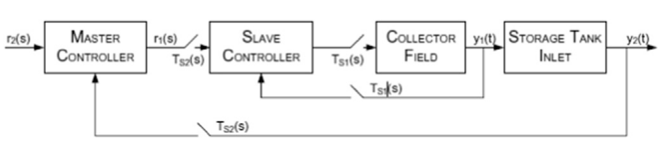

Fig. 10. Multirate cascade control [70].

functioning of PID controllers [73–75]. PID also suffers from integrator windup issue which occurs when the actuators are saturated resulting in worse step and disturbance responses. This issue is generally combated with an anti-windup control scheme as shown in Fig. 8.

A feed forward controller is also required for PID based control schemes for reducing effects of measureable disturbances [76]. Based on a developed model, the sensed disturbances are used to determine the manipulated variable so as to keep the control at desired reference point. The feedback compensates modeling errors [77]. The scheme can be implemented in serial or parallel configurations. Serial configuration is illustrated in Fig. 9. Other issues with the use of PID controllers have been discussed in [78,79].

A PID controller with interpolating gain for energy control of a distributed solar collector has been developed by Johansen and Storaa in [80]. This research involves implementation of a hybrid feedback/feedforward control incorporating time varying and non-linear gains. LQR based control has been applied by Alepuz et al. [81] for controlling grid system filtration process, inversion process, DC link and controlling grid side. PLL based control has been implemented in [82] to resolve issues arising due to mismatch of generated frequency in grid and measured frequency. Oscillations, stability, control and automation issues of smart grids are overcome by using standardization and classification [83]. Adaptive PI controllers are investigated using feed forward control in Camcho et al. [84].

Cascade control is a technique which uses inner loop for compensating disturbances and outer loop for controlling process output. Fig. 10 illustrates block diagram of a cascade control. A master controller controls the collector field through a slave controller. Cascade control of a solar field in Distributed Control System (DCS) mode for controlling average temperature and mixing oil requirements is reported in [85,86].

Adaptive Stochastic Control (ASC) is capable of optimization of sources and loads present in the smart grids as shown in Fig. 11. These systems can identify the worst scenarios happening in the plants [23].

FLC is a fuzzy based technique which employs different set of rules on the process variables, which in turn reduces uncertainty and imprecision in the system. FLC scheme can be applied with different variations depending upon the controls objectives. Fig. 12 shows direct FLC with a feed forward control. Quite often, FLC is combined with other control techniques like PID or its variants e.g. incremental fuzzy PI control.

Volt-VAR Control (VVC) is also extensively applied for maintaining operational requirements for smart grid distribution system. The basic purpose of VVC is to attain acceptable voltage levels at all operating points in distribution system ensuring all loading scenarios. This control methodology results in improving efficiency and maintains voltage level due to “self healing”. The different approaches to VVC are utilized including standalone, On-site Voltage regulator (OVR), rule based DA control, heuristic voltage regulation and distribution based model VVC [88]. The concept of Conservation Voltage Reduction (CVR) is used to maintain delivered voltage to the acceptable lower limits.

Automatic Generation Control (AGC) ensures the stability of smart grid frequency and power setting scheduling. The load forecasting

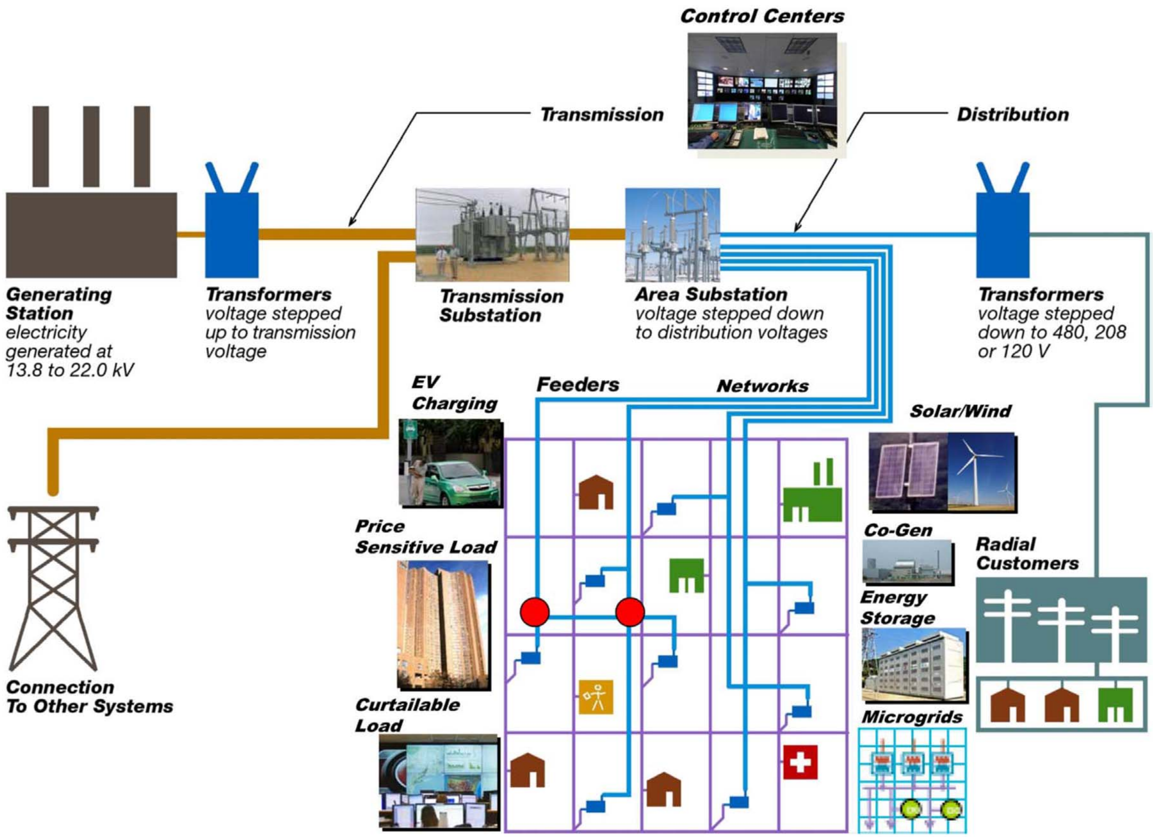

Fig. 11. The adaptive stochastic control of Smart Grids [23].

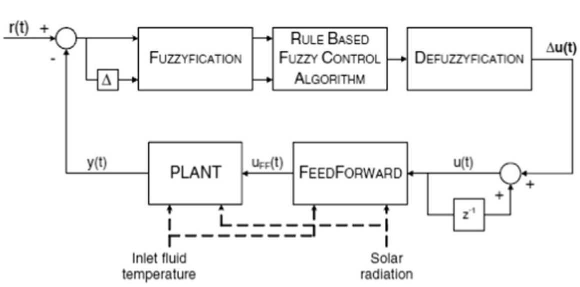

Fig. 12. Block diagrams of direct FLC [87].

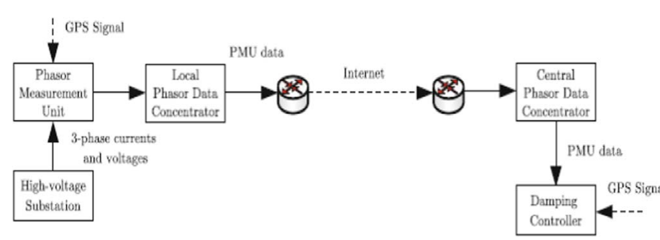

Fig. 13. Power Damping Controller [91].

errors and uncertainties are reduced by using AGC approach [89].

The Optimal charging Control strategies are used for autonomous Plug-in Electric Vehicles (PEVs). The PEVs coordination schemes are of two types centralized and decentralized or distributed strategies. The coordination and grid level analysis for PEVs is performed in Ma et al. [90].

The Adaptive Power Damping Controllers are utilized for rectifying latency and phasor quantities present in smart grid systems. The Power system electromechanical mode damping controllers are of two types which include Power System Stabilizers (PSS) and Flexible AC Transmission Systems (FACTS) controllers. Various aspects of Phasor Measurement Units (PMU) for damping control are proposed in Joe et al. [91]. The Adaptive Power Damping Controller block diagram is shown in Fig. 13.

Model Reference Control (MRC) approach is implemented for ensuring stability and robustness in smart grid system. Aranya et al. [92] have proposed three steps MRC approach namely Model reduction, Aggregate Control and Control inversion. This scheme is very advantageous in dealing damping issues.

Multirate Model Predictive Control (MPC) approach is proposed for coordinating demand response and regulation. The varying dynamics, rates updation and constraint limits are uncertainties which are controlled by applying Multirate MPC scheme [93].

Adaptive Logic Controller (ALC) manages the flow of energy in the solar systems, smart grids, storage devices and consumer's load. This approach also takes care of weather conditions and balances power flow. ALC has learning ability and can develop own controlling and optimization algorithms for energy demands, pricing signals, resources availability and loading timings etc. [94]. Fig. 14 presents a typical block diagram of ALC.

The integrated control systems are employed for forecasting, estimation and solar system heliostat calibration. Supervisory Control and Data Acquisition (SCADA) is a type of Process Control System (PCS) which is capable of gathering, analyzing and monitoring information in a smart grid system. PCSs are comprised of Remote Terminal Unit (RTU) and Programmable Logic Controller (PLC) integrated with sensors and actuators [95].

4.2. Optimization approaches for smart grid

The smart grid is considered a complex system and the sub components in a smart grid are defined by certain criteria: homogenous components, interacting elements, intelligent or common interest features. The single optimization algorithm can be applied for a

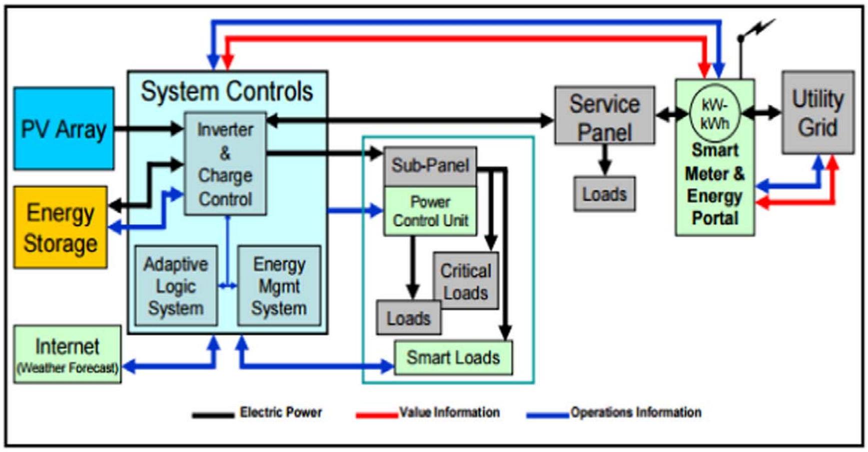

Fig. 14. Adaptive Logic Controller [94].

residential area which requires certain amount of electricity having same characteristics. Local optima are employed in sub components of smart grids which guarantee transparency and anonymity. Thus global optimum is also ensured because of this self-regulation. Optimization of smart grid is challenging task even if computer models are used. The classical and game theoretical methods are usually utilized for achieving optimization ensuring flexibility and scalability [96]. The optimized solutions for smart grid systems are described as follows:

Distributed Generation: The central optimization is very costly in terms of memory and time therefore optimization is carried out in a distributed manner at all grid levels.

Home Automation: Home automation is also beneficial and it also fulfils consumer's needs. Smart devices in home automation thus reduce the overall energy consumption.

Energy Storage Device: The optimized mechanisms are employed combined with energy storage devices in all grid activities. This results in regulating energy consumption and reduces the peak loads.

Transmission & Distribution Losses: The optimized local and global algorithms reduce the transmission and distribution (T & D) losses and routing errors are corrected.

Intelligent Price Control: The electricity unit prices are varied according to the consumer's new needs. The intelligent price control regulates per unit electricity rate. Per unit rate is high at peak hours and rate is less at low demand hours.

Heuristic optimization is a modern technique utilized for complex systems. It offers flexibility and robustness. The development time is shorter as compared to classical approaches. The missing data information is considered uncertainty and this optimization approach is also insensitive to noise. Heuristic optimization methods are employed for analyzing forecasting energy demands, weather conditions, per unit cost, control and system planning, lost data, storage systems and energy demand response [97].

Smart grid optimization is dependent upon estimating network's state. The real time information is gathered from Advanced Metering Infrastructure (AMI) and two sided communication. The Distributed Generation (DG) which includes fuel cells, turbines, renewable sources is optimized for grid enforcement. The benefits include reducing power loss, load factor improvements, system upgrades elimination, system integration, efficiency and reliability improvements. The objectives of DG optimization comprise reduction in active power losses, enhancing capacity and load minimization. The DG optimization is ensured using Voltage control, Feeder configuration and Phase balancing [98].

The transmission optimization is also vital as transmission network is huge even crossing international borders. The failure in any region may cause the breakdown of entire network. The control equipment for ensuring computation of power flow on milliseconds level is required. Jacobian-free Network-Krylov (JFNK) methods are proposed for solving grid algebraic system equations. Parallel computing schemes are also employed using multilevel approaches. The faster flow solver results in faster calculations, quick decision making, restoration and faults diagnosis [98].

The Least square estimation method is used for unconstraint nonlinear optimization problems. Many approaches including Trust Region, Quasi-Newton, Newton-Raphson, Conjugate gradient, Levenberg-Marquardt (LM) and double dogleg are utilized for system grid optimization [98].

The voltage optimization is effective for increasing efficiency. Its advantages include demand reduction (1.5–2%), energy reduction (1.3–2%), cost effectiveness for already existing devices and short implementation schedule. This scheme also ensures early prediction of voltage regulation and voltage quality issues [88]. The voltage optimization schemes such as DMS based Volt-VAR and Auto adaptive Volt-VAR optimization are also applied in smart grid systems.

The market-clearing optimization approach is utilized for obtaining reliable and effective cost function depending upon various system constraints. The network losses and reduced line capacity are major constraints present in grid systems [99]. The end-use optimization is used for load forecasting (substation, feeder, section) levels and handling demand management issues.

4.3. Power generation, storage, management and automation techniques

A review of new techniques for generation of renewable energy is reported in [100], which discusses Approximate Dynamic Programming (ADP) and others strategies that find potential in automation and control of next generation smart grids. Werbos et al. [101] have further investigated the skills required for management of mathematical system parameters. The intelligent control development for distributed energy and storage capability of smart grid systems is discussed and implemented in [102]. It also relates the development work with the required demands of the market.

Blaabjerg et al. [6] have investigated the trends occurring in power electronics fields and control of renewable energy systems. Many control design strategies have been investigated and implemented for DG in context of Distribution System Automation (DSA). With invention of new Intelligent Electronic Devices (IEDs), it is easier to replace faulty equipment and also process large amount of data with high speed. DSA offers these services by utilizing communication protocols and advances in IED technologies [103]. DG plays an important role from energy generation to energy conversion and is mainly used for smoothing load requirements. With increase in energy consumption and energy demands, Green House Gases (GHG) emission needs to be reduced [104–107]. Another DSM refers to development plans for ensuring decrease in energy consumption. It also accounts for keeping balance of supply and demands of electricity [108].

The performance of the system can be enhanced using advanced electronic systems. Photo Voltaic (PV) systems are also an important choice in developing smart grid systems with their topology and modulation determining behavior of the system [6]. PV systems and Concentrated Photo Voltaic (CPV) are very efficient and provide high electric voltage and thermal energy [109]. Associated problems include voltage changes, frequency fluctuations and power quality issues [110]. DC/DC converters are also mounted for power factor boost and they also result in lowering efficiency because of high duty cycle [111]. Al Saffar et al. [112] have proposed techniques to reduce switch stresses. To maximize profit and efficiency, electronic circuits sizing is also carried out for finding suitable circuits and inverters which are suitable for operation in smart grids [113]. AC power generation, stability and synchronization issues have been discussed in [114] that reviews renewable integrated technology techniques to resolve these issues.

For maintaining a uniform and fixed load, biomass generators are an important choice for smart grids [115]. Diesel generators for wind turbines are proven to be reliable and efficient source for reducing fuel costs [116]. Molina et al. in [82] have described the integration techniques for wind turbines using Permanent Magnet Synchronous Generator (PMSG).

4.4. Control of overloads in smart grid

Over the years, the load on the grids has reached its limit due to immense increase in demand. The overload scenario occurs when demand supply is more than the generated power of the smart grid. In such situation, Battery Energy Storage Systems (BESS) plays a vital role for sustaining constant electric supply. The effective utilization of BESS is responsibility of Energy Management System (EMS) [117], which results in giving more back up time in case a smart grid is overloaded. Each battery bank of BESS works as a separate parallel string [118]. EMS charges BESS backup batteries at a faster rate using shorter cycles at low State Of Charge (SOC). This quick charging technique results in enhancing battery current rate and BESS batteries are fully charged in normal operating conditions of the smart grid. For maintaining effective usage of BMS systems, Ah balancing is very crucial step for determining SOC. The balancing technique for overload control of smart grids considering different variable losses and timings have been proposed by Duryea et al. in [119]. Wade et al. have conducted the experiments to prove validity and effectiveness of the BESS storage system by maintaining voltage and power flow for 11 kV system in Great Britain [120].

The abrupt changes in the load and generation of smart grids results in oscillations due to uneven behavior. For overcoming oscillations produced in the grid system, voltage and phase control is required, which is achieved by controlling the inverter switches [19]. By exploiting useful features of fuel cells, these oscillations can also be reduced for mitigating changes in load and power generation in smart grids [121]. The overloaded condition can also be resolved by Building Integrated Photovoltaic (BIPV) systems where PV acts as a power producing source [122]. The control of wind turbine in overloaded conditions is suggested by Chen et al. [123] by using Islanding control architecture. Garcia and Houpis have thoroughly reviewed various strategies of wind energy systems from control engineering design perspective [124].

4.5. Development of operational schedule of sources and loads

Demand Management System (DMS) regulates and optimizes the voltage and power generated in the smart grid system. DMS also ensures minimum losses and keeps track of BESS system. DR calculates and manages the available power in the grid system and electric power required by the consumers [41]. A DR program has been successfully implied on 33 smart grids for scheduling solar and geothermal power sources in Queensland Australia for shifting loads of peak hours by using economical load model and price control [125]. Another DR program using load profile improvement has also been tested on Iranian smart grids [126]. This technique saved power by reducing peak loads by up to 8% and increased overall DR by 40% [127]. For stability of smart grid systems, DMS programs are of three types [19]; Environment based, Network based and Economic/market based.

Researchers at Independent System Operator-New England (ISO-NE) have successfully implemented two types of DR programs; Price Response Program (PRP) and Real Time Demand Response Program (RTDRP). In PRP, consumers are able to control energy consumption on hourly basis tariff. In RTDP, internet based technology is used to gather online meter data which can be used for DR programming [128]. New York ISO (NYISO) has four different types of DR; Day Ahead Demand Response Program (DADRP), Energy Demand Response Program (EDRP), Demand Side Ancillary Service Program (DSASP) and Installed Capacity (ICAP) Special Case Resource (SCR). These all DRs provide feasible, effective and cheap solutions to the energy scheduling problems [19].

The scheduling of power generation problem is sorted out by dividing it in sub-problems and developing Lagrangian functions [129]. Multi Agent System (MAS) is also suggested for scheduling of energy sources using Artificial Intelligence (AI) [130,131]. MAS method is developed considering mathematical tools, DRES and lumped loads as shown in Fig. 15. Various advantages including fulfilling, exporting and rescheduling of energy demands are offered

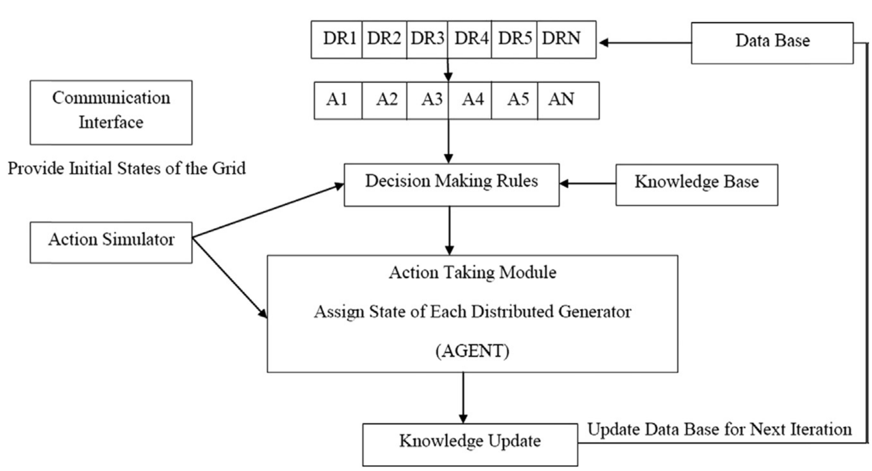

Fig. 15. Energy scheduling based on muti-agent system [19].

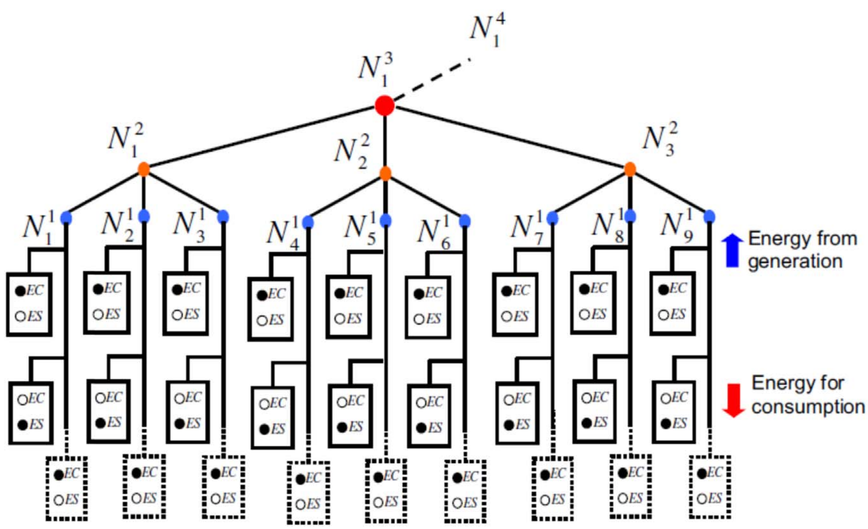

Fig. 16. Smart grid energy flow networks for scheduling [140].

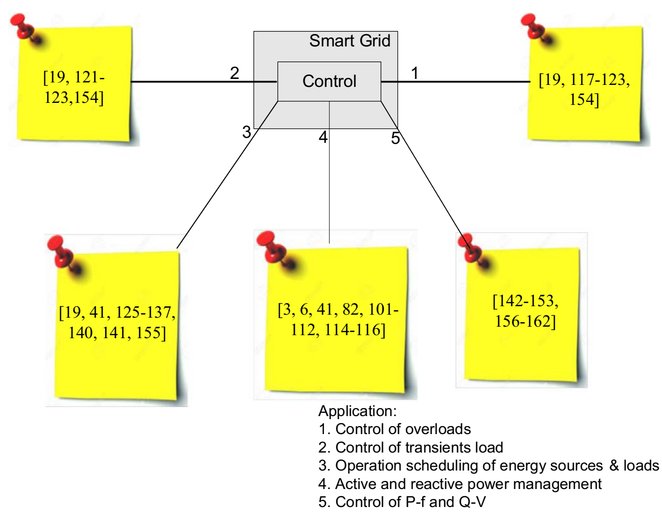

Fig. 17. Overview of research trends in applications of control systems in smart grid [154,156–162].

by MAS method [19]. For enhancing control and generated power in smart grids, cloud computing is also applied by Jin et al. [132], which uses Cyber Physical System (CPS) to efficiently control power and communication systems. DSM can be accomplished based on game theory [133], where energy consumers act as a game player and their strategies play a role as usage of energy. The power company can set the tariff rates for different timings by watching the trends and strategies of the consumers [133].

Artificial Neural Network (ANN) is also being investigated for predicting energy generation for day ahead scheduling [134]. This prediction is very useful for DSM and plays an important role for easing energy scheduling tasks. An intelligent decision support structure system has been proposed by Guan et al. in [135] for generated power dispatching. This dispatching process comprises of decision making and security of the control systems. Planas et al. have presented a centralized scheme based on hierarchical control [136]. Applicable on grid, field and management levels, the scheme ensures importing and exporting of real and reactive power. The variations in frequency, voltage fluctuations and amplitude restoration problems are also controlled for isolating and connected grids as well. The decentralized control scheme for shifting loads has been implemented by Ahn et al. [137]. Load is managed by coordinating power generation and charging system patterned through optimization solutions based on linear programming. A priority based scheduling mechanism has been suggested by Liu et al. [138]. In this scheme, a weighted function is used for load reassignment. Depending upon load conditions, weights are assigned as per priority values. Smart meters are used to collect real time data from consumers and cost function is assigned for priority control scheme.

A multi-layer optimization control scheme is proposed by Taft et al. [139] for Cisco systems, in which scheduling problem is divided in two groups; master (global solution) and sub (local solution). The local solutions are controlled by main master solution. A tree like User Modified Network (UMN) is suggested in [140] for depicting Energy Supply (ES) and Energy Consumer (EC) pattern as shown in Fig. 16. Fuzzy logic based adaptive algorithm is proposed in [141] with a focus on reduction in CO_2, heat losses and fuel consumption achieved by a Non-Dominated Sorting Genetic Algorithm II (NSGA-II). For multi operation management other algorithms like Adaptive Modified PSO (AMPSO) and Chaotic Local Search (CLS) are suggested for finding out best solution for the energy and load scheduling issues.

4.6. Control of Active power v/s frequency (P-f) and Reactive power v/s voltage (Q-V) in smart grids

With advances in renewable energy technology applications, such as PV, wind turbines, fuel cells etc, the power sharing in the smart grid systems is actively being researched [142]. For power sharing, two techniques are commonly used to overcome the problems arising from sharing operations namely *P-f* droop control and *Q-V* droop control [143]. These droop control methods are utilized for balancing active and reactive power which in turn regulates voltage and frequency amplitude [144]. The droop control techniques give an autonomy to smart grid as additional DGs can be added or removed from the grid system without interrupting other operations of the grid [144].

Many droop control techniques and their variants are reported in the literature. Wang et al. have proposed a *Q-V* droop control mechanism [144] based on fuzzy logic and reciprocal characteristics. In comparison with conventional droop techniques, fuzzy logic based approach improves the stability of the grid. However, the deterioration occurs because of dependence of reactive power on line impedance. To overcome such issues, an improved *Q-V* has been proposed by Lee et al. [145]. The droop control results in improving reactive power sharing among parallel connected inverters. The multi agent consensus based reactive control techniques have also been considered in research [146–148]. Bolognani et al. [149] have explored the distribution control strategies for reactive power compensation. Etemadi et al. [150,151] have developed the robust control and power management strategies for reactive power. The stability issues of *P-f* has been studied in [152] using consensus based control design techniques. Voltage control and optimization issues have been thoroughly explored in Uluski et al. [88] by proposing an auto-adaptive approach for overcoming active and reactive power sharing. Vornaus et al. [153] have proposed the distributed voltage control schemes for active and reactive power. With an investigation on stability and control aspects, they have improved the existing conventional techniques.

A concise look on the reported literature illustrating research trends in various control applications in smart grid is presented in Fig. 17.

4.7. Reported system and technologies used in smart grids

Numerous technologies are playing an important role for successful control and automation of smart grids. These technologies help smart grid designers to have a cost effective solution and also enable consumers to participate in the grid system operations [3]. The technologies are related with one or more components of the overall smart grid system shown in Fig. 18. Most important technologies are mentioned briefly.

Automatic Voltage Regulators (AVR): AVR find applications to control, manage and interface various entities of the system to counter effects of disturbances. Generators are also dependent on AVRs and govern their smooth and disturbance free operation. AVR keeps the voltage constant by adjusting generator field and its reactive power.

Energy Management Systems (EMS): EMS ensures safe and secure operating points to achieve Supervisory Control And Data Acquisition (SCADA). EMSs help in adjusting control consumption, storage and generation of electricity and vehicle charging. Energy management is considered as a large scale optimization problem and is still implemented in many commercial and industrial sectors. The power sector has many uncertainties including consumer preferences, pricing, generated power and distributed power. Smart grid systems and devices are ensured to behave optimally under these uncertainties and challenges [3].

Automatic Generator Control (AGC): AGC employs closed loop control and rescheduling of set points to cope frequency variations and tie-line flow requirements [3]. AGC matches the area matching between generation and load i.e. to control system frequency and matching tie-line interchanged with the current schedule. It also changes load distribution among various generators present in a smart grid [164].

Advanced Metering Infrastructure (AMI): AMI is usually implemented for two-way meters/utility communication. AMI offers various benefits such as lowering cost of data gathering, permitting disconnection/re-connection of consumers, managing load control, save theft of energy, monitoring quality of power and its usage. AMI increases the efficiency and also results in reduction of losses. Fortum's intelligent system ensures management of electrical consumption using AMI devices for gathering and analysis of data. Vattenfall's ‘automatic household electricity consumption metering system’ also remotely measures consumer data. AMI based methods and techniques have been thoroughly reviewed in [165].

Meter Data Management (MDM): MDM ensures automation of real time processes and sharing of data within key business applications thus resulting in effective and efficient operations. It improves decision making process easy for the enterprises. MDM helps in handling large volume of data and is being successfully used by large companies.

Distribution Management System (DMS): DMS system is used for modeling distribution areas and prediction of transmission, power generation, power outage, variation of voltage/frequency etc. In return cost is reduced and existing resources can be better utilized. DMS offer different rate options and gives solutions to various problems in renewable energy generation. It also manages change stations. As an example, Elektra's DMS provides solutions for improving service quality using advanced devices which ensures management and control of data.

Demand Side Management (DSM): DSM is used for providing energy control to the consumer's side of the meter. DSM programs help efficient use of system resources without installation of new transmission and generation structures. These programs offer efficient energy conservation, response demand management and load management issues. DSM also provide reduction and shifting in consumption of energy [166–168].

Geographical Information System (GIS): GIS is used for management of infrastructure, modeling and integration of data onto graphical maps. Its usage results in simplification in planning, analysis and lowering the response time. Smart grid accepts lot of data from different applications such as AMI, renewable energy, SCADA, asset management, weather etc. GIS visualization is an important solution for converting this huge amount of data [169].

Outage Management System (OMS): OMS provides solutions for restoration of energy. They also minimize manual reporting and provide automatic solution for reported problems. The previous outage data is analyzed which can identify the improvements. OMS also

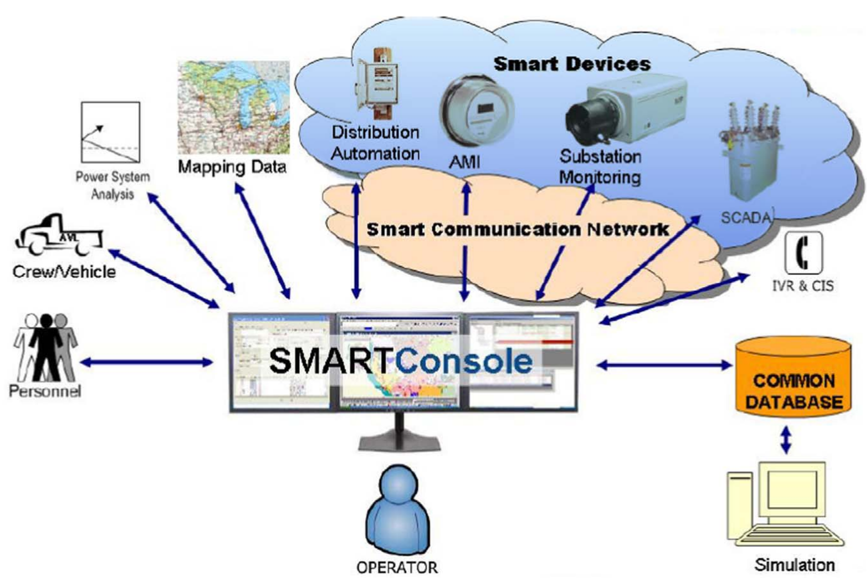

Fig. 18. Smart Grid technologies [163].

Table 1
Literature at a glance – Advances in control and automation of smart grid.

Technique	Ref.	Year	Author (s)	Affiliation	Salient features
AVR	[171]	2014	Ting-Chia et al.	Inst. of Nuclear Energy Research, Taoyuan, Taiwan etc.	1. Hybrid algorithm for AVR. 2. For controlling power, Fuzzy logic SMC is used. 3. Stable power generation is achieved by Recurrent Radial Base Function Network (RRBFN).
	[172]	2010	Morris et al.	Deptt. of Energy, Milan, Italy etc.	1. AVR control based on sensitivity theory. 2. Ensures distributed voltage regulation. 3. Follows topological approach.
EMS	[117]	2012	Rahman et al.	Center of Research Excellence in Renewable Energy, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia.	1. For effective operation of BMS. 2. For charging backup batteries speedily.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. EMS ensures reduction in uncertainties and challenges in smart grids.
	[120]	2010	Wade et al.	School of Engineering and Computing Sciences, Durham University, UK etc.	1. Validity and effectiveness of BESS system for 11 kV systems.
	[118]	2007	Kaiser et al.	Fraunhofer-Inst. for Solar Energy Systems, Freiburg, Germany.	1. Charging of BESS speeded up by using shorter cycles at low SOC. 2. More backup time for overloaded conditions.
	[119]	2001	Duryea et al.	Western Power Corp., Jandakot, Western Australia etc.	1. Losses reduction by using Ah balancing control technique. 2. Effective usage of BMS system.
AGC	[172]	2014	Siddharth et al.	Deptt. of Electrical and Computer Engineering, Iowa State Univ., Ames, US.	1. Study the impact of data integrity on AGC. 2. Smart attack detection and mitigation. 3. Attack detection algorithm through simulation.
	[164]	2012	Ali et al.	Deptt. of Electrical Engineering, Ohio State University (OSU), Columbus, US.	1. New AGC structure for tackling intermittency in smart grids. 2. Control of high frequency load fluctuations.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Reduction in uncertainties and challenges in smart grids. 2. Ensuring constant value of frequency and tie-line flows.
AMI	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Lowering cost of data gathering. 2. Managing load control. 3. Theft control of energy. 4. Disconnection/re-connection of consumers.
	[155]	2011	EIA/SAIC	US Deptt. of Energy, Washington DC.	1. Data for AMI legislation and regulation. 2. Adapted AMI plans and requirements. 3. Dynamic pricing using AMI.
	[165]	2010	TFCC Inc.	Twenty First Century Communications Columbus, Ohio, US.	1. AMI/Smart grid communication issues discussed. 2. Lowering cost and improving customer service using AMI communication. 3. Tips for implementing successful AMI/Smart grid communication.
MDM	[173]	2013	Zheng Qin	Washington Univ. in St. Louis,	1. MDM for networking issues 2. Wide area, Local area, Home area and Multimedia technologies
	[174]	2012	Jesika et al.	MaRS Market Intelligence, Toronto, Canada etc.	1. Market impact of MDM data. 2. Balancing energy generated and demand issues. 3. Giving control to consumers for effective solution.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Automation of real time processes. 2. Sharing of data within key businesses and application.
	[175]	2009	Sharelynn Moore	Itron Inc., Washington, US etc.	1. Market impact 2. Maximizing investment.
DMS	[176]	2013	John Dirkman	Schneider Electric, France	1. DMS is built on precise and up to date information of network infrastructure. 2. Small corrections in smart grid model with DMS.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Prediction of power generation and transmission. 2. Cost reduction. 3. Provision of different rate options.
DSM	[166]	2012	Thillainathan et al.	National Univ. of Singapore (NUS), Singapore	1. DSM using heuristic optimization.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Management of Infrastructure. 2. Modeling and integration of data.
	[133]	2010	Amir et al.	Univ. of British Columbia (UBC), Canada	1. DSM based on game theory energy consumption.
GIS	[176]	2013	John Dirkman	Schneider Electric, France	1. Improved quality and timeliness of GIS. 2. Modeling connectivity for demand management. 3. Reduction in data duplication. 4. Database management.
	[169]	2012	Dao Viet Nga et al.	Deptt. of Electronics and Communication Engineering, Univ.	1. GIS for buffer special analysis.

(continued on next page)

Table 1 *(continued)*

Technique	Ref.	Year	Author (s)	Affiliation	Salient features
				Tenaga Nasional Selangor Darul Ehsan, Malaysia	2. GIS for Google earth display.
	[177]	2012	Schneider Electric	Schneider Electric, France	1. Effective smart grid strategies based on GIS. 2. GIS based model for maintaining data accuracy of network model. 3. Reduced design time and backlog. 4. Efficient workflow. 5. Accurate availability of network information.
	[178]	2009	Esri Inc	Esri Inc., California, US	1. Role of enterprise GIS in smart grid. 2. Utility challenges.
OMS	[176]	2013	John Dirkman	Schneider Electric, France	1. OMS for normal operations and emergencies. 2. OMS for better decision support and workflow. 3. Prediction roadmap.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Restoration of energy. 2. Automatic solutions for reporting problems.
	[163]	2007	Intergraph Corp.	Intergraph Corp., Madison, US	1. OMS for operational benefits. 2. Network control supported. 3. Integration of OMS with other technologies.
WAMS	[179]	2013	Lee-Cheun Hau et al.	Faculty of Engineering and Science, Univ. Tunku Abdul Rahman, Kuala Lumpur, Malaysia	1. Literature survey for WAMS techniques. 2. Ensuring network reliability before implementation of WAMS schemes. 3. Prediction, diagnosis and recovery methods.
	[180]	2013	M. Junaid et al.	Univ. of Engineering and Tech., Peshawar, Pakistan.	1. WAMS for transmission line through GSM.
	[3]	2011	Eduardo et al.	Univ. of Sevilla, Spain etc.	1. Ensuring accuracy and synchronization. 2. PMU for precise measuring. 3. Disturbance analyses.
	[181]	2010	Wang et al.	Chongqing Univ., China	1. Reliability analyses for WAMS. 2. WAMS evaluated on IEEE 14-bus system.
	[182]	2010	M. Vaiman	V & R Energy Syst. Res., Inc., Los Angeles, US	1. Region of Stability Existence (ROSE) for WAMS. 2. Implemented ROSE on ISO NE transmission network.
BESS	[117]	2012	Rahman et al.	Center of Research Excellence in Renewable Energy, King Fahd Univ. of Petroleum & Minerals, Dhahran, Saudi Arabia.	1. Effective utilization of BESS. 2. More backup time for overloaded condition.
	[120]	2010	Wade et al.	School of Engineering and Computing Sciences, Durham Univ., UK etc.	1. Validity and effectiveness of BESS system for 11 kV systems.
	[118]	2007	Kaiser et al.	Fraunhofer-Institute for Solar Energy Systems, Freiburg, Germany.	1. BESS working as a parallel string. 2. Speeding up of charging process for BESS.
	[119]	2001	Duryea et al.	Western Power Corp., Jandakot, Western Australia etc.	1. Ah balancing control technique.

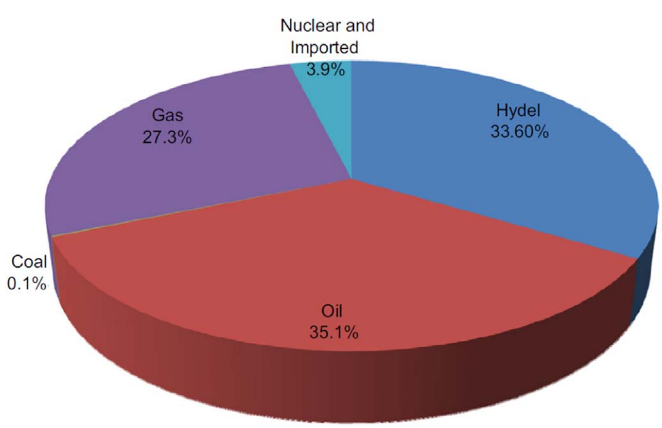

Fig. 19. Electricity mix of Pakistan [185].

addresses issues of regulation and provides better response times.

Wide Area Management System (WAMS): WAMS is implemented in high voltage power grids to ensure accuracy and synchronization. WAMS, through PMUs provide precise and time stamped measurements. These systems also provide disturbance analysis, verification of Flexible AC Transmission Systems (FACTS) control and systematic validation of dynamics models.

Battery Energy Storage Systems (BESS): BESS employs electrical and mechanical storage systems and is used to enhance efficiency and performance. The batteries must have good charge/discharge cycle and should take minimum amount of time for charging [170].

There is rapid growth with many in progress projects to propose better solutions for implementation of smart grids. Table 1 presents reported systems and technologies used in smart grid.

5. Smart grids in Pakistani perspective

Modern energy services are indices for economic and social development of any country. Pakistan is facing huge energy deficits since the primary energy supplies are unable to cope up with energy demand. This has resulted in a huge population of the country deprived of electricity. Existing infrastructure mainly depends on hydro-electric power generation since availability of fossil fuel particularly oil is neither locally sufficient not can be imported on a wider scale due to economic and energy security constraints. Now, it has been growing realization that the development model of the country cannot rely on oil since this source will not last too long keeping in view the exponential rise in energy consumption [183]. Fig. 19 depicts the contribution of different energy production method currently available in Pakistan. As a viable long-term solution to energy crisis problem, Pakistan needs to exploit its inherent resources like solar, hydropower and wind. Immediate actions are needed to bring energy shortage down in future. This will require fundamental knowledge and technical expertise to efficiently utilize these affordable and clean energy resources to produce electricity. Furthermore, smart grids can be introduced to overcome these challenges and to minimize Transmission and Distribution (T & D) losses [184].

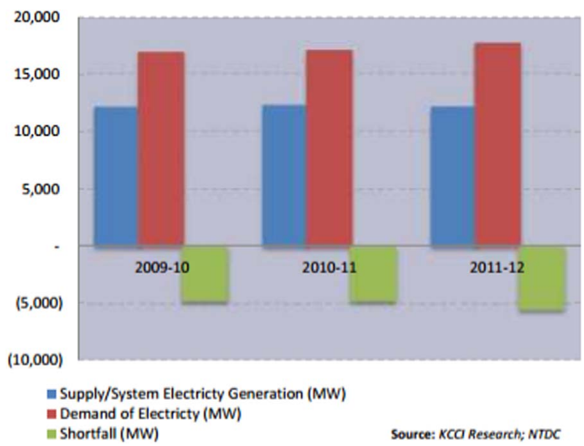

Fig. 20. Electricity generation, demand and shortfall in Pakistan [186].

Pakistan energy crises has arisen up from last several years and this issue gets worsened every year in summer season when demand exceeds the generated supply by more than 8000 MW. The actual generation is far below than the actual capacity due to circular debts, line distribution losses and power plants inefficiencies [186]. Fig. 20 presents the yearly basis profile of electricity in the country while trend of installed energy capacity is highlighted in Fig. 21.

National Electric Power Regulation Authority (NEPRA) has approved reverse or net metering regulation and tariff guidelines 2015 for surplus electricity generated by consumers through solar panels and wind turbines. In this case, a special meter having capability of recording both in and out flow of electricity is provided. The consumer will be billed for the net electricity usage. After implementation of net metering, the commercial and domestic users are encouraged to install their wind turbines and solar power systems. This scheme is anticipated to improve over all electricity crisis [187].

Table 2 shows the overview of renewable energy projects in Pakistan with their recent status.

5.1. Institutional infrastructure of Pakistan

One of the main tasks of WAPDA is to ensure generation and supply of uninterrupted power supply to all consumers. Besides, there are around 20 independent power production houses that contribute significantly in electricity generation in Pakistan [189]. Essentially, the balance between demand and supply of electricity is vital to guarantee uninterrupted power supply. Increasing demand of electricity in Pakistan is only possible with alternative energy recourses. To excel in this domain of primary importance, Govt. of Pakistan established two institutions namely Pakistan Council for Renewable Energy Technologies (PCRET) and Alternative Energy Development Board (AEDB) in 2001 and 2003 respectively. PCRET was aimed at strengthening the linkages between private sector and customer for promotion of renewable energy in the country. AEDB acts as the central national institution with the primary objective of facilitating and encouraging developments of renewable energy in Pakistan so as to achieve 10% target of renewable energy proportion by 2015.

5.2. Wind energy potential in Pakistan

The last decade of 20th century witnessed doubling of worldwide wind capacity in every 3 years. The generation cost of electricity from wind sources has reduced since early 1980 by a factor of 1/6. These trends are anticipated to be continued making wind as one of the main renewable energy technologies around the globe [190]. Pakistan has 346 GW potential of wind energy [191]. The topography of coastal areas in Pakistan mostly lie in the region's trade wind corridor [184]. Most of wind energy resources are in provinces of Baluchistan and Sindh. Cities of Gawadar and Pasni in Baluchistan and Hyderabad in Sindh have wind speeds ranging from 6.9m/s to 7.4 m/s. Various preliminary comparative studies [192,193] apparently show that the wind potential is not uniformly distributed along the coastal belt of Pakistan. Fig. 22 highlights the potential areas on the costal belt of Pakistan which can be used for wind energy production. Regardless of the country's potential, the infrastructure to significantly generate electricity from wind energy is practically non-existent at the moment.

Wind energy sector has now gained much attention in Pakistan and major hurdles in realization of wind power projects have been overcomed. The generation licenses have been issued to numerous companies including Green Power Ltd., New Park Energy Ltd., Tenage Generasi Ltd., Zephyr Power Ltd., Dawood Ltd., Zorlu Enerji Pakistan Ltd., Arabian Sea Wind Energy Ltd. and Milergo Pakistan Ltd.

5.3. Solar energy potential in Pakistan

Among all the renewable technologies that exist for large-scale power production, solar thermal technology is perhaps the best option to make significant contributions of clean energy because of its use of relatively conventional technology and ease of scale-up. To date, major solar thermal technologies include solar parabolic trough, solar power tower, linear fresnel systems, solar dish-engine and zero to low concentration low temperature solar thermal systems [195].

Pakistan is gifted with higher solar insolation compared to most countries of the world. The Energy Information Administration (EIA) describes the daily solar energy potential for Pakistan as 5.3 KWh/m^2 (1.93 MWh/m^2 annually), which depicts a great potential in solar resource for the country [191]. Being existent on 'solar belt', Pakistan has massive solar resources to be exploited for applications involving Photovoltaic (PV) as well as Concentrated Solar Power (CSP). Fig. 23 illustrates annual solar radiation map of the country. The mean global

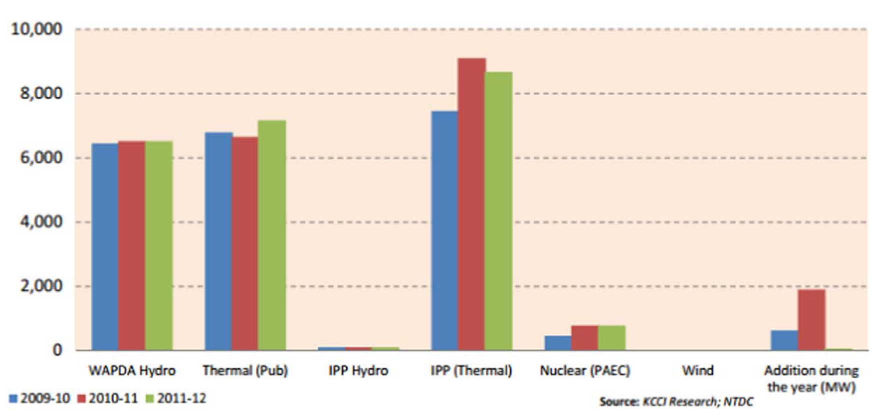

Fig. 21. Trends of installed energy capacity in Pakistan (in MW) [186].

Table 2
Renewable energy projects in Pakistan [188].

S. No.	Resource	Company Name	Type / Location	Capacity (MW)	Status
1.	Solar	M/s Appolo Solar Development Pakistan Ltd.	Quaid-e-Azam Park, Bahawalpur, Punjab	100	Completed on 6th Nov. 2015
2.		M/s Quaid-e-Azam Solar Power (Pvt.) Ltd.	Quaid-e-Azam Park, Bahawalpur, Punjab	100	Completed on 13th Nov. 2015
3.		M/s Best Green Energy Pakistan (Pvt.) Ltd.	Quaid-e-Azam Park, Bahawalpur, Punjab	100	Construction in process
4.	Wind	M/S Sachel Energy Development (Pvt.) Ltd.	Jhimpir, Sindh	50	Completed on 17th Dec. 2015
5.		Zorlu Sindh Wind Farm, Yunus Jhampir Wind Farm and Fauji Jamphir II Wind Farm	Gharo and Jhimpir, Sindh	156	Financial closure
6.		Fauji Kuttikun I and II Wind Farm	Kuttikun, Sindh	100	Financial closure
7.		AES Sindh Wind Metro Gharo Wind Farm	Gharo Corridor in Thatta, Sindh	100	In pipeline
8.		Gul Ahmed Sindh MasterWind Sindh Sapphire Jhampir Wind Farm	Jhampir, Sindh	150	In pipeline
9.	Biomass	M/s JDW Sugar Mills Ltd. (Unit III)	District Ghorki, Sindh	26	Completed on 25th April 2014
10.		M/s Chiniot Power Ltd.	Chiniot, Punjab	62.5	Completed
11.		SSJD Sindh Biomass Plant	Hyderabad, Sindh	12	Financial closure
12.		M/s JDW Sugar Mills Ltd. (Unit II)	District R.Y. Khan, Punjab	26.35	Completed on 25th April 2014
13.	Hydro	K-Water Star Patrind HPP	Jhelum river, AJK	147	Financial closure
14.		White Chrystal Suki Kinari HPP	Kunshar River, Kaghan Valley, Mansehra, KPK	840	In pipeline
15.		Yunus Asrit-Kedam HPP	Swat River Kalam, KPK	215	In pipeline
16.		Mira Gulpur Hydropower Plant and Mira Kotli HPP	Poonch River, Kotli, AJK	200	In pipeline

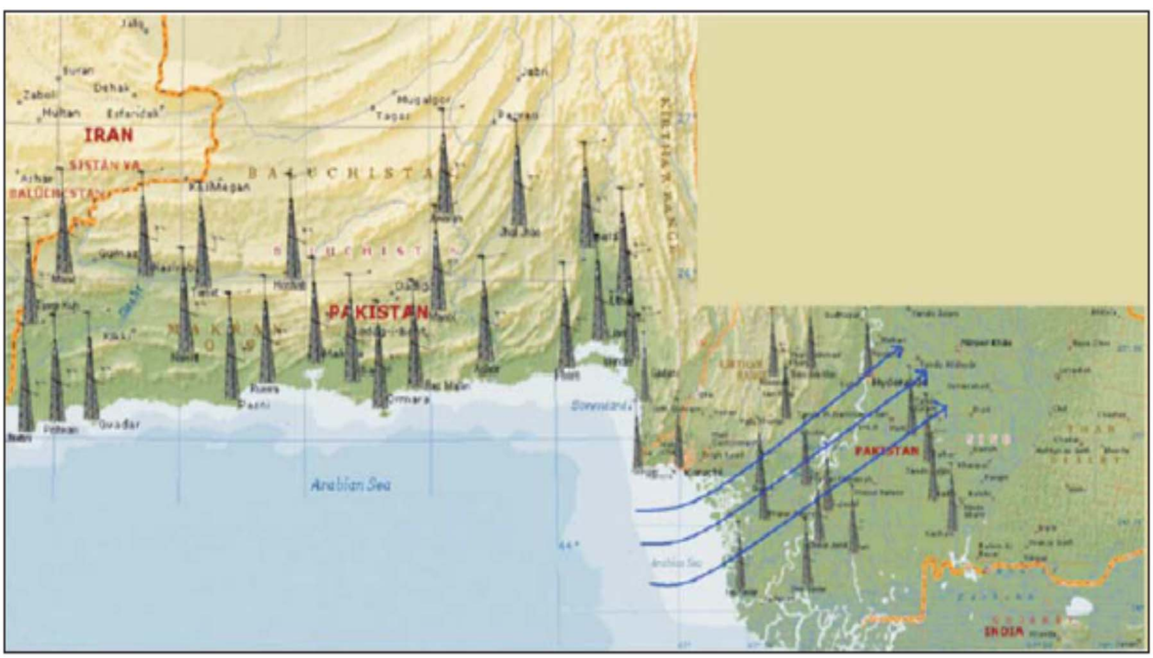

Fig. 22. Wind meteorology masts installed by Pakistan Meteorological Department (PMD) [194].

irradiation falling on horizontal surface in Pakistan is about 200–250 W/m^2 per day with about 1500–3000 sunlight hours in a year [196]. As per available statistics, the south-western province of Baluchistan receives the largest solar energy with an average daily global insulation of 19–20 MJ/m^2 a day with annual mean sunshine duration of 8-8.5hrs. Such conditions are ideal for PV and other solar energy applications [197] to generate electricity particularly for off-grid localities in northern mountainous zones as well as in western and southern deserts.

AEDB has initiated another program to provide solar power electricity for the development of rural areas. In the first phase, solar systems are planned to be set up in 100 and 400 villages of Sindh and Baluchistan respectively. In Sindh, 3000 solar home systems have already been installed [198].

5.4. Renewable energy and smart grid: ultimate solutions to national energy crisis

While Pakistan's strategic policy makers have long been realized the benefits offered by exploiting potential of renewable energy, suitable priority to promote and develop these small-scale setups has not been unfortunately given. Hurdles to adopt and establish renewable energy culture on a national level are related with institutional, fiscal, regulatory and technical expertise issues. These barriers have ultimately led to the present energy crisis in the country, which finally urged the government circles to awake in order to improve socio-economic circumstances of public. The need of the hour is to improve national infrastructure along with technological uplifts of R & D and productions setups. Public should be convinced and educated with practical demonstration to develop pilot scale setups. The government

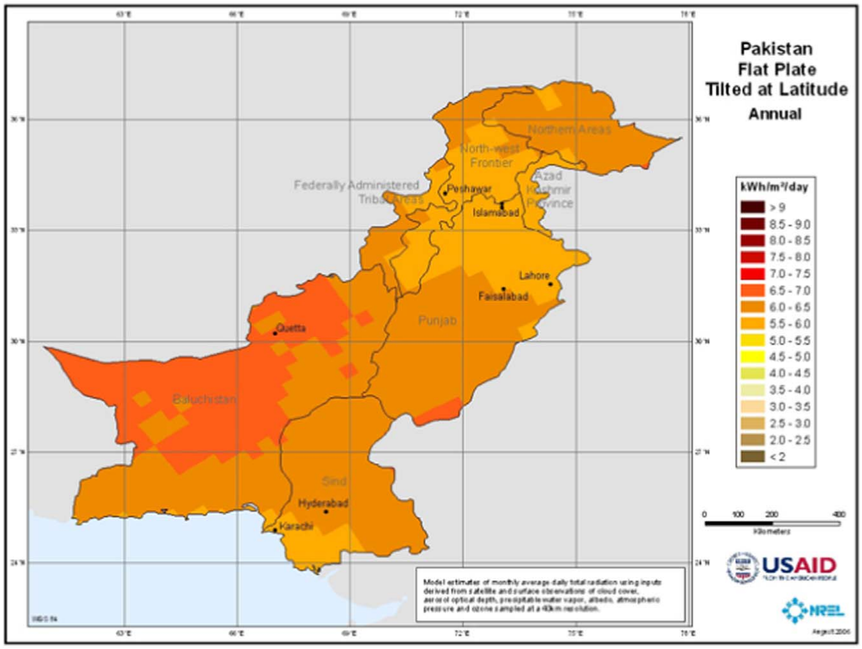

Fig. 23. Pakistan flat plate tilted at latitude annual solar radiation [199].

Table 3
Energy integration plan for on-grid applications [200].

Resource	For 2018 [in MW]	For 2025 [in MW]
Wind	1750	3500
Small Hydel	180	500
Solar PV	1000	2000
Biomass/Waste to energy	800	1500
Total	3730	7500

Table 4
Energy integration plan for off-grid applications [200].

Energy Appliances	Quantity for 2018	Quantity for 2025
Solar Home Systems	16,000	26,900
Solar Water Heaters	30,000	84,000
Solar Pumps	2320	8520
Heat Pumps	1295	5545
Solar Street Lights	4700	14,800

Table 5
Total grid stations and Grid lines in Pakistan [201].

Grid station capacity (KV)	Number of grid stations	Length of gridlines (km)
500	13	5077
220	37	7359
133	Information not available	23,994
66		9169

should provide financial assistance to support development and deployment of renewable energy resources. Legislation and policies are needed to promote and establish alternate energy setups, to generate electricity from them and finally to integrate these setups with smart grid. Incorporating recommendations of World Energy Council (WEC) [196] into national policy will help in formulation of long term strategies. Transformation of traditional grid to smart grid will certainly boost commercial and industrial ventures in these recent technologies. This transformation can be achieved by updating the

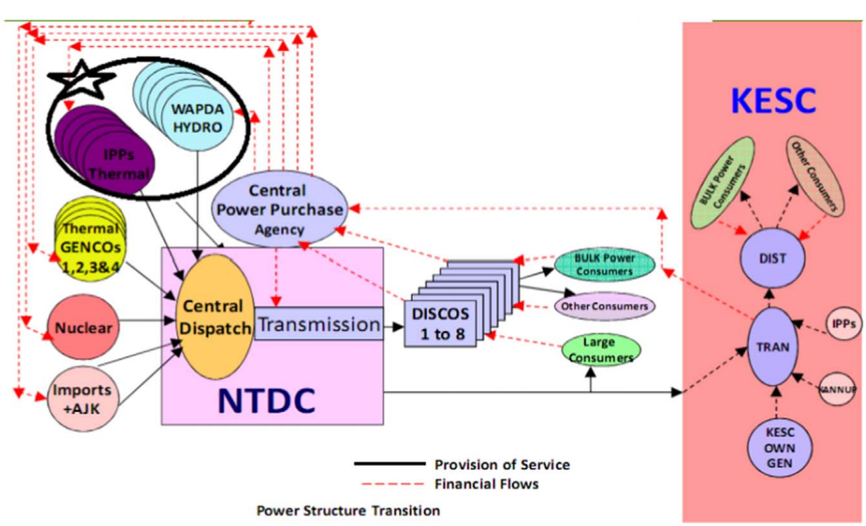

Fig. 24. Power transmission and distribution infrastructure in Pakistan [201].

Fig. 25. Distributed energy resources with transmission lines of 500 kV and 220 kV [201].

infrastructure of national grid and by integrating various technologies like Advance Metering Infrastructure (AMI), Home Area Networks (HANs), Distribution Automation (DA) and bi-directional communication between IED's and Control Station (CS).

5.5. Short and medium term targets for renewable energy resources

Considering the potential of various renewable energy resources currently being explored in Pakistan, a target of 4130 MW (10% of total installed capacity) has been suggested by 2018. The target for year 2025 is set to generate at least 7500 MW (10% of installed capacity). The short term and medium term targets for on-grid applications are tabulated in Table 3.

The investment from private sector to achieve short term and long term goals for 2018 and 2025 is estimated to be 7 billion and 13.5 billion US Dollars respectively. The government must ensure attractive and hassle free policies for private companies. Strengthening and improvement of national grid system is also required. Small scale industries are also being encouraged by putting up their own generated electricity into the grid system, therefore Net Metering is also being employed. From Net metering, 3000 MW electricity can be generated into the system [200]. The grids are also being updated to overcome T & D losses. The government is also encouraging solar power generation for tube wells, street lights, commercial loads (billboard lights, search lights, outdoor lighting) and rural electrification.

The off-grid applications for renewable sources will also prove to be considerably effective solution for energy crisis and developing the country's infrastructure. Some consistent subsidiary mechanism is also required from the government to achieve these targets. The short term and long term targets for off-grid applications are mentioned in Table 4.

Additionally biogas plants are being promoted in agriculture, domestic and commercial sectors. The renewable energy resources can also be utilized for water cleaning and captive power plants. The Battery charging can also be accomplished by renewable energy sources. The major focus is to facilitate projects of public-private partnership to setup new plants as well as to enhance capacity of existing projects.

5.6. Challenges of control in perspective of Pakistan

In Pakistan, National Transmission and Dispatch Company (NTDC) operates and maintains most of the grid lines and grid stations. Fig. 24 shows the power structure transition where NTDC and Karachi Electric

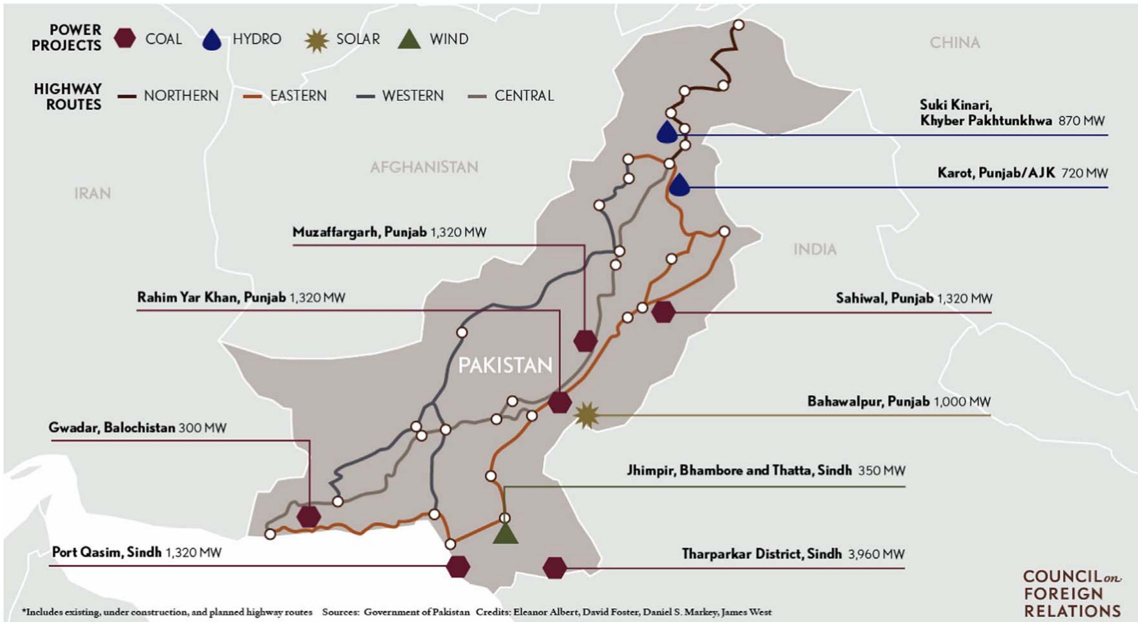

Fig. 26. Major projects of CPEC [206]. Power related projects are highlighted.

Table 6
CPEC projects related with renewable energy [207].

Category	S. No.	Title	Province	MW	US $ M	Progress Update
Priority	1	Quaid-e-Azam solar park, Bahawalpur	Punjab	1000	1350	– Commercial Operational Date (COD) of 1st 100 MW achieved – 2nd and 3rd 100 MW under testing
	2	Dawood wind farm, Bhambore	Sindh	50	125	– Financial Close (FC) achieved – Construction started – COD September 2016
	3	UEP wind Farm, Jhimpir	Sindh	100	250	– FC achieved March 2015 – Construction started – COD September 2016
	4	Sachal wind farm, Jhimpir	Sindh	50	134	– FC achieved – Construction started – COD June 2017
	5	Suki Kinari Hydro power Station	KPK	870	1802	– Supplemental Agreement Approved – Land acquisition in process – COD 2020
	6	Karot hydropower station	AJK & Punjab	720	1420	– Land acquisition at advance stage, near to resolution – FC August 2016 – COD 2020
Actively promoted	1	Kohala hydel project	AJK	1100	2397	– Feasibility study (stage–1) Tariff announced by NEPRA – Land acquisition process started – Environmental impact assessment study being updated – Expected COD 2024
	2	Pakistan wind farm II Jhampir, Thatta	Sindh	100	150	–

Supply Company (KESC) are two major systems of energy transmission and distribution in the country. Detailed information of grid lines and grid stations in various parts of the country is provided in Table 5 and Fig. 25.

The smart grid usage in Pakistan is challenging because transmission network in Pakistan is not reliable. Whereas, the smart grid can only be connected to the main grid when the phase conditions are compatible and synchronized with the main grid. Furthermore, the allowable source voltage must be within the required limits to feed the main grid from distributed energy sources [202].

The number of planned and forced outages in the network and their duration are the important indicators subject to the reliability of a transmission network. The transmission network of Pakistan is unreliable; according to a report in 2010 the NTDC system encountered total 140 and 657 planned and unplanned outages in 500 kV and 220 kV lines respectively [201]. Moreover, the focus has recently been shifted towards renewable energy in the country, therefore, until now most of the renewable energy resources are being utilized in islanded mode. In Pakistan, these energy resources are distributed from north to south with lot of potential of micro-hydel energy in north, solar energy in south Punjab and upper Sindh region and wind energy in the southern coastal belt.

Therefore, due to the above stated conditions in the country, the smart grid can be implemented up to secondary level of control in decentralized mode. Since most of the renewable energy resources are distributed, synchronization and energy management system at centralized level is not apparently possible at the moment.

5.7. China Pakistan Economic Corridor (CPEC)

The government has jointly initiated investment projects with various partners in energy sector with China as the main contributor. CPEC is an ongoing 'game and fate changer' multi-faceted mega project which is expected to be completed by 2030. With the economic corridor at the center, energy has been identified as one of the key areas for collaboration with expected investment of approximately $33 billion [203]. The Energy Planning Working Group of CPEC is undertaking fast-track implementation of power projects with targeted production of 21,690 MW [204]. Following 'Early Harvest' paradigm, about 10, 400 MW is estimated to be generated by March 2018. Both renewable (e.g. solar, wind, hydropower) and non-renewable energy (e.g. coal, gas) form the prominent resources in these projects [205]. Fig. 26 illustrates installations of power projects across the country.

The breakup of renewable projects with capacity and portfolio investment is presented in Table 6 [207]. In total, approximately 2790 MW is planned to be generated on priority basis while actively promoted projects constitute 1200 MW. Quaid-e-Azam solar park located in Bahawalpur is the world's largest solar power plant spreading over 6500 acre and is in final completion stage. It started generating 100 MW power in 2015 with further targeted capacity of 900 MW to be installed by Zonergy under CPEC. Wind farm projects of 250 MW are planned in Jhimpir. Hydro potential is unleashed by three projects of 2690 MW power in Azad Jammu Kashmir (AJK), Khyber Pakhtunkhwa (KPK) and Punjab. Timely execution of these flashing projects is anticipated to bring prosperity to Pakistan making it energy sufficient economy thereby changing its destiny [208].

6. Conclusion

A comprehensive review of smart grid features has been presented with a focus on control and automation aspects. Recent trends and reported techniques on the subject matter are thoroughly discussed with investigation of current energy crisis in Pakistan. At the moment, the country is experiencing numerous challenges due to shortage of generated electricity, distribution losses and electricity theft issues. Also with increase in electricity demands in commercial and household sectors, electricity prices are soaring. Pakistan has a lot to learn from other highly populated and developed countries, which are moving towards smart grid solutions to explore benefits of renewable energy. The concept of smart grid can also be successfully applied in Pakistani energy sector to realize a viable, cheap and environmental friendly solution.

It is highlighted that proper prioritizing of smart grids and renewable energy sector will certainly bring prosper in Pakistan. To achieve these outcomes, the review discusses related practicalities including supervisory control, energy storage and planning, distribution and assessment of the energy resources. Countries having similar dynamics can also beneficiate from this in depth review and suggestions.

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