

Research Article

Variable Load Demand Scheme for Hybrid AC/DC Nanogrid

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This paper addresses the use of nanogrid technology in resolving the issue of blanket load shedding for domestic consumers. This is accomplished by using different load management techniques and load classification and utilizing maximum solar energy. The inclusion of DC-based load in basic load and DC inverter load in regular load and scheduling of the burst load during the hours of maximum solar PV generation bring novelty in this work. The term “nanogrid” as a power structure remains ambiguous in various publications so far. An effort has been done in this paper to present a concise definition of nanogrid. Demand side load management is one of the key features of nanogrid, which enables end users to know major characteristics about their energy consumption during peak and off-peak hours. A microgrid option with nanogrid facility results in a more reliable system with overall improvement in efficiency and reduction in carbon emission. PV plants produce DC power; when used directly, the loss will automatically be minimized to 16%. The AC/DC hybrid nanogrid exhibits 63% more efficiency as compared to AC-only nanogrid and nearly 18% more efficiency as compared to DC-only nanogrid. Smart load shifting smoothens the demand curve 54% more adequately than during conventional load shifting. Simulation results show that real-time pricing is more economical than flat rate tariff for a house without DG, whereas flat rate results are more economical when DG are involved in nanogrids. 12.67%-21.46% saving is achieved if only flat rates are used for DG in nanogrid instead of real-time pricing.

1. Introduction

In the past few years, power shortfall is considered as a vital issue with the increasing demand of electricity. An electric grid was made more than a century ago, which supplies energy from generating units to the consumers. It is, no doubt, the largest physical network on earth which has a worldwide effect on all the nations. It is predicted that by 2030, the total consumption of global energy will rise up to 37000 terawatt hours and the population will double up in the upcoming forty years. Two-third of the total global demand is utilized in cities [1]. Long distance transmission line losses are increasing, which reduces the grid efficiency. The electricity cost of fossil fuel-based power plants is increasing day by day as almost 31 billion tons of CO₂ is annually produced which has an alarming effect on global warming [2]. Even then, the almost 1.2 billion population living in remote areas is still deprived of electricity access due to an uneconomical utility grid [3].

Renewable energy resources (RES) are gaining popularity as they meet the ever increasing demand with their

salient features. They are cheap, long-lasting, and have lower running cost as compared to the conventional energy resources. But the main hindrance faced is integration of these alternative energy resources with the existing grid due to the old design and trends. The main focus now is to meet the energy demand and consumption along with regulating the generation of electrical power. In the conventional system, generation is regulated in accordance with the rate of consumption, but in microgrid, the consumption is controlled in accordance with the availability of energy in the system.

Conventional electric grids have already been using telemetry, power line communications, remote terminal unit (RTU), digital energy meter, microwaves, and supervisory control and data acquisition (SCADA) systems. Hence, the concept of microgrid has emerged, encompassing the cyber-physical infrastructure including wide-area monitoring, bidirectional power flow, and communication facilities.

Due to its contribution to economic development and environmental advancement, microgrid has reached specific concern in the twenty-first century. It has the capability to

operate on both the supply side (SS) and the demand side (DS). Production and delivery of electric power are executed by the power supply side. It is also capable of providing adequate electric power at the suitable standards and high-grade reliability.

Due to its vast demand, electrical energy has become a limited resource in the developing countries and hence generation should be utilized efficiently. This will help in improving the reliability and efficiency of the power supply system [3]. In this regard, microgrid is termed as the easily accessible source to compensate the increasing energy crisis and to allow the distributed generation (DG) for new generating plans.

Solar PV DG could be used to overcome the energy shortage on the supply side and on the demand side at the consumer end. Different strategies could be adopted to manage the load such as controlling the load directly, or by using a remote device, the consumer could be able to control the load management (LM) whenever required. Microgrid further help to manage each load individually by classifying load in different categories, depending upon their priorities. DC/AC hybrid nanogrids play a crucial role in the performance of microgrids by increasing system efficiency and reliability. This results in financial saving of high-cost electric bills.

The various grids of small or large scale are all interconnected with each other. Some of the grids are capable of islanding themselves and hence work independently, but most of the grids use the smaller ones as their building blocks and create their foundation on it. These grids give rise to a meganetwork with all the various grids with varied magnitude interlinked and sharing information and communicating to give rise to a stable and secured power network. The chart representing the various grids interlinked or islanded is presented in Figure 1.

Microgrid comprises of a network of local nanogrids, with battery storage, and acts as distributed generation in macrogrid which is also known as the conventional grid. The nanogrid, on the other hand, organizes end user power usage and is considered as a single domain of power in terms of voltage, capacity, reliability, energy management, and financial saving.

A simple microgrid can be as small as a mesh of nanogrids, without any localized entity. A microgrid controller can manage the information and the command over the nanogrid units present within and is also capable of interfacing to a utility grid. Utility grids, on the other hand, differ across geographies by various parameters, e.g., voltage, AC frequency, and communication techniques. Microgrids are solely responsible for accommodating utility grids and therefore are specific by location. The nanogrid interfaces are generally the same everywhere. They can operate independent of the utility grid.

Other than nanogrid and microgrid, picogrids and femtogrid are gaining popularity. The picogrid may be larger than the nanogrid, but they are basically off-grid networks with independent and isolated distributed generation. They do not rely on the utility grid for their functioning and hence are capable of managing the load independently in far-off and inaccessible areas where larger grids cannot be linked.

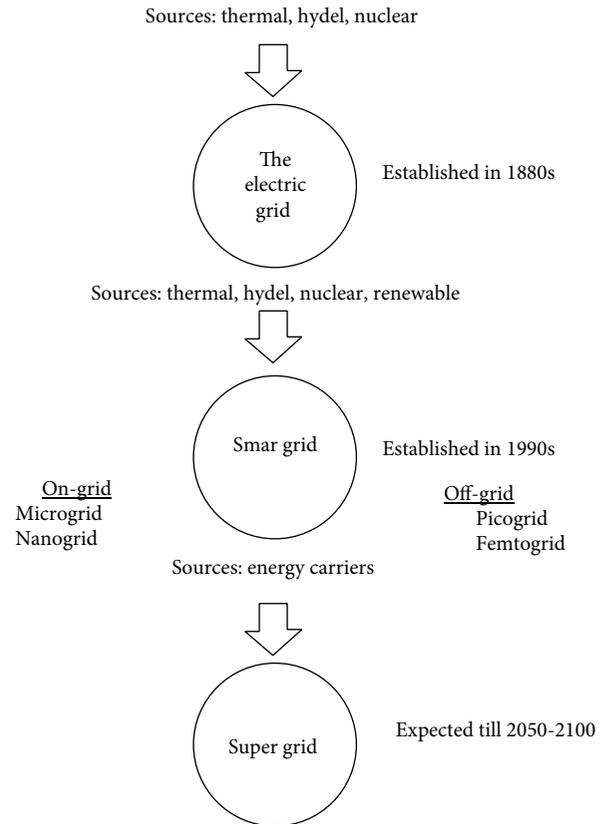


FIGURE 1: Chart explaining various grids interlinked or islanded.

1.1. Related Literature. In literature, various hybrid architectures are reported for advanced states where the utility grid system is very much stable [4–7]. 20% of electricity is wasted due to 100-year-old legacy grids in underdeveloped countries [8]. In [9], AC and DC grids are presented on the same structural design to get additional advantage for both types of loads for developed countries. In [8, 10], renewable energy power distribution works as a base load unit where continuous supply of power is available. In [6], it is presented to reduce both AC and DC power for hybrid implementation in the grid-tied system for developed countries. The proposed schemes as presented in [6, 10] are very much suitable for developed countries where availability of continuous power is not an issue. Moreover, reduction in losses for hybrid AC/DC grid implementation and gain in comparative efficiency are not presented in the above-mentioned studies. Therefore, a storage-based hybrid AC/DC system architecture is needed for such weak grids with maximum system efficiency.

There is an increasing demand for energy in Pakistan due to urbanization, expanding industrial sector, and increase in population. The total energy consumption in Pakistan is shown in Figure 2.

Due to the ever increasing demand of electricity in the past few decades, vital steps need to be taken for effective management of the production and consumption of electricity in various sectors. In Pakistan, due to the conventional electricity production systems and the use of fossil fuels for

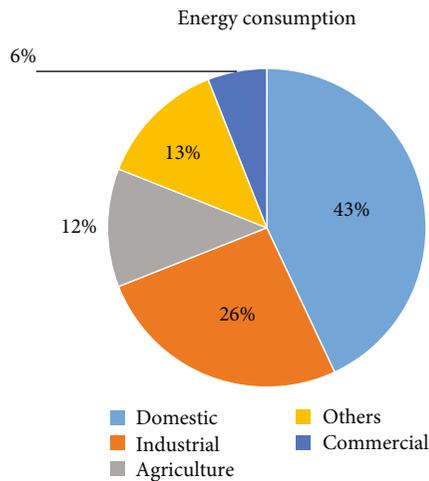


FIGURE 2: Energy consumption in Pakistan [8].

electricity generation, the total production capacity currently is maximum of 41% less than the demand hence resulting in a drastic power shortfall. The only solution to overcome this shortfall is excessive load shedding which is unannounced most of the time. It puts a huge strain on the economic growth and on the daily life of the consumers. The ever increasing unit cost of the utility further puts a financial strain on the consumers. It calls for a dire need for a reliable and cheaper solution to this dilemma.

The consumers mostly escape this issue by the use of uninterrupted power supply (UPS) and gasoline generators at the time of load shedding. It might seem to be a suitable solution, but rather than bringing comfort, it adds an additional strain on the monthly bills. These generators have a limited efficiency, and the running cost is no less. The daily maintenance cost is another cumbersome issue with the generators. The other option of UPS is smooth-running, but it puts a heavy burden on the batteries by increasing the charging and discharging cycles per day and hence decreasing the life cycles of the batteries, which results in their annual replacing cost.

To avoid the above-mentioned issues, the use of renewable energy resources, e.g., a solar PV system, is an ideal solution in our country with solar energy potential of at least 5.4-5.8 kWhr/sq.m [8].

Despite being an expensive solution, it can easily be installed with proper knowledge and handling. But the solar PV system also has some major drawbacks. Without load categorization and classification, it is impossible to manage the existing load efficiently. It requires a minimum of 7 sq.m area at the rooftop for the installation of 1 kW of solar PV, and still, if the load is not properly classified, this huge infrastructure of PV cells will be unable to manage the load of a single house. This problem can be resolved by using nanogrids and load classification at the domestic level. Additionally, the variation in the intensity of sunlight per day has a substantial effect on the power output. This fluctuation in the power production needs to be handled beforehand to ensure an uninterrupted and smooth power

flow for the whole system. The scheduling of the load can easily help in managing the maximum load-consuming task during peak PV production hours. Another issue faced is the costly installment of the solar PV system. Also, the batteries connected to the system have a limited number of charging and discharging cycles; since price of a lead acid battery of 200 Ah is 50% more as compared to the price of a 200 W monocrystalline solar PV panels, the financial strain lingers. It can easily be managed if the batteries are not allowed to discharge completely hence maintaining their life cycles. Further, different techniques are developed to increase the battery life by categorizing the load and scheduling different time slots.

This necessitates the use of a controlled power structure to enhance the interaction between the PV power production and its consumption, thus increasing the financial viability of the solar PV system. There is a need of a continuous supply of energy with improved efficiency at minimum cost. Consumers' demand and concern change accordingly with the change in region and their necessity. Nanogrid along with a proposed load classification and management techniques is capable to fully address these issues in a very economic and reliable manner.

Appropriate load classification for power consumption is needed for efficient load management in nanogrid. In [11], similar techniques are presented in smart home, and three load categories are defined on the basis of the characteristics of appliances:

- (i) Basic load is defined as power consumption of those appliances which must be served at any time. Examples of these appliances include lighting, fan, and computing and network devices. Basic load should not be overlooked while considering the available capacity
- (ii) Regular load is defined as power consumption of those appliances that are always in a running state for a long duration, for example, air conditioning and refrigeration at home. Due to higher power consumption, these loads put heavy burden on the whole system, which needs to be dealt with beforehand
- (iii) Burst load is defined as the power consumption by the electrical appliances which operate at specific time and for fixed time duration. These appliances are the clothes dryer, dishwasher, washing machine, etc., as these appliances result in sudden increase of peak load. This critical issue needs to be resolved as it puts continuous strain on overall efficiency and energy cost

In [12], the simulations confirm that the proposed load classification system is often capable of scheduling all loads but with some limitations. These limitations minimize the amount of time during which it operates above the capacity limit. So, further classification is done in this work along with nanogrid to manage all the load with more reliability and economy.

1.2. Contribution. This paper covers the techniques, control, and features of interconnected nanogrid networks. The various milestones set out for this research are as follows:

- (i) An initial literature review was crucial for the research within nanogrids, microgrid, and load classification and to gather data related to the research. It helped in gaining successful approaches that would be essential to guide the research in the proper direction. The gaps in the identified research further helped in converging this work and delivering possibilities for improvement
- (ii) On the basis of the knowledge gathered, primitive solutions were formulated. It includes the load categorization, load switching, and different priorities for the use of the solar PV system
- (iii) The load categorization is already done in the literature in the form of basic, regular, and burst load. But this was not sufficient for effective load management. In this research, maximum benefit will be obtained by involving DC load in the basic load
- (iv) On the basis of this DC load, a DC-AC nanogrid will be developed at the domestic level ensuring a reliable and efficient system for basic load
- (v) In regular load, DC inverter loads will be introduced, e.g., DC inverter air conditioners and DC inverter refrigeration units. DC inverter technologies consume almost half of the power consumed by the conventional air conditioning and refrigeration units. This will almost double the efficiency of regular load
- (vi) In burst load, priority load is involved, which compels the end user to switch their devices only during hours of maximum solar PV generation in order to avoid stress on battery backup and minimize the utility electric bills. Maximum load-consuming tasks like washing, water pumping, ironing, and cleaning are done at specific time slots during hours of maximum PV production
- (vii) Resistive loads like electric irons, toaster, and heaters have maximum efficiency when operated on AC supply instead on DC supply. DC load is to be run directly on DC, and the resistive loads are to be run directly on AC supply as they have up to 100% efficiency when run by AC supply
- (viii) To maximize the efficiency of DC-DC converter for DC loads, it is necessary to set the input supply voltage as close to the output voltage as possible. This strategy can be done by summing 2VDC battery cells in series to the nearest desired output voltage, which is further regulated to the exact voltage level required by the specific DC load. Using this technique shows that there is no obvious indication that the generated power is being wasted anywhere

- (ix) Several protocols are developed in this paper which ensure the smooth-running of all of the load, i.e., running of basic load 24/7, a decrease of up to 56% of using DC inverter loads for regular load, and almost all of the burst load shifted to solar PV, which is about 40% of the total domestic load
- (x) Energy management system (EMS) which has proposed the AC-DC hybrid distribution system will assist in shifting and managing the auxiliary load and compels the consumers to run a particular load at certain time slots. These adaptations will further aid to control the excessive load during peak and off-peak hours
- (xi) In order to access the feasibility of this solution, the simulated comparative study of the work is undertaken. This would assess the utility power consumed by the system with and without the proposed solution. The attainment of the outcome would be quantified by the scale in which the usage of utility power by the household was minimized. Five houses with the same load capacity with and without EMS and solar PV will be simulated using different tariff charges, to ensure a fair and unbiased result
- (xii) Initially, the problem has been implemented practically at the domestic level; practical results are recorded and compared with different houses with/without EMS and further simulated in MATLAB Simulink to confirm practical results. This comparison will give a clear picture of how the proposed solution minimizes the electric charges and enhances the reliability of the whole installed system
- (xiii) This paper focuses on offering a complete analysis for AC-only, DC-only, and proposed hybrid AC/DC nanogrids in terms of losses and efficiency. The case study for implementing the proposed architecture will be presented for typical residential load and will further present the results and discussion

1.3. Scope of Work. As mentioned previously, the main objective of this research is the implementation of a new improved energy management system and to remove the restraints of practical implementations to enhance the drawbacks mentioned in existing schemes and to integrate the renewable energy resources with the existing dump grid in a more efficient and cost-effective manner.

- (i) The goal is to eradicate total load shedding and challenging blackout situations, further proposing user-friendly and continuous supply of electricity for both micro- and nanogrids
- (ii) The overall efficiency is enhanced by all this functioning, in terms of maximum 56% more economical system and leading to a smart nanogrid for domestic load

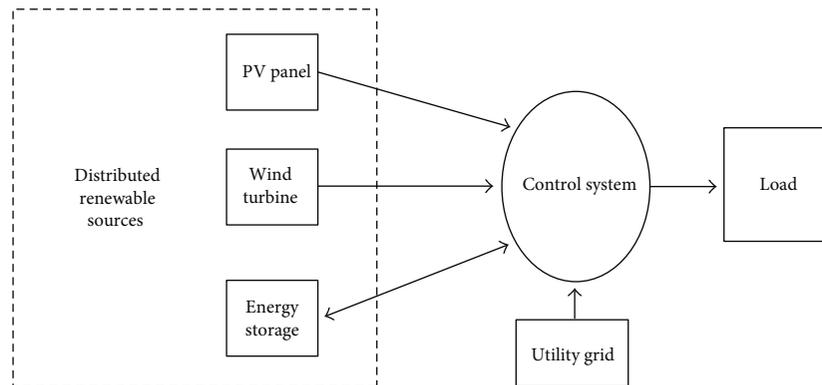


FIGURE 3: Distributed energy model.

- (iii) Continuous supply of power is possible during hours of unplanned load shedding at the domestic level
- (iv) Utilization of maximum solar energy with load classification schemes along with nanogrid reduces the expensive utility tariff
- (v) The dependency of consumers on utility is reduced by interacting with both utility and end user at a single platform in order to reduce the load demand
- (vi) Rescheduling of maximum power-consuming tasks is done during hours of maximum PV generation which flattens the load curve during peak hours
- (vii) DC nanogrid implementation reduces the power conversion losses for basic load
- (viii) Proposed series and parallel combination of solar PV array reduces line losses for high-rise buildings
- (ix) Proposed algorithm used for charging and discharging battery storage and shifting load back to utility helps in minimizing battery discharge, further enhancing the life of storage
- (x) Specific machines are remotely controlled using a wireless circuit breaker and rescheduled to a healthy time slot as up to 40% of load is decreased if considering washing and drying only
- (xi) EMS determines the practical application of the DC-AC network with incorporation of solar PV and battery storage within available infrastructure. A remarkable improvement is seen in using the hybrid AC-DC framework in terms of reliability and efficiency. The proposed scheme becomes a novel, economical, and reliable EMS by integration of the above-stated features, for the weak and interrupted grid in underdeveloped countries

2. DSM in Nanogrid, Microgrid, and Smart Grid

The research areas related to the paper have been reviewed in this section in order to converge the work and affirm its novelty. This paper spans the work in the nanogrid and micro-

grid areas. Various related trends and contributions are outlined and discussed. The conventional electric grid is mainly composed of the power generation, transmission, distribution, and its appropriate utilization. The small grids already installed have an electromechanical type in nature, but larger grids have built-in intelligent electronic devices (IED) such as SCADA, telecom, computer, and telemetry systems which make them almost intelligrid if not ideal smart grid (SG). SG supply consumer access to the utility network that has resulted in heavy losses to utilities through electronic intrusions [9]. This has been happening with credit cards and online banking in the past, but now, technology has matured enough to conduct electronic transactions, e-business, and e-auctions. The smart grid involves integration of digital, computer, and information technologies (IT) to existing electro-mechanical power systems [13].

Microgrid's most important application is to encourage home and business owners to invest in distributed energy resources (DER) in order to generate their own electricity to reduce energy shortage and also to reduce the load on power grid [14]. Solar energy and wind energy are the most popular renewable sources of electricity, as they reduce the greenhouse gases. The microgrid generation model consists of different energy resources like the wind turbine, photovoltaics, and fuel cell. A generic model of energy resources is shown in Figure 3.

Unpredictable fluctuations may appear at output due to intermittency of renewable energy resources. Imbalance in the system is subject to the demand of energy generated by the renewable energy resources. Batteries, fly wheels, ultracapacitor, water pumping, and compressed air can be used to resolve these issues.

Batteries can be used to meet the peak demand or non-availability of renewable energy. Battery storage defines the effectiveness of peak demand or nonavailability of energy from renewable resources and depends on the storage capacity. Due to multiple energy resource requirements, a resource management system is required to manage the energy resources. Energy from these resources can be used to power the load or to charge the battery. This leads to development of an algorithm to manage the renewable energy resources and utility to compare the cost as well as to manage the energy consumption; it can also be used to charge the batteries. Nanogrid is in the development phase, and much

research work is carried out in papers and lab experiments. These developments have been implemented through difficult simulations of real-time environment, and different software are used to manage energy.

The smart applications are used as monitoring hubs that can be used to collect real-time data, and this data is communicated with the end user. They also provide rapid energy information and control options to consumers. Present management software does not have the feature of real-time operation of demand-side management.

Demand-side management is an important aspect of the power system operation in energy-deficient utilities as the demand is continuously increasing but the generation is not following the demand accordingly due to global economic collapse. It is better to save a watt than generate a new one. Generating more and more power to meet the ever-increasing demand has many concerns regarding the smart use of limited fossil fuels and high carbon emissions. High carbon emissions deteriorate our environment and put a question mark on our sustainability. Though the renewable energy resources are the cleaner form of energy, the energy density and technological maturity of the fossil fuels still dominate their use. Experts predict future vision of smart and super smart grids consisting of sensors and renewable energy networks [15].

The major concern faced by the electricity utilities is peak demand, but our issue is the lack of adequate generation which worsens at peak loads because peak demand puts stress on the system stability, enhances the gap between supply and generation, and has adverse economic effects. Load shedding is a technique of disconnection of some of the load from the power system to cope with the increasing overload or mitigate the after effects of the disturbances. However, the current load shedding system consists of predefined schedule of cutting of the load which results in excessive under shedding. It is necessary to develop a system which should adoptively and intelligently shed the load according to the requirements and avoid the blackouts [4].

The concept of the dynamic energy management system consists of energy-efficient end-use devices, energy resources which are smart distributed, integration of the communication structure, and modern whole building control systems. Currently, the scenario of increasing demand and low generation is being met by the complete feeder shut down in order to avoid overloading and to maintain the grid stability. But this procedure causes the blackout which circulates among feeders on scheduled bases. The aim is to develop a system of selective load cut to avoid blanket load shedding by integrating the wireless networking and smart meters in the distribution system [5].

There are several methods to control load shedding, but the proposed dynamic priority-based load shedding scheme will give a relief from blanket load shedding calamity. Implementation of the smart grid dynamic system will help in automatic and even in manual load shedding to reduce the power consumption during peak hours. In summer, normal revolving load shedding for air conditioning facility may be used through smart circuit breakers [6].

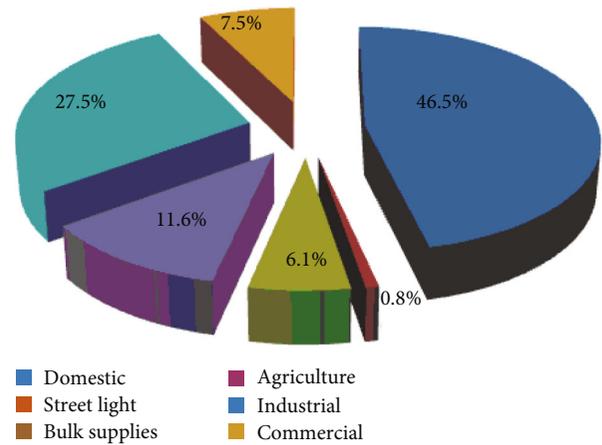


FIGURE 4: Sector-wise electricity consumption [16].

To meet up with the cumulative energy needs, smart grid technologies are presently undergoing speedy development in an effort to upgrade the power grids. The efficient bidirectional communication systems will assist the structure for real-time monitoring and transmission control, usage of available energy resources, and the distribution and end user consumer assets for effective coordination. In addition to this, at the distribution and consumer level (e.g., smart meters), the computer automation integration enables smart grids to improve the entire system power quality, reliability, and security, rapidly self-regulate and heal, and more efficiently manage the energy consumption and delivery [7].

The plug-in electric vehicle (PEV) is predicted to become a vital part of smart grids when hydrogen will become a normal fuel [10]. It is proposed that the smart daily-use electrical appliances, e.g., refrigerators, air conditioning, washing machines, clothes dryers, dishwashers, and PEVs, could “talk” to the grid and adopt on how to run and schedule their activities automatically, at planned times based on existing power generation [11].

Pakistan is a country of approximately 179 million people. Despite being the world’s seventh nuclear power, it is facing the worst crisis of its history regarding energy issues specially of load shedding of electricity. Electricity shortfall fluctuates between 3000 and 7000 MW according to the variations of weather [12].

The contribution of the thermal power plants in electricity generation of Pakistan is 64% while hydel and nuclear power provides 33% and 3.9%, respectively. The gap between demand and supply is increasing although almost 40,000 villages still need to be electrified. According to the energy year book 2018 of Pakistan, the generation and consumption details are shown in Figure 4.

Load shedding has become a serious issue, and its severity is increasing day by day because domestic users, being the biggest consumer, have been suffering so far. Violent protests are being observed across the country against load shedding. The industrial sector which consumes almost 35% of the total commercial energy available and 27.5% of the total electricity generated is also suffering adversely from load shedding. According to some estimates, almost 500,000 people have suffered unemployment due to load shedding [17].

TABLE 1: Line losses of different DISCOs.

DISCO	Line losses (%) (2017-18)	DISCO	Line losses (%) (2017-18)
LESCO	13.78%	IESCO	09.80%
FESCO	10.48%	QESCO	20.68%
GEPCO	10.98%	HESCO	34.79%
MEPCO	18.94%	PESCO	36.91%
Punjab Ave	13.54%	KESCO	34.89%

There are many reasons for load shedding of electricity; some of them are dependency upon costly imported furnace oil, decreased share of hydel generation in electricity generation, pile up of circular debt, poor management, older and traditional load management techniques, high line losses due to electricity theft, noncooperative behavior of government organization regarding pending bills, and political intervention.

The energy saving step proves helpful in decreasing severity of electricity crisis. The government has advised the usage of air conditioners after 11 am in offices and has also directed early closing of markets since the last few years, for the maximum use of daylight. It is needed to have a comprehensive and effective energy saving program for the country as many countries like Canada and Hungary have reported many environmental and health-related positive impacts through their energy saving programs. Control of higher than standard line losses is also a serious concern for WAPDA. A comparison of normal line losses in different distribution companies of Pakistan is shown in Table 1 [14]. According to the table, electricity thefts are the highest in Hyderabad, Karachi, and Peshawar regions.

The smart grid is a future power grid which offers more efficiency, reliability, and transparency for customers along with new functionalities like load shedding and scheduling and demand-side management with better communication capabilities and intelligence [16]. To cope with the increasing shortage of electricity, new power generation plants need to be added in the system; new generation capacity requires a huge capital cost round about 4 billion per MW, and the running cost is additional. At the same time, for the development of transmission and distribution, the same capital is required, so nanogrid is an economical solution for it. There are basically two methods: (i) supply-side management and (ii) demand-side management. Demand-side management (DSM) is cheaper and fast as compared to the supply-side management (SSM) [18]. Nowadays, most of the demand-side management techniques and methods interact between users and utility; some researchers are focusing on smart pricing like RTP, time of use pricing (ToUP), and critical peak pricing (CPP). On the other hand, Direct Load Control (DLC) is a technique through which utility directly controls the energy consumption and operation of user home appliance. But it has the deficiency in terms of privacy [19].

In demand-side management (DSM), as shown in Figure 5, energy conservation is a way through which we can reduce energy consumption by setting priority of load in terms of separating lighting load, heating, ventilation,

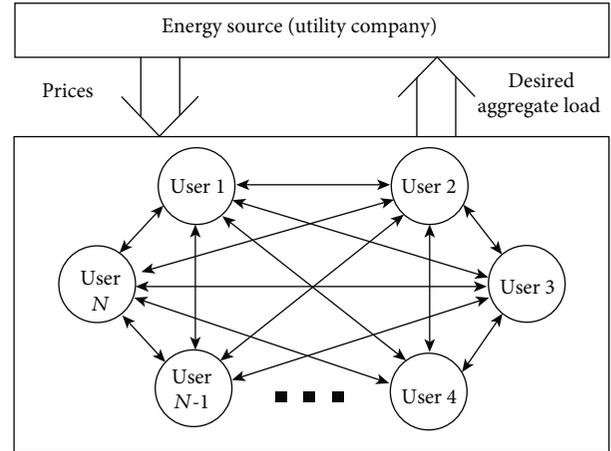


FIGURE 5: DSM rough layout [4].

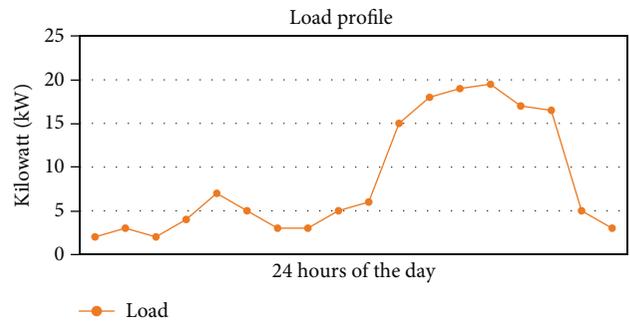


FIGURE 6: Daily load profile of household.

and air conditioning and has the impact of reducing load shedding [20].

In [21], the author proposed a day-ahead demand-side management by using the load shifting technique for the future smart grid. A very informative concept was introduced by the author in [22] for AC and DC hybrid microgrid. In this type of grid, AC and DC supplies are available which can be used cumulatively by an interlinking inverter.

A day-ahead load shifting technique is used for three different loads which are controllable; one of them is residential, another is commercial, and the third one is industrial load [21]. In the demand-side management, the researcher divides the residential load into three categories: (i) basic loads, (ii) regular loads, and (iii) burst loads. The combination of baseline loads and burst loads creates a peak load problem [22].

The proposed scheme in [23] is used to set the priority of the individual load and reduce the energy consumption for given intervals for load shedding. It mainly uses the shiftable load characteristics. It reduces the cost by minimizing the load by setting the consumer load priorities which are predefined.

The increasing interest in DSM programs resulted in the development of smart grid. DSM is the implementation of strategies and actions to control, regulate, and reduce energy usage. To collect data related to time and energy consumption, various activities of the utility and consumer can be determined. A household electricity usage is shown in Figure 6. System load profile can be changed by using DSM

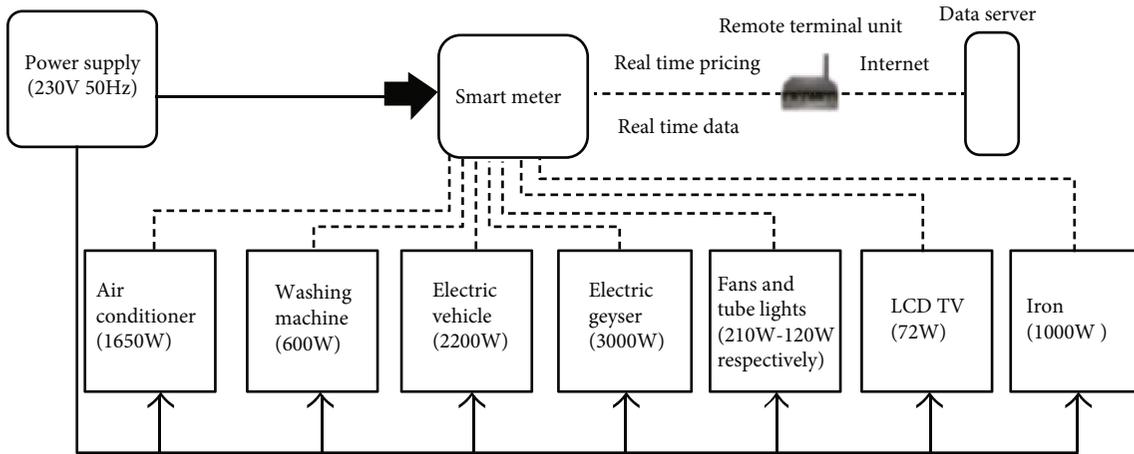


FIGURE 7: Block diagram of home area network [27].

to reduce the electricity cost. There are some common techniques to properly shape the load profile, and those techniques are peak clipping, load shifting, valley filling, strategic load growth valley filling, and flexible load shaping.

In [24], user-friendly demand-side management using information and communication technology technique is introduced. This technique is based on time-varying price information and three other factors like electricity price, usage pattern, and peak load. There are two steps of the proposed scheme in [25], i.e., to determine the objective function based on usage and then to minimize the electricity price and maximize the usage similarity. To avoid blackout and reduce peak load, a load balancing algorithm is applied. This proposed technique shifts the load to the off-peak hour and leads to electricity price saving and customer satisfactory ratio.

In [26], a genetic algorithm is used to optimize the domestic loads according to the constraints and input signal. The main objective is to minimize the load according to user preference and to maintain the quality of service. Main constraints involved are the power level, time duration of load, amount of available power, and end user preference. If the dynamic structure of pricing is known, then the user can determine the scheduling of the next 36 hours. The domestic and commercial loads are the effective ways to control the load profile of distribution. From the utility point of view, a flat rate of energy does not provide incentives to users. Price should be varying according to time. A smart meter provides the solution to measure the power usage and use the real-time signal sent from the utility company. The home energy controller (HEC) controls the home appliances to reduce the energy cost and to increase the reliability and transparency as shown in Figure 7. All the results are verified with the help of MATLAB [27].

In [28], an intelligent residential DSM system for rooftop-installed residential solar PV is practiced. The applied DSM technique is aimed at reducing the utility cost of customers along with the power losses on the grid. The model was introduced to deal with the challenging constraints of supply-demand balance raided by the intermittent nature of the PV system. The conventional generation cost,

utility losses, and CO₂ emission were all accounted for the user's monetary cost.

Four possible scenarios are proposed for incorporating the household solar PV systems into local microgrid [29]. It is possible to include DC technology and battery storage within the design which makes the system more flexible and robust in use. Information and communication technology (ICT) incorporation within the system makes it smart. The smart power system for home (SPSH) proposed two different loads, DC and AC loads [30], and the results are simulated in MATLAB. The synchronization of DC power from the solar panel and battery storage has been successfully achieved. The SPSH increases the system efficiency when the load demand becomes more than the generation capacity.

The maximum output of the PV system is at midday when working families are away from homes [31]. It introduces the concept of the electrical management system for smart homes. The proposed smart system allows a percentage of the PV generated energy to be used during working hours. Also, the proposed system gives the individual total control to maximize the use of generated energies, to reduce the electricity bills and the impact on environment.

Demand-side management techniques found in literature are overviewed, and the novel electricity demand control technique using real-time pricing is proposed in [32]. The proposed method consists of modern system identification and control that would enable user load control. This would potentially balance the demand side with the supply side more efficiently and would also reduce peak demand and make the whole system more efficient.

Microgrid equipped with heterogeneous energy resources and a bank of energy storage device presents the idea of small-scale distributed energy management (DEM) [33]. Renewable energy resources and ICT make the microgrid an ideal candidate for distributed power systems. The energy management of microgrid can perform real-time energy forecasting of renewable resources, energy storage, elements, and controllable loads in making proper short-term scheduling to minimize total operating costs. Cooperation among different microgrids in a smart microgrid

network (SMN) brings the energy sharing and management issues under one platform.

In [34], it is stated that the poor service life of batteries is one of the major issues that hinder the development of standalone microgrid. Hybrid energy storage systems (HESS) and novel power management strategies have been proposed by researchers to address this issue and to improve the battery cycles.

In [35], it is mentioned that the electricity consumption becomes smarter and more efficient by employment of home energy management programs. The benefits of home energy management (HEM) comprises increase in savings for consumers as well as utilities and reduction in peak to average ratio (PAR) and peak demand. Home energy management is probably the most important application of smart grid technologies. For the smart grid, new pricing schemes like real-time pricing (RTP), time of use (ToU), Inclining Block Rates (IBR), and critical peak pricing (CPP) have been proposed. For efficient consumption of electricity, DER and home appliances coordinate along with different tariff schemes.

In [36], several home energy management schemes are discussed where different pricing schemes have been applied to get economic and social advantages and more efficient, user-friendly home energy management systems for future microgrid.

In [37], the author presented the solar home energy management system which helps to connect the rooftop solar PV easily to the grid using an AC-DC hybrid distribution system. There are several advantages of using a DC nanogrid network as the technology is advancing. The user has a significant role to play and can control his own system, thus empowering the user. For the system, there are some additional requirements like controls and batteries. From simulation results, it can be seen that the system stabilizes the peaks in the grid demand hence making it more reliable. It could even improve the reliability and performance of the AC grid system.

Both the wind and solar systems are nonreliable if there are insufficient capacity storage units like batteries [38]. The microgrid reliability increases when both systems are combined with storage devices. The sufficient storage battery bank capacity is needed to feed the load demands with power in cloudy and nonwindy days.

In [39], a new and smart distributed DC microgrid suitable for high penetration and that efficiently utilizes energy available from distributed, renewable generators is presented. It is shown that energy saving in excess of 10% is feasible using the proposed DC power distribution system when compared to the current approach where inverters are used. Today's solid-state switching DC-DC converters that transform DC from one voltage level to another have a power conversion efficiency in the range of 95%.

As mentioned in [40], almost 68.9% of electrical loads are comprised of brushless DC motors; LED lights and PCs and telecom gadgets accept DC power. Before it is applied to the load, the DC is converted into AC by using inverters. DC-AC conversion is expensive and complex as it has a maximum of 85% efficiency. This paper [41] proposes a battery energy management system (BEMS) for photovoltaic (PV) powered microgrid, where the system would like to reduce the opera-

tional cost batteries. BEMS is designed to manage multiple types of batteries to reduce DG run time while extending battery lifetime by controlling the battery charge and discharge rate. The control methodology will keep the battery charge and discharge rate within the safety limit.

By dividing the load into three categories, an energy management problem is formulated in [42]. The three categories are the basic load, regular load, and burst load. The appliances which consume power at any time fall under the basic load; regular loads are those appliances which are used for refrigeration and air conditioning load which turns on automatically upon feedback from thermostats. Burst loads are appliances which turn on at any time depending on the task duration such as washers, dryers, and dishwashers, hence adding a critical issue of excessive power consumption which puts harmful impact on overall efficiency and cost on the demand side.

Binary integer programming was involved to solve the problem which gives useful impact for home appliance scheduling and minimizing operation cost; further, we have divided load categories more precisely to achieve better results. This approach has given a useful solution for house appliance scheduling and cost minimization which will be discussed in the next section.

Load shedding spans from 7 to 9 hours in cities and almost 12-14 hours in urban areas. This is due to the high energy demand from the last few decades. This shortfall calls for an urgent action to be taken to overcome this energy gap. According to a study in 2015, the energy gap between generation and demand is almost 5200 MW. Almost 22076 MW is the installed capacity, but the generation during this time period is almost 16500 MW [43]. This electricity deficiency results in a huge economical loss which still remains to be resolved to fill the energy gap. According to a report by the state bank, this energy loss rises up to 210 billion PKR annually [44]. The Water and Power Development Authority (WAPDA) and Karachi Electric Supply Corporation (KESC) are responsible for generation, transmission, and distribution of electricity throughout the country.

3. Background of Nanogrid and Definition

The introduction of nanogrids and microgrids in the power sector has plunged us in the early stages of an expansion of distributed generation, which is already lessening the need for costly long-distance transmission. The main focus of this research is on nanogrid, and smart grid techniques are employed on it to enhance its reliability and performance. The nanogrid control presented here would not be possible without load classification and nanogrid smart techniques. Therefore, the novelty of the paper is upheld by the pattern in which nanogrid and smart grid techniques are brought on the same platform.

The literature related to nanogrid comprises mostly of the hardware, control, and power converter with a wide range of procedures. The current literature is still deprived of properly defined nanogrid with various characteristics and boundaries. On the basis of various definitions in literature, a brief definition of nanogrid architecture is developed, and their values and devalues are discussed in the current section.

As the opinion and the limitations of power infrastructure are ambiguous, the power structure cannot be exactly defined. The point of reference can be used as an initiative to elaborate it more precisely. As explained in [45–52], nanogrid is considered the same as microgrid. In order to identify the two power structures individually, the similarities between the two need to be discussed at the first step.

Basically, nanogrid is a power distribution system just like a microgrid [53–63]. It is capable of operating in both grid connected and islanded modes [64–74]. Although in literature nanogrid seems to favor a DC-based power structure [75, 76], it is capable of operating as DC as well as AC and is even able to work as a hybrid structure [77]. Both the nanogrid and microgrid often consist of renewable energy source [78] and any type of load [79]. In order to create a quantitative parameter to differentiate a nanogrid from microgrid, the implication of relative size of the two systems needs to be elaborated. The term low power cannot be restricted to a certain value. In [80], it is defined as a few watts to 5 kW; on the other hand, it is categorized between 10 and 100 kW by [81]. The complexity of this structure, its control strategies, and optimization techniques increase as the nanogrid research widens [82]. As compared to microgrids, nanogrids are mostly considered to be of lower power and lesser complexity. These conflicts still tolerate a level of uncertainty around the definition.

Another definition is presented in [83], which rather changes the nanogrid structure. It states that the “nanogrid” is the term of the unit ground, for following parameters, comprising of the value in terms of price, voltage, reliability, and its qualitative analysis, all working under common concerns.

Nanogrid includes power systems like power over Ethernet (PoE), universal serial bus (USB), and power-related small-scale structures. The term “nanogrid” can be confused due to the wide generalization of these structures. A unit house belongs to nanogrid [84] whereas multiple houses or buildings belong to microgrid [85]. The definition of microgrid is not limited to a unit house or building; rather, these single units come under the term “nanogrid.” Hence, the single power distribution systems fall under the nanogrid definition, and the multiple power structures are termed as microgrids.

3.1. Definition of Nanogrid. On the basis of the above discussion, a summarized definition of nanogrid can be presented as follows: “The nanogrid is a single unit power distribution system which is capable of connecting or disconnecting with other power units through a gateway. In this system, the local loads are powered by the local power production and can even opt to utilize a control system or the energy storage.”

The basic components of nanogrid are shown in Figure 8.

- (i) *Distributed Power Production.* Increasing the overall efficiency of nanogrid uses distributed generation for the residential load. The incorporation of a variety of nonrenewable and renewable energy sources can be supported by these systems. The diesel generators fall under nonrenewable energy sources whereas the solar power and wind power are renewable energy sources [86]

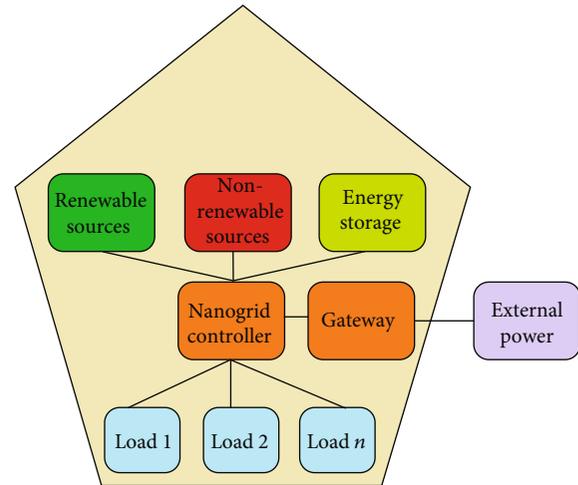


FIGURE 8: Nanogrid block diagram.

- (ii) *Gateway.* These are bidirectional power flow ways between nanogrids, microgrids, or other national grids. They can communicate with other local power grids when required, but communication with the national grid is not possible. In the islanded mode, these gates can disconnect nanogrids from external power units, further enhancing the fanatical advantage of distributed power generation; these gateways allow the nanogrids to sell or purchase power to or from other power entities [87]
- (iii) *Local Load.* These are electrical domestic appliances which are powered by local generation using nanogrid [88]. Examples of such loads are lighting, water heater, oven, and televisions
- (iv) *Energy Storage.* These are optional in nanogrids, but they improve the stability. It further adds reliability and backup capacity for the residential load
- (v) *Controller.* A nanogrid controller is not completely essential, but it helps in managing the load and supply demand mutually

3.2. Nanogrid vs. Microgrid. Distinction between nanogrid and microgrid is not commonly restrictive. Due to the flexible nature of the nanogrid, it is possible to integrate multiple nanogrids in order to make a microgrid [89]. Figure 9 represents the grouping of nanogrids to form a microgrid.

3.2.1. The Type of Nanogrid Technology. Various discussions are conducted on DC and AC. As mentioned in [90], when the grid was initially established, there were some technical constraints, which were responsible for the AC grid. In distributed generation, the DC often comprises both power supply and energy storage, which enhances its efficiency; thus, the benefits of DC grid are still under discussion [91]. The primitive block diagram of AC and DC nanogrid networks is represented in Figures 10 and 11, respectively.

The sources used for power generation are quite similar and are explained below:

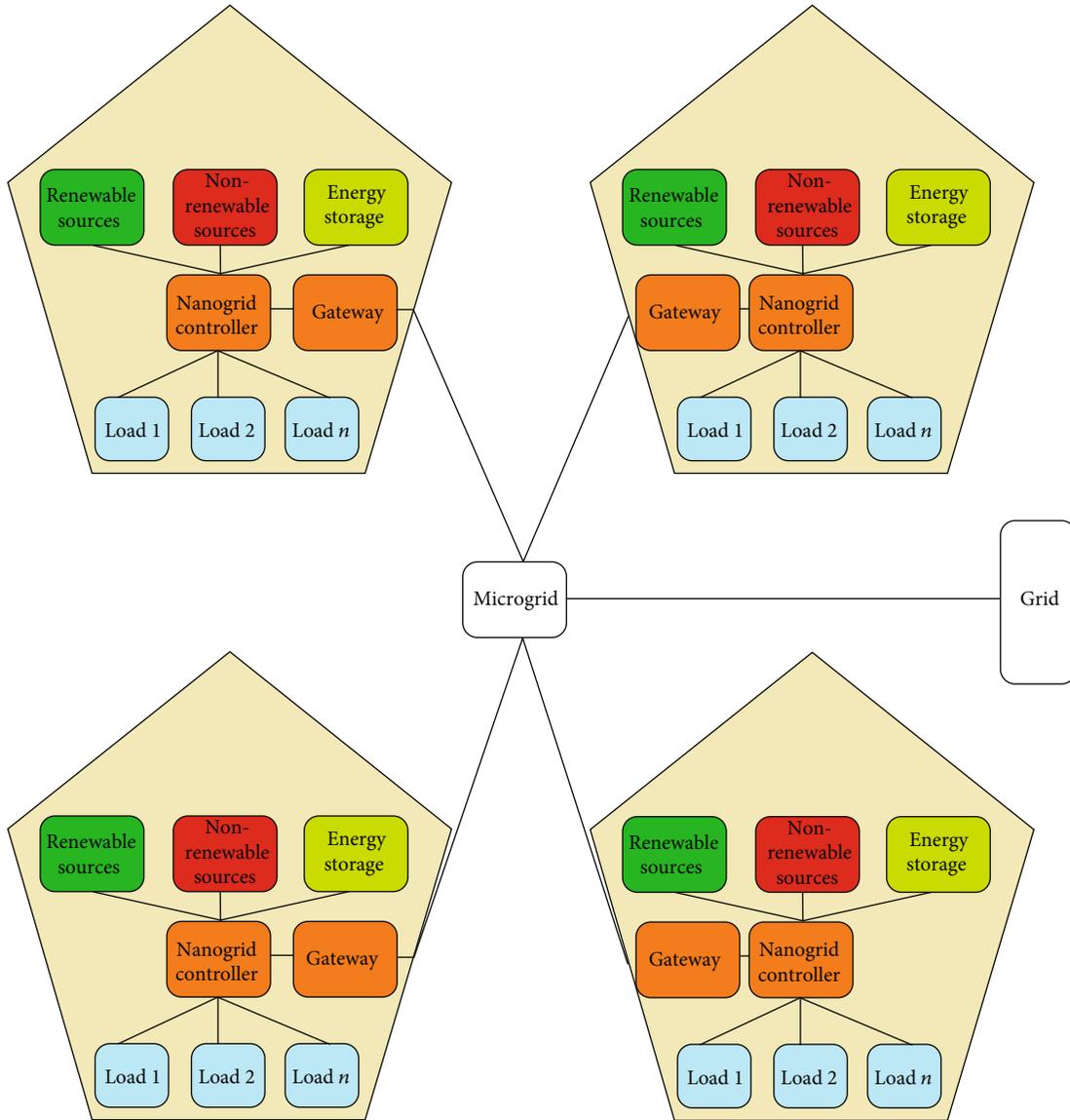


FIGURE 9: Multiple nanogrids form microgrid.

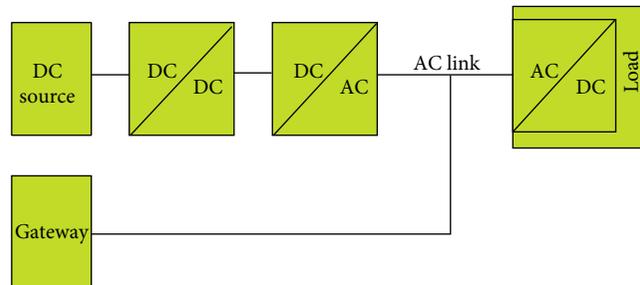


FIGURE 10: Basic block of diagram AC nanogrid.

(i) *The DC Source.* At the source end, the power generation uses the renewable or nonrenewable resources. The generally used resources are the solar photovoltaic (PV) and wind turbines (WT), which include the power generation in

AC, and generally, the outputs are in DC because the battery storage prefers DC supply [92]. Distributed generation also involves a diesel generator and fuel cell but not as much as WT, PV, and batteries [93]

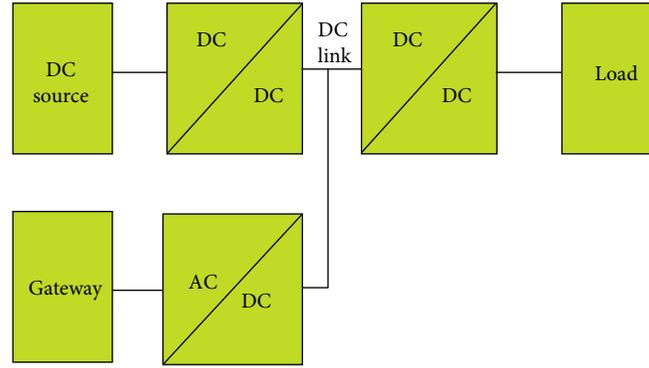


FIGURE 11: The basic block diagram of nanogrid comprising DC.

TABLE 2: Voltage and power for a number of PV units.

Brand	Rated power (W)	Output voltage (VDC)
Shell Aman	150	20.2
Cell Germany	200	36.5
Canadian Solar	300	36.7
Nizam Solar	250	30.4
Hisel Solar	265	31.6

- (ii) *A PV Module or WT Output Voltage Which Is Less than 50 V* [94]. PV or WT are connected with batteries for storing charge during hours of minimum generation. Batteries come in values of 2V which means that by connecting multiple batteries, common values can be achieved such as 2V, 4V, 6V, ..., 18V, 24V, 48V. Also, connecting PV or WT in series gives rise to voltage, and current remains the same, where a parallel connection gives rise to current while voltage remains the same. The number of photovoltaic/small-scale wind turbine (PV/SSWT) modules may increase depending upon the power requirement of load for specific nanogrid. Table 2 shows power and voltage for a number of PV units
- (iii) *DC-DC Converter Source*. It is a circuit that accepts a DC input voltage and converts it to a higher DC level or a lower DC level for any of the desired application. Source voltage needs stepping up; therefore, boost or buck boost converters are used
- (iv) *Multiple Source Interfaces*. Nanogrids can have multiple sources, e.g., the hybrid power system is capable of having a PV array or WT and energy storage, hence supplying power to the nanogrid. The characteristics of an energy source are different, and for integration, a DC-DC converter is required. This converter provides protection and voltage regulation [95]
- (v) *Bus Voltage*. Source voltage could be boosted using DC-DC converters to the desired voltage level [96] of approximately 380V at the industrial level and

hence becomes standard for the industrial sector [97]. Rectification could be done in case of AC voltage. It also uses DC bus as an additional advantage to regulate the nanogrid

3.2.2. DC Nanogrid. The load is at the other end of the DC source, and it uses the converter which is DC-DC for integrating with the DC bus and also the AC power required for the gateway. The following are some commonly used converters.

- (i) *DC-DC Load Converter*. At the load end, the converter used is DC-DC which boosts up the bus voltage up to the desired load level. The external buck converter used is DC-DC which performs the boost-up function for the DC nanogrid. Just like the step-up converter, the buck converters show an excellent efficiency of more than 80% [98]. For this stage, the voltage levels of standard telecom are either 24V or 48V [99]. DC loads generally operate efficiently at 12V, 24V, or 48V. As compared to the DC loads, the AC loads have a minimum range of application [100]
- (ii) *Bidirectional AC-DC Converter*. For interfacing the local nanogrid with the national grid, a bidirectional converter is required [101]. The nanogrid is capable of selling its excess power to the grid (DC-AC) [165] and vice versa (AC-DC). If its generation is not sufficient, the nanogrid can purchase electricity from the grid, to fulfill its demand. The efficiency of the AC-DC converter that is bidirectional should be up to 80%, and advance design converters should have effectiveness up to 95% [102]

3.2.3. AC Nanogrid. The AC nanogrid has additional conversion as compared to DC nanogrid. It takes place as follows:

- (i) *DC-AC Converter*. The output of this type of converter is 230VAC. From the source, it takes the DC voltage and provides rectified AC to the commonly used loads. The nanogrid also receives the same amount of voltage level from the national grid. Inverters discussed in [103] have conversion efficiencies greater than 90%

TABLE 3: The efficiency of AC-DC conversion for AC loads [105].

Appliances	Average efficiency of AC-DC conversion (%)
Refrigerator	87
Computers/laptops	80
TV/LCDs	85
Lighting/fans	82
Home audio	79

- (ii) *AC-DC Load Converter*. For converting AC-DC, power adaptors are used, for example, cell phone, television, and personal computers. For the load less than 15 W, the efficiency varies between 20% and 75% whereas the devices consuming high power have greater power conversion efficiency of 50% to 90% [104]. The efficiency of conversion of some of the household appliances is shown in Table 3 [105]

3.3. DC Nanogrid/AC Nanogrid Comparison. While comparing the DC and AC nanogrid, it is hard to decide which one is superior, without considering a number of elements. DC nanogrid has advantages over AC nanogrid if only considering efficiencies [106]. The DC-DC converter has similar efficiencies for both topologies. The operating conditions (magnitude of power often passed through) for DC-AC converter hardware drastically effect the efficiency of the system. In the AC nanogrid, the largest loss is the AC-DC conversion at the device level and is almost 14% of the total loss of the system [107].

In the future, the DC nanogrid is foreseeable. Most of the product appliances at home are still AC loads. There is a need for compatible DC load, or the existing AC load needs to be modified to operate on DC-based power; this will enhance the initial capital necessary for installing a DG at the domestic level and the increased efficiency in the long run and will be capable of covering the additional cost. More DC appliances are being sold by companies as PV and batteries have huge impact on the overall system.

It is defined in literature that protection is also an issue for DC nanogrid [108]. The ground fault and the short circuit line fault can occur easily at loads, storage, and switching devices, which can burn the whole system [109]. Advance safety schemes and circuit breakers can resist against these faults as in [110, 111].

3.3.1. Nanogrid Control. This can be split up into two groups: supply-side management (SSM) and demand-side management (DSM).

The former controls the supplies of nanogrid such as solar PV/wind turbines in order to power local loads and to optimize the state of charge for battery banks. And the latter manipulates the load to meet the characteristics of the supply.

Supply-side management is a crucial step in nanogrid control, because the multiple sources are linked and their integration needs to be synchronized in order to select a specific source to supply to the nanogrid, e.g., PV supplies power

to the load at first priority, and the rest of the load is shifted on the utility. Also, maximum power point tracking (MPPT) is employed in PV-based nanogrids. In order to ensure the maximum power extraction, these trackers are in series with the PV modules hence increasing their efficiency. In [112], supply-side management (SSM) is implemented with MPPT for solar PV modules. This results in the adjustment of power from an additional power source, e.g., grid, to enhance the PV system hence reducing the power losses.

Demand-side management (DSM) on the other hand can be achieved in a number of ways. A related technique is load shedding, in which a desired control goal can be achieved by switching off the loads. In [113, 114], load shedding is used by the authors for peak load demand reduction and for overload prevention of the DC bus. This technique adds adjustability to DSM. The control system calculates an appropriate time for the load operation rather than switching off the loads. The control system is obtained in the form of real-time pricing for the utilities in [115, 116]. It uses the dynamic power pricing by shifting power consumption to low power pricing time slots. A rule-based system is proposed in [117] which switches or reduces the load at peak hours.

In [118], a flattening peak demand is suggested as another form of load scheduling. Here, the difference between the crests and troughs of the power usage is reduced or flattened. This helps in reducing the grid functioning costs and hence the transmission, generation, and the fuel costs.

3.3.2. Nanogrid Hardware. Converter topologies dominate the nanogrid technologies. These converters are used to meet the voltage requirement for the specific load. It integrates the nanogrid source supply with the national grid. The nanogrid converters are categorized as DC-AC, DC-DC, and AC-DC.

The DC-AC converter uses DC supply voltage as an input and AC supply voltage as an output. To ensure the desired DC level before conversion to AC, these converters have a DC-DC converter at the front. These converters are similar to AC-DC converters, but the functioning is reversed in them.

DC-DC converters use DC voltage as an input and a modified DC voltage level as an output. This can be achieved by using reactive components in the converter and also by using diodes as switching components. In the buck style DC-DC converter, the output voltage is always less than the input, whereas in the boost style, the output voltage is always greater than the input voltage, and in the buck-boost converter, the output voltage can be either less or greater than the input. Other than converting the voltage, these converters can be used as MPPTs or for controlling a battery bank charge and discharge.

The research on the nanogrid focuses mainly on enhancing the converter efficiency and boosting the power quality for the load. The nanogrid control can be enhanced by reducing the physical size of the system.

3.4. Microgrid. Microgrid uses nanogrid as its building units. Nanogrid is an adaptable power system which is ideal to

establish an interconnected system which satisfies the individual demands of diverse consumers. When these interconnected nanogrids form a network, they give rise to microgrid. Microgrid is a power distribution system just like the nanogrids as it can also isolate itself from the linked power utilities. Microgrids cover large entities such as hospitals, institutions, and small communities, whereas nanogrid is restricted to a small system mostly a single house or building. The supremacy of microgrid can be evaluated as follows:

- (i) Sharing power in bidirection is the utmost priority of the microgrid. A small utility mostly has varied curves for power consumption, and also, the production of power at a small level shows a varied pattern, but in the microgrid, the diversity in the various utilities within favors the utilization and sharing of excess power. This reduces the power purchase demand from the national grid hence resulting in financial saving of the consumers
- (ii) Communication is another crucial attribute in microgrid, which is responsible for the intelligence of this network. Numerous technical and security-based considerations form the multiple layered communication within the microgrid. The controllers survey the data gathered and implement the desired control strategies. This communication can deal with the sharing of power back to the grid and microgrid as well
- (iii) Flexible schedulability is a unique property of microgrid. The microsource and load in this system give it an advantage over the large grid. This property of flexibility makes it possible to ensure an uninterrupted power supply to the priority load in case of accidental blackout. It minimizes the losses due to natural disasters and helps in covering up the flaws of the large grids
- (iv) The diversity in the microgrid composition gives it an edge over larger grids. It is comprised of both the traditional power and renewable energy. Meanwhile, it also includes energy storage devices crucial for the system stability and operation. It can deal with the diverse variety of loads spanning the sensitive type, nonsensitive type, controlled type, non-controlled type, etc.
- (v) Controllability is another characteristic of microgrid. As per varying operating conditions, it can opt from different operation modes and the ideal control strategy gives improved reliability and guaranteed security
- (vi) Accessibility is another problem solved by using microgrids. Microgrid makes use of the distributed energy and hence can work out the difficulty in providing power in remote areas where the power grid cannot be built and thus plays its role in economic development of these areas

3.5. *Smart Grid*. Continuous supply of power is an utmost necessity of today. The increase in generation without major changes in infrastructure has made the system more unrealistic and unreliable; these problems lead towards the black-outs and grid failure [119]. There is a great need to upgrade the existing grid to cope with the challenges for tomorrow such as increasing demand, economic progression, and extreme power demand. The power generation system is required without any CO₂ emission, tariff reduction, and integration of renewable energies which can communicate with end customers, with increasing efficiency and reliability. Thus, the most reliable and efficient system known as “smart grid” was introduced.

A smart grid is an updated legacy grid where the customer and supplier can communicate with each other and collect and act upon information; such information is behavior of the customer as well as supplier in an automatic way to enhance the reliability, efficiency, and sustainability of the distribution system [120].

Distribution generation, home energy management systems, automatic switching, and plug-in vehicles lead to an efficient grid.

The main goal is to increase the throughput without increasing more generation, hence using smart techniques. Saving one watt is better than generating more. In comparison to the traditional grid, the smart grid offers two-way power flow, which opens new ways for utilizing DG for individuals in a more effective manner. It enables more services such as charging of plug-in electric vehicles (PEVs), self-healing capability, reduced tariff, peak off, and peak power consumption and minimizes the environmental discharges. SG is best described as the strengthening of the 21st century power grid, also known as the future grid or intelligent grid, which could be capable of making its own decision in both normal and worst conditions.

3.5.1. *Advantages of Smart Grid*. In comparison with the traditional grid, SG has many other advantages.

- (i) End users are well informed and involved about their load profiles
- (ii) SG uses digital devices such as microprocessors as compared to the traditional grid having electromagnetically operated devices
- (iii) SG offers two-way communication and power flow whereas the conventional grid offers only one directional power flow
- (iv) SG can integrate the distributed power generation whereas in the conventional grid, the power generation is centralized
- (v) There is limited safety in the conventional grid whereas SG gives more protection, self-monitoring, and control
- (vi) In the conventional grid, electricity cannot be restored automatically whereas SG have self-healing capability

TABLE 4: Comparison between traditional grid and smart grid.

Traditional grid	Smart grid
Electromechanical	Digital technology
Less consumer choice	More consumer participation
One-way communication	Two-way communication
Slow reaction time	Fast reaction time
No energy storage	Energy storage
Manual operation	Self-healing capability
Manual checking	Self-examining
Centralized generation	Distributed generation
Utility control only	Utility control along customer participation

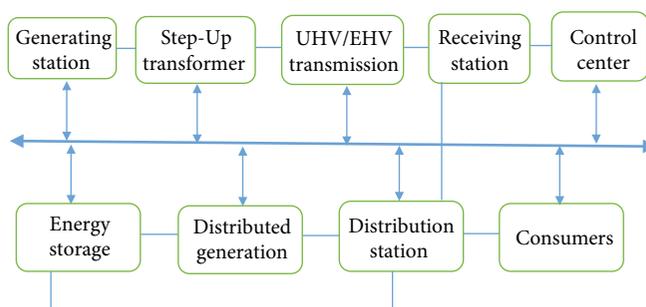


FIGURE 12: Smart grid illustration.

(vii) Remote monitoring is offered by SG whereas it is not present in the conventional grid

(viii) Reliability of the smart grid is predictive whereas on the other side, it is estimated

The smart grid has the ability to handle unpredictable loads; hence, it allows real-time interference of end users using various communication protocols and intelligent devices/sensors. The comparison between the traditional and smart grid is tabulated in Table 4.

3.5.2. Smart Grid Illustration Worldwide. The smart grid is considered to be an intelligent power system which can meet unpredicted load curves and can integrate any distributed resources along with energy storage. The SG offers more electric power utilities, accurate business standards, end-to-end power distribution control, and further a secure framework [121]. Figure 12 is representing general work of SG.

At the present stage, the major concerns are safety, power losses, optimal power utilization, conservation, and sustainability of energy. In view of latest scientific innovations and developments, the application of SG is very potential in the global energy system. In order to acquire a clean, friendly, economical, safer, intelligent, and flexible grid, various organizations and nations including Pakistan have to accept and implement SG on a wide scale. Figure 13 characterizes the development of SG technology among major regions of the globe [122].

3.5.3. The Components of Smart Grid. The following are some of the basic components of a smart grid.

(1) *Monitoring and Control.* Monitoring and control in the traditional grid have no reliability, resistivity, and capability to repose against the fault. With the incorporation of new sensors, the ability to accommodate real-time power flow, improved phasor measurement unit (PMU), phasor data concentrator (PDCs), accelerates old grid to a new grid in the form of smart grid with integration of renewable technologies, enhanced grid capacity and greater productivity and dependability [123].

(2) *Transmission Network.* In the transmission component, load stations and substation are interconnected, which is the main component of the power system. The traditional system can be made smart using smart tools like smart sensors, PMU, and some communication components. It enhances the system reliability and customer satisfaction and increases the power quality issues [124].

(3) *IT, ICT, and IoT.* The grid is now more advanced because of the integration of information and communication technology (ICT), which allows bidirectional communication, between the user and the utility. Reliability of the consumer and direct feedback to the supplier increase the demand and supply in equal proportion. Definitely no wastage of energy or the saving of power leads to a smarter system. Utilization of communication

Countries	USA	Europe	China	Finland
Advancement	Smart metering	Smart meters, renewable energy storage etc	High efficiency Tx, low losses lines T&D	AMI, smart meters etc
Implement	Smart grid related project	Development of smart metering & intelligent devices	Development of HVDC & HVAC along with distributed transformer	Installation of Smart meters with advance ICTs
	Reduction in annual electric bill	Power quality improvement, grid efficiency	Economical distribution of power along the country	Fault diagnosis, volt & reactive power control

FIGURE 13: Smart grid development in major countries.

protocols, topologies, and wireless network increases reliability and remote control access. The wireless communication system is as helpful as the wired systems. ICT makes it more convenient for both systems equally.

(4) *Smart Energy Meter.* Smart energy meters offer both way communication between the consumer and the utility and the power flow. In case of individual local distribution generation, if more power is produced than the consumption, this excess generation could be fed to the national grid. It is beneficial for both the energy supplier and the user. Automatic billing, data logging, and many other such incentives can be availed. Advance metering infrastructure (AMI) has more advantages over advance meter reading system (AMR) [125]. AMI gives two-way communication for data logging between the central system and the meter, whereas AMR allows one-way communication only.

(5) *Virtual Storage System.* Smart storage plays an important role for PV solar systems; the storage devices commonly used are batteries, capacitors, and mechanical fly wheels. Batteries are more commonly used for long-term storage. The major cost of the system depends upon the storage, as the increasing life of batteries reduces the running cost of the system. Smart grid storage design will offer different techniques for managing renewable energy and distribution generation.

3.5.4. *Advances in Smart Grid.* In the past few years, a lot of research work has been done on smart grids. The main goal of this work is to develop more reliable and robust systems for catering the power demand.

Along with the research within smart grids, the current power network involves the implementation of distributed

generation sources [126]. Rooftops of homes have become more popular for PV solar systems. These PV systems are further connected to the local grid using many inverters and can produce many harmful impacts such as harmonics in the national grid. There is remarkable power loss due to conversion from DC solar PV to AC power at the traditional grid and then back to DC for our digital devices and DC loads. The preferable source of power for most of appliances is DC, due to the increasing research in electronics [127].

Inefficient rectifiers and power supplies have been used until now, which add harmful impact on over all power systems. Many devices like LED lights, televisions, mobile chargers, personal computers, and audio systems use DC supply. An alternate smart grid is designed, and it is suggested to minimize the variable power conversions. A smart control priority is also defined for the system which provides extra benefit during the peak hours and maximum utilization of solar PV at daytime and smart battery storage during nighttime with the prediction of weather conditions and load forecasting [128].

Another viewpoint is user accessibility to control the load and operation of the grid. With the integration of solar PV, end users are participating in the operation of that system. It is significant to give them a little bit of ability to control their usage and have some influence over the grid as well.

Nowadays, we have solar photovoltaic array on the rooftops and the plug-in electric vehicles (PEVs) on the roads [129]; if the PV power is not converted to AC, the efficiency of this whole system would be much higher. In between are the battery storage cells which allow compatibility for different DC appliances just like toys with different series and parallel combinations of cells but here with more ampere hour rating, many combinations to produce variable DC voltage

levels than going DC-AC-DC conversion. These conversion losses alone effect the overall efficiency of the system.

Some researches indicate various issues for proper integration of solar PV with existing grid and battery storage systems [130]. They also explain multiple ways of setting up for the battery storage system in the smart grid. The authors in [131] present a small model of the DC-DC buck-boost converter which offers the desired DC voltage level for specific DC appliances. However, the authors in [132] focused on the perfection of energy productivity in solar PV systems. They introduced many ways to increase the efficiency of solar PV systems. They analyzed and surveyed the proposed approaches for increasing the efficiency of the said system. It was found that maximum power point tracking (MPPT) along with battery charging and discharging techniques plays a vital role for maximum efficiency in solar PV systems.

In the field of the smart grid in the last few years, numerous discoveries have been made. Their goal is to make the existing system more reliable, cheaper, economical, and smarter to cater the current power supply demand using the smart grid in addition to utilizing maximum solar PV distributed generation. Proper use of rooftop solar array systems has turned out to be truly useful for local home-based practices. There is about 22% loss of power due to various conversions from DC to AC and then AC to DC. Most of the appliances accept DC power; therefore, they are directly coupled with solar PV and battery storage. For other devices which do not accept DC, the conversion problem still prevails. If power is converted from low-level DC voltage to higher-level AC voltage, then it is needed to step up a low level voltage from a solar PV to the conventional voltage level (220 V) and then further convert to AC.

These solar PV arrays are fed to the local grid using different inverters with conversion losses, because solar PV produces DC supply and existing utility accepts AC only. Series combination of solar panels thus adds up the voltage to the desired level instead of using step-up transformers to avoid the transformer as well as conversion losses.

3.5.5. Electric Grid Challenges. The legacy grid in Pakistan and in other nations is source-defined, and all are centralized power distribution systems. The demand of electricity is increasing in the world due to the rapid increase in population. The present grid infrastructure design is outdated, and it cannot be expanded easily with the increasing power demand [133]; it faces many challenges that can be outlined in three points. First of all, it has an infrastructure problem that is not feasible for increasing demand resulting in congestion on the network because it does not have the ability to react timely on this issue. Ultimately, such imbalance of load leads to blackouts that will be very costly for utilities; this is due to the lack of communication technology between the utility and its control center. The second flaw is that there is a need of more transparency and information relative to the market for customers to make their decisions to reduce consumption of electricity during peak hours. Finally, the third and the most important aspect is the integration of renewable sources like the wind mill and solar. The present grid does not support the renewable energies or other forms

of renewable resources that make the system more sustainable. In the upcoming years, the demand will rise up to 19% and the present infrastructure is capable of generating only 6% of the increasing demand. In fact, renewable energies are facing serious problems with a grid that does not propagate information to control centers [134]. All these problems can be solved by the smart grid through improved communication technology with numerous benefits for supply and demand sides of the electricity market.

3.5.6. Load Management in Smart Grid. A lot of contribution in overall improvement in efficiency of the power system is expected by the utilization of the smart grid technology specially the demand-side management, but demand response is also a technique to reduce the energy demand [135]. For example, in DSM, turning off the load in peak hours for a short time will result in overall improvement of electricity price. In this way, less redundancy on distribution and transmission lines and less utilization of generators lead to lower prices [196]. With the passage of time, the load connected with the power grid fluctuates considerably. This load is the sum of the individual load, overall load is not stable, and growing of the load is sudden and slowly varying. If a popular television program starts and millions of television start up, this load will rise and the system reacts badly. To respond to the increasing power demand, a stand by generator or any other source is required. The TV users might be cautioned to turn off the large load temporarily by the smart grid or start a generator to back up the load. Communication and smart metering are used in homes to reduce the overburdening in the peak hour's usage demand when the load demand is high. It also tracks the usage of energy and can also communicate with the utility and customer's devices directly to prevent the system overloads [136].

Electricity price during peak hours is high and lower in off-peak hours, so in the smart grid, it is assumed that consumers will tend to use less electricity during peak hours; it is also possible for the user and devices to be aware of peak hour tariff. In this way, tradeoffs can be made by switching of devices like ACs or dishwashers at 11 pm instead of 7 pm. When the customer and supplier see their direct economic benefits of using energy at off-peak hours and include all operational cost in their devices and building construction decisions for efficient energy usage, it will be beneficial for both supplier and user [137].

3.5.7. Demand Response in Smart Grid. Demand response cooperates with the generator and loads automatically in real time to compress the spikes. By eradicating these high spikes, the user can remove the cost of the reserved generator and increase the life of equipment and reduce the electricity bill by using the energy in lower tariff hours. Demand response is a demand that can be changed by a trigger. Changes in the electric usage by end use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [138].

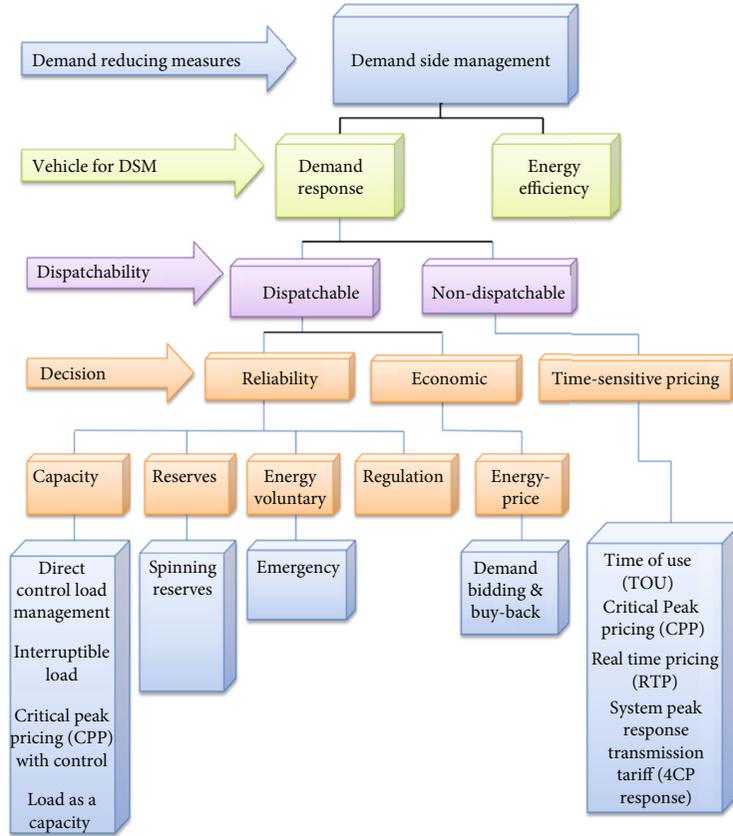


FIGURE 14: Demand-side management catalog [140].

Power grids have a variable degree of communication for their exclusive characteristics, i.e., power transmission and distribution lines and in power plants. It is basically one-way communication from the user to utilities. The supplier struggles to come up to the mark to variable degrees of black-out. The total sum of power demand by the customer has broad probability distribution which needs extra power plants to generate power in response.

The major issue faced is the inaccessibility of data flow as the one-way communication is very costly, which is a major issue in power grids. Some early meter infrastructures receive data with as long as a 24-hour delay deprived of any response by the supply or demand load [139].

3.5.8. Demand-Side Management. Demand-side management is a method to adjust the consumer demand of energy through financial encouragement and education. It was realized the first time in 1970s that there is need to regulate the demand to shape the load profile. The main aim behind the demand-side management is to convince the user to use less energy during peak hours and shift towards the off-peak hours [140]. Peak clipping, peak shifting, valley filling, and increasing energy efficiency are major objectives of DSM. It helps the users to reduce their utility bills and utility to minimize the need of peaking their plant capacity. End users want cheap supply of energy with minimum interruption whereas the utility's all-time goal is to balance the load curve with the least

peak to average ratio (PAR). It is not necessary that the demand-side management should reduce the total consumption of the power, but it should decrease the investment on the networks and power plants to cope with the rapidly increasing demand. DSM, demand response (DR), and load management (LM) are all the same inter-connecting concept and are used mutually.

Demand-side management is one of the most important techniques for optimum flow of energy management where the consumer's behavior is subjected to manage the electricity demand [141].

There are different types of demand-side management (DSM):

- (i) Energy efficiency (EE)
- (ii) Demand response (DR)
- (iii) Dynamic demand (DD)

The demand-side management catalog is given in Figure 14. In the energy efficiency program, less energy is used to perform the same task. Demand response includes all the programs which are used to reduce the peak demand of end users that are intended to change the timing and total electricity consumption whereas in dynamic demand, the power factor of the power grid is monitored as well as their individual parameters and the intermittent loads are switched on or off to balance the overall system generation.

3.6. Electricity Tariff Schemes. There are two types of pricing: flat rate and dynamic pricing. The flat rate is a simple pricing mechanism, and it also has the least risk. Whereas in dynamic pricing, the main benefits are reduction in the customer's bill, and it also reduces the network congestion. Dynamic pricing has greater benefit for distributed energy resources, and it has less environmental concerns.

In flat rate pricing, all the usage is charged at a fix rate for the given time period, whereas dynamic pricing has varying rates according to the time of day or season in the year. Dynamic pricing enables the customer to reduce the usage during peak hours.

According to the literature, dynamic pricing has five types given below.

3.6.1. Real-Time Pricing (RTP). Real-time pricing is a pricing model that intends to reflect the price of electricity for each hour out of 24 hours. It varies from hour to hour. A tariff based on spot price is called the real-time pricing model. If the real-time pricing tariff is announced, the customer will alter their energy usage accordingly [142].

The significance of RTP can be explained as follows.

- (i) Maximum financial remuneration in comparison to other dynamic pricing [143]
- (ii) A fine form of dynamic pricing and ideal from the signal pricing point of view
- (iii) Customers pay their bills according to the electricity cost on an hourly basis

To realize the benefits of the smart grid, "smart rates" are essential. So RTP encourage the consumer to conserve and shift their loads when electricity has low rates. It also motivates the consumers to utilize the renewable energy resources during peak hours to avoid the network congestion. Use of distributed energy resources (DER) improves the financial benefits. It also encourages the customers to invest in energy-efficient devices to conserve energy during the peak hours.

3.6.2. Time of Use (TOU). The TOU energy pricing model is the time rate where the price of electricity depends upon the energy usage, and also, different hours have different prices, e.g., peak, off-peak middle, summer, and winter have different prices [144].

3.6.3. Variable Peak Point (VPP). It is the combination of real-time pricing and time of use. Different time periods are defined in advance, but peak hour price is defined by the utility and market [145].

3.6.4. Critical Peak Pricing (CPP). It is a dynamic pricing model where high pricing is used to handle the high demand of electricity. It is only charged on certain events of electricity usage [146].

3.6.5. Critical Price Rebate (CPR). Critical peak rebate is a pricing model where the utility company pays the customer

for reducing their consumption in peak hours and the company only pays for reduced kWh [147].

3.7. Super Grid. The super grid is an emerging concept which employs a wide-area transmission network for great distances and transmits electricity through this wide range in bulk. It is also termed as "mega grid." The super grids integrate the local smart grids intelligently into a single wide area super grid through a long-distance transmission layer. This bulk transmission of energy uses HVAC and HVDC lines. The near future predicts the use of experimental superconducting "super grid" technology, to avoid the voltage loss, where the liquid hydrogen pipeline will be used to cool the transmission cable. The smart grid technologies will be used in controlling the network, in order to detect the flaws in the network due to the abrupt changes in the availability of renewable energy resources.

4. Simulation Design

Basic flow of energy from solar and utility is shown in Figure 15. The detail of implementation of the system is given as below.

The procedure of implementation and techniques to verify the required results is explained here. All the experimental work is further performed in MATLAB Simulink. MATLAB is a programming language where the system is simulated and results were produced. Simulink is a graphical programming environment which is used for simulation and analysis. Simulink supports system level design, Simulink code generation, and testing and verification of the embedded system.

4.1. Global Controller. A global controller is a controller which is used to control the basic, regular, and burst loads, respectively. It checks the power of solar, and according to the predefined threshold, it switches the load on or off. If the power is less than the desired load power, it will automatically shift the load towards the utility by initially checking whether the power is enough to switch on the basic load; otherwise, the total load is shifted on to the utility. Every house has its own global controller, and in the houses with no solar system, the controller switches off the load at peak hours. The flow chart of the global controller is shown in Figure 16.

4.1.1. Load Controller. A local controller is a controller which is used to control the individual load of every house. There are three local controllers for a single home: one for the basic load, one for the regular load, and the last one is for the burst load. This controller will check the solar power and compare it with the load demand. If the power is enough to derive the load, then the load will automatically shift on to the solar system; otherwise, it will remain on the utility. The flowchart of each controller is shown. Controllers are discussed in the form of cases.

(1) Case 01. Case 01 is for the basic load where three basic loads were connected like lighting, TV, and fans. When the solar power is greater than any of the above-mentioned load, that load is switched on. Next, if the demand of the remaining load is still less than the solar power produced, it will be

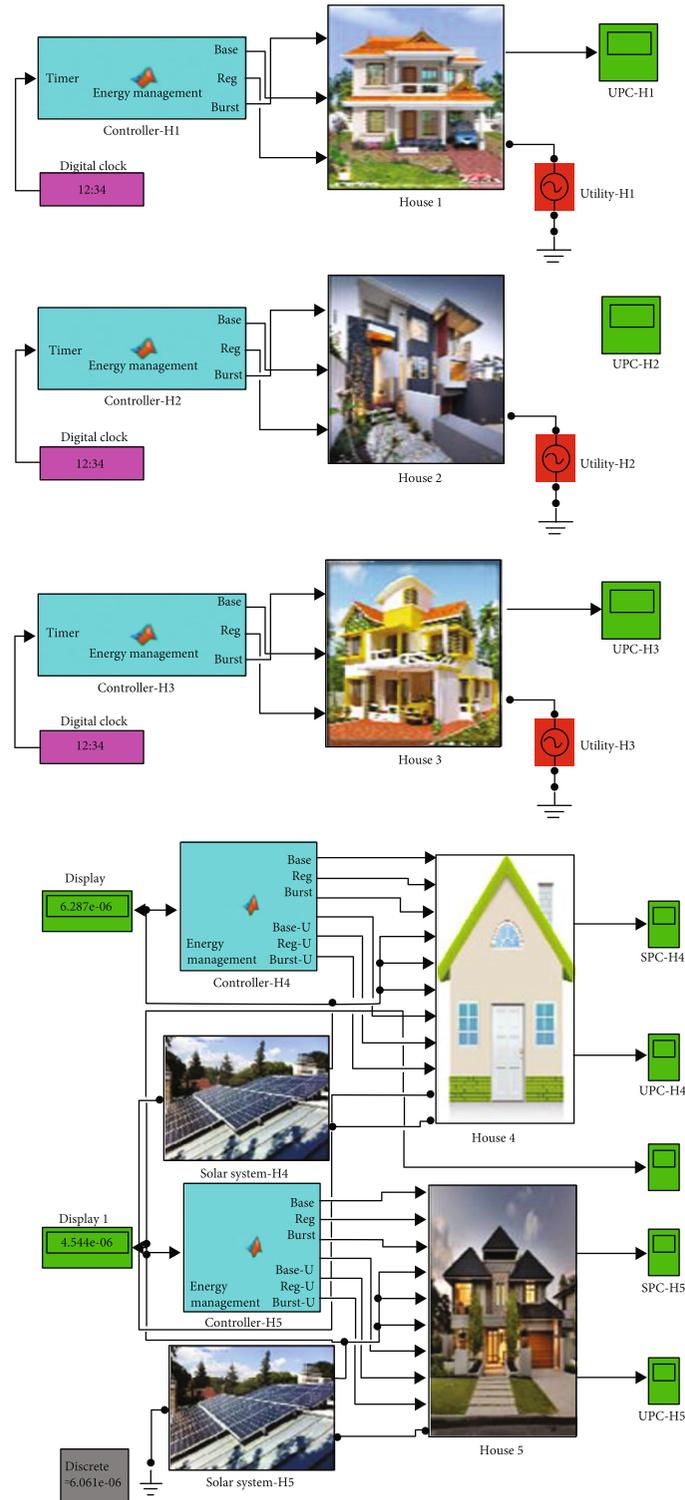


FIGURE 15: Proposed energy management system.

switched on accordingly; otherwise, the load shifts to utility automatically. The flowchart of the controller is shown in Figure 17.

(2) *Case 02*. Case 02 is for the regular load where four loads are connected like the fridge, water heater, and central cool-

ing. When the solar power is greater than any of the above-mentioned load, that load is switched on. Next, if the demand of the remaining load is still less than the solar power produced, it will be switched on accordingly; otherwise, the load shifts to utility automatically. The flowchart of the controller is shown in Figure 18.

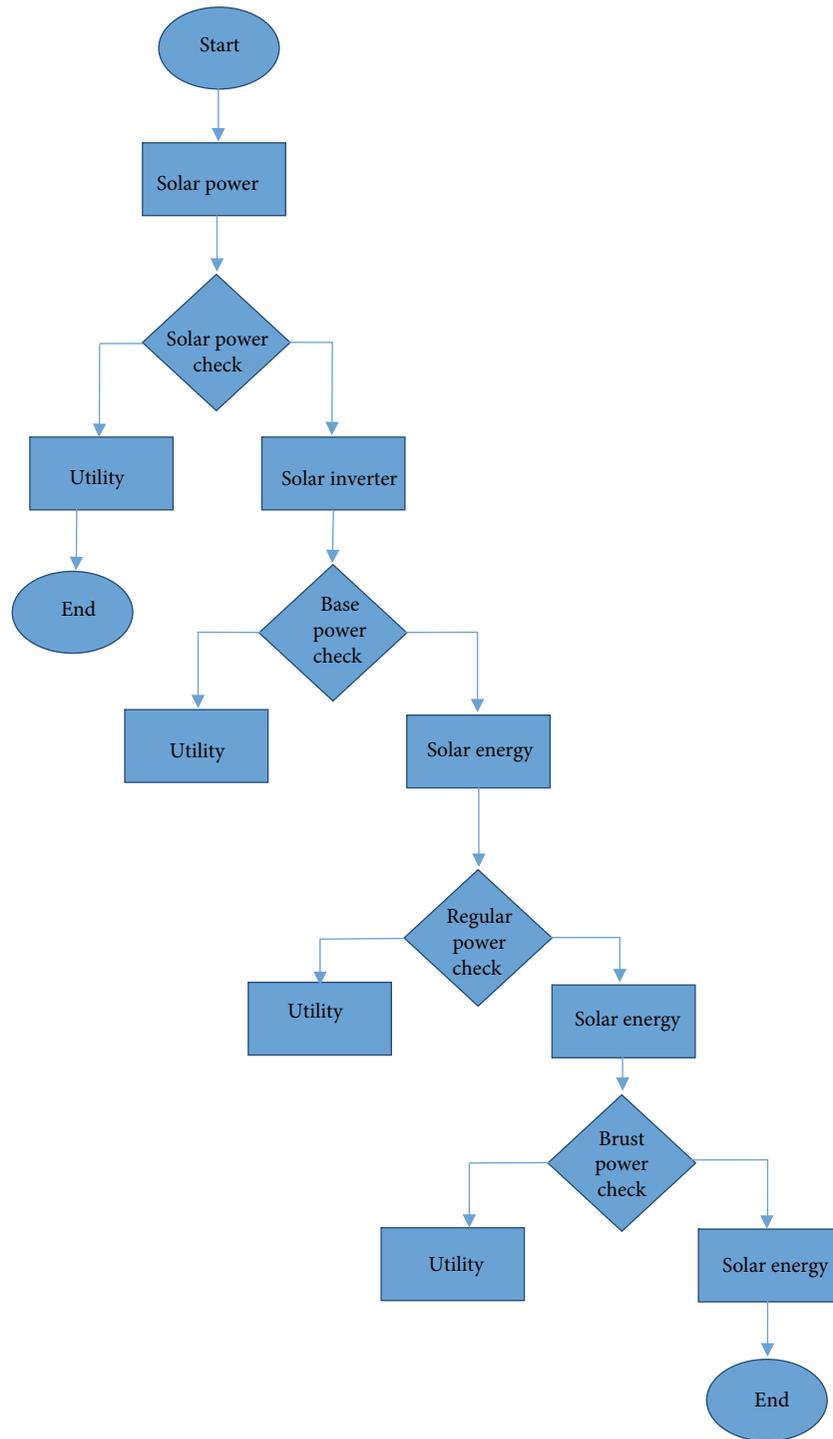


FIGURE 16: Global controller flow chart.

(3) *Case 03.* Case 03 is for the burst load where four basic loads are connected like the electric iron, water pump, and dishwasher. When the solar power is greater than any of the above-mentioned load, that load is switched on. Next, if the demand of the remaining load is still less than the solar power produced, it will be switched on accordingly; otherwise, the load shifts to utility automatically. But this burst load will only be switched to the solar during peak solar pro-

duction hours; otherwise, it will remain on the utility. The flowchart of the controller is shown in Figure 19.

4.1.2. Solar Profile. The solar system is designed for 15kW at 1000 irradiance (W/m^2); the profile is shown in Figure 20. When the solar irradiance is at its peak, then the power generated from panels is 12 kW; average voltage is 482 V.

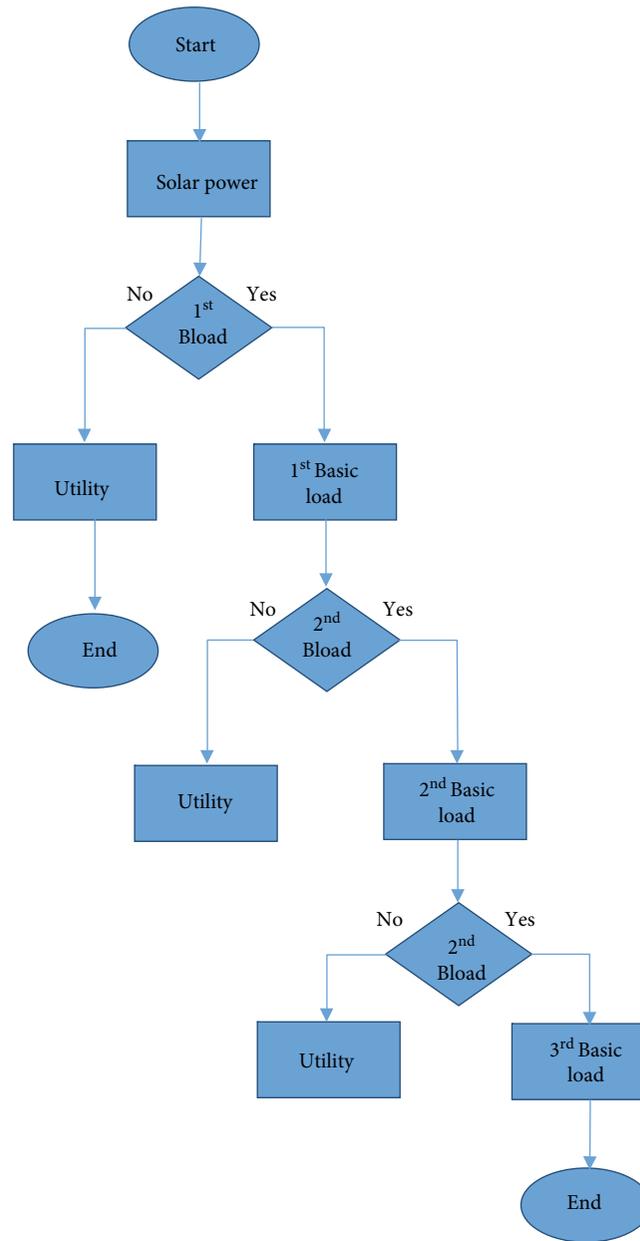


FIGURE 17: Basic load controller flowchart.

4.1.3. Energy Management Unit (EMU). In the energy management unit (EMU), energy generated from solar is controlled by specifying the power generated through the solar PV system. From the PV system, power is introduced to the controller. It has six outputs and one input where basic, regular, and burst loads are switched through a circuit breaker. This controller contains two circuit breakers, one connected to the PV system and the other to the utility. Each load has an individual controller connected with a local controller. When solar power is less than the basic load, it will be operated through utility; a similar pathway will be followed by the regular load and burst load.

4.1.4. Nanogrid Implementation in Simulink. Five houses are developed where the switching scheme of the load was simulated. The first three houses do not have solar systems installed in order

to compare the flat rate and real-time pricing with house nos. 4 and 5 where the solar system is installed. Real-time pricing and flat rates are compared in the later section. The parameters for nanogrid implementation in Simulink require the following steps.

4.1.5. PV Array Sizing. To design the solar system in Simulink, the required solar panels need to be calculated. Calculation of solar panels for house no. 4 is given:

$$\text{Total load of House 4} = 15000 \text{ watts.} \quad (1)$$

To calculate the watt hour, we multiply the backup hours with total watts of load which needs to be switched on:

$$\text{Watt hour} = \text{watts} \times \text{hrs/day.} \quad (2)$$

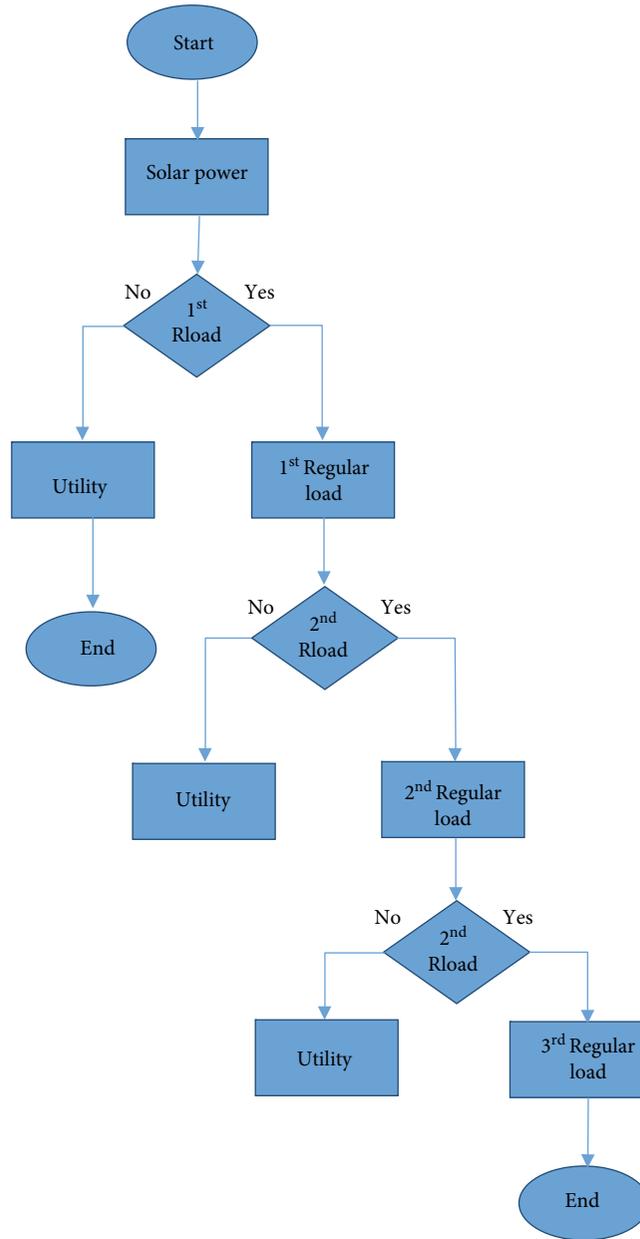


FIGURE 18: Regular load controller flowchart.

The load will remain on the solar system for approximately 10 hours, so

$$\text{Total load in Wh} = 15000 \times 10 = 150000 \text{ Wh.} \quad (3)$$

To compensate the power lost in wires, battery, and controller, one needs to install 130 Wh capacity to meet the appliance energy demand of 100 Wh [148]. Therefore, it is recommended to multiply appliance watt hour demand by 1.3 to install the desired capacity of the PV system panels or modules:

$$\begin{aligned} \text{Panel energy} &= \text{Wh} \times 1.3, \\ \text{Panel energy} &= 1.3 \times 150000 = 195000 \text{ Wh/day.} \end{aligned} \quad (4)$$

The calculation of solar panels for house no. 5 is given:

$$\text{Total load of House 5} = 10000 \text{ watts.} \quad (5)$$

To calculate the watt hour, we multiply the backup hours with total watts of load which need to be switched on:

$$\text{Watt hour} = \text{watts} \times \text{hrs/day.} \quad (6)$$

The load will remain on solar for approximately 10 hours, so

$$\text{Total load in Wh} = 10000 \times 10 = 100000 \text{ Wh.} \quad (7)$$

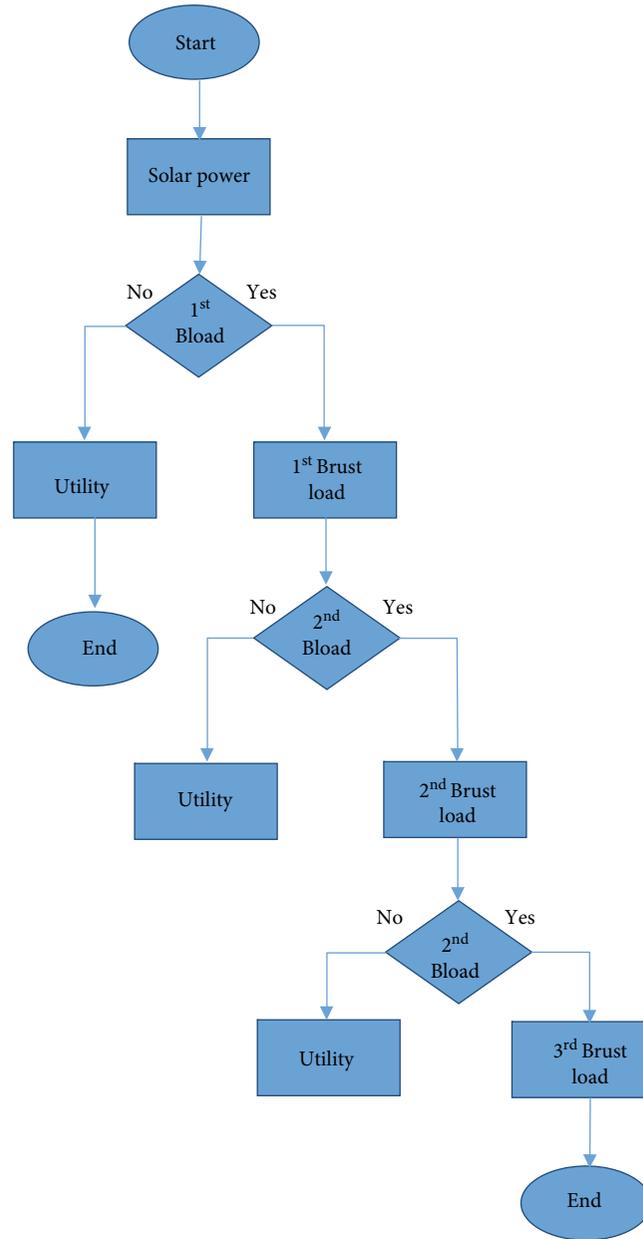


FIGURE 19: Burst load controller flowchart.

To compensate the power lost in wires, battery, and controller, one needs to install 1.3 times capacity to meet the appliance energy demand required load [149]. Therefore, it is recommended to multiply the appliance watt hour demand by 1.3 to install the desired capacity of the PV system panels or modules:

$$\begin{aligned} \text{Panel energy} &= \text{Wh} \times 1.3, \\ \text{Panel energy} &= 1.3 \times 100000 = 130000 \text{ Wh/day}. \end{aligned} \quad (8)$$

For peak power generation, the panel generation factor is given in Table 5.

To compensate the environmental effects, one needs to calculate the panel generation factor. It varies from area to area, and for that reason, values are given in Table 5 [150].

Peak panel power generation for house no. 4 is given:

$$\begin{aligned} \text{Peak panel power} &= \text{Wh} \div \text{PGF}, \\ \text{Peak panel power} &= 195000 \div 3.43 \\ &= 56851 \text{ Wh} = 5685.1 \text{ watts}. \end{aligned} \quad (9)$$

Peak panel power generation for house no. 5 is given:

$$\begin{aligned} \text{Peak panel power} &= \text{Wh} \div \text{PGF}, \\ \text{Peak panel power} &= 130000 \div 3.43 \\ &= 38000 \text{ Wh} = 3800 \text{ watts}. \end{aligned} \quad (10)$$

4.1.6. *PV Generator Design.* To calculate the PV panel size, the total peak panel power is divided from the available panel

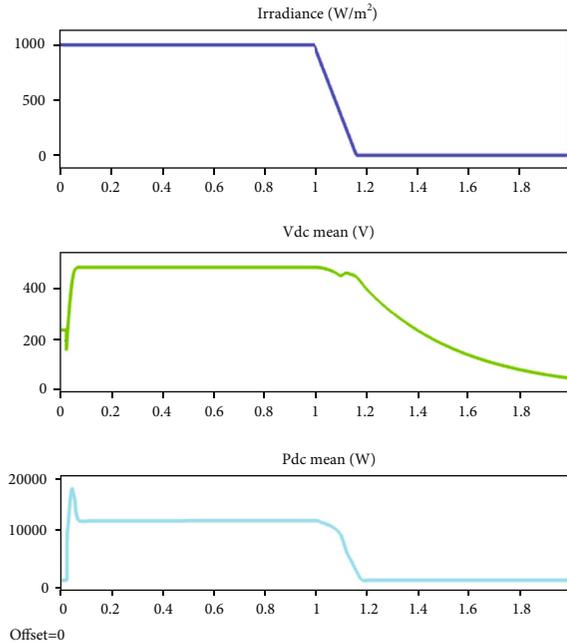


FIGURE 20: Solar profile.

TABLE 5: Panel generation factor (PGF).

S/no.	Environment	PGF
1	Desert area (Balochistan)	3.86
2	Land area (Punjab)	3.43
3	Cloudy area (5-7 days/month)	3.00
4	Cloudy area (>10 days/month)	2.57

size power. Available panels are 100, 200, and 250 watts. In this work, 250-watt panels are used. So, the total no. of panels for house no. 4 is calculated as

$$\begin{aligned} \text{No. of PV panels} &= \text{peak power} \div \text{panel size}, \\ \text{No. of PV panels} &= 5685.1 \div 250 = 23 \text{ panels.} \end{aligned} \quad (11)$$

The no. of panels for house 5 is given in the equation

$$\begin{aligned} \text{No. of PV panels} &= \text{peak power} \div \text{panel size}, \\ \text{No. of PV panels} &= 3800 \div 250 = 15 \text{ panels.} \end{aligned} \quad (12)$$

4.1.7. Battery Storage Design. For battery size calculation, the specific load will be switched on/off which is approximately 2000 W for house 4 and 1500 W for house 5. It is always recommended to increase the panel size from 20 to 30% of the minimum capacity to increase the battery life:

$$\begin{aligned} \text{Total current of load} &= \text{total load} \div \text{battery}, \\ \text{Total current for house 4 load} &= 2000 \div 48 = 42 \text{ amperes.} \end{aligned} \quad (13)$$

Load shedding was considered for 5 hours. To back up the 2000-watt load, a 220 Ah battery is required, so a total of four batteries of 220 Ah are connected in series to make this 48 voltage. The battery configuration for house no. 4 is given in Figure 21. Similarly, for house no. 5, to give a backup to the 1500-watt load:

$$\text{Total current of load} = \text{total load} \div \text{battery voltage},$$

$$\text{Total current for house 5 load} = 1500 \div 48 = 32 \text{ amperes.} \quad (14)$$

So, by considering 5-hour load shedding for a 1500-watt load, a 180 Ah battery with 48 V is required so four batteries will be connected in series. The configuration of batteries for house 4 is shown in Figure 21 and for house no. 5 in Figure 22.

4.1.8. Priority Load Switching. In this work, the domestic load is distributed into three categories as follows: basic load, regular load, and burst load, as defined earlier. In the basic load, television, fan, and lighting are included, whereas in the regular load, fridge, central cooling system, and water heater, and similarly, the burst load involves HVAC, electric iron, dish washer, and water pump. The proposed system for load priority switching is shown in Figure 23.

4.1.9. Graphical User Interface. A graphical user interface (GUI) has been designed to calculate the daily electricity bill of a customer. In this GUI, five houses have been designed and every customer's usage was compared with the flat rate and real-time pricing. The houses with no solar system installed were also compared with flat and RTP rates. The GUI is shown in Figure 24.

It is observed in the simulation below that flat rates are more suitable for PV installed houses where real-time pricing is more reasonable for houses without solar systems.

4.1.10. Electricity Charge Calculation. Electricity charges were calculated by using the IESCO electricity bill, all the IESCO charges, govt. charges, and total charges using the exact surcharges and taxes [151]. The flat rate from the IESCO website is tabulated in Table 6.

Further calculations regarding govt. charges and GEPCO charges are described:

$$\begin{aligned} \text{total kWh} &= \frac{(\text{watt} \times \text{time})}{1000}, \\ \text{financing charges (FC) are } &0.43/\text{kWh} : \text{FC charges} \\ &= 0.43 \times \text{kWh}, \\ \text{tariff rationalization surcharge (RS) } &1.54/\text{kWh} : \text{TR charges} \\ &= 1.54 \times \text{kWh}, \\ \text{Neelum-Jhelum surcharge of 10 paisa per kWh} &: \text{NJ charges} \quad (15) \\ &= 0.01 \times \text{kWh}, \\ \text{Pakistan television fee (PTV fee)} &= 35, \\ \text{duty on electricity bill at govt. charges} &: \text{duty on electricity} \\ &= 0.015 \times \text{total charges}, \\ \text{General Sales Tax (GST) on electricity} &: \text{General Sales Tax} \\ &= 0.1725 \times \text{total charges}. \end{aligned}$$

By adding all the equations, the total bill was calculated.

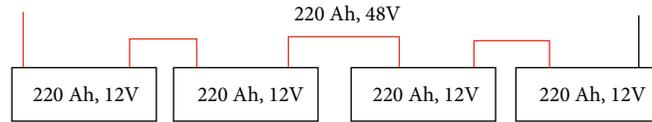


FIGURE 21: Battery configuration house 4.

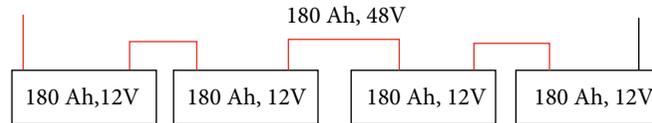


FIGURE 22: Battery configuration house 5.

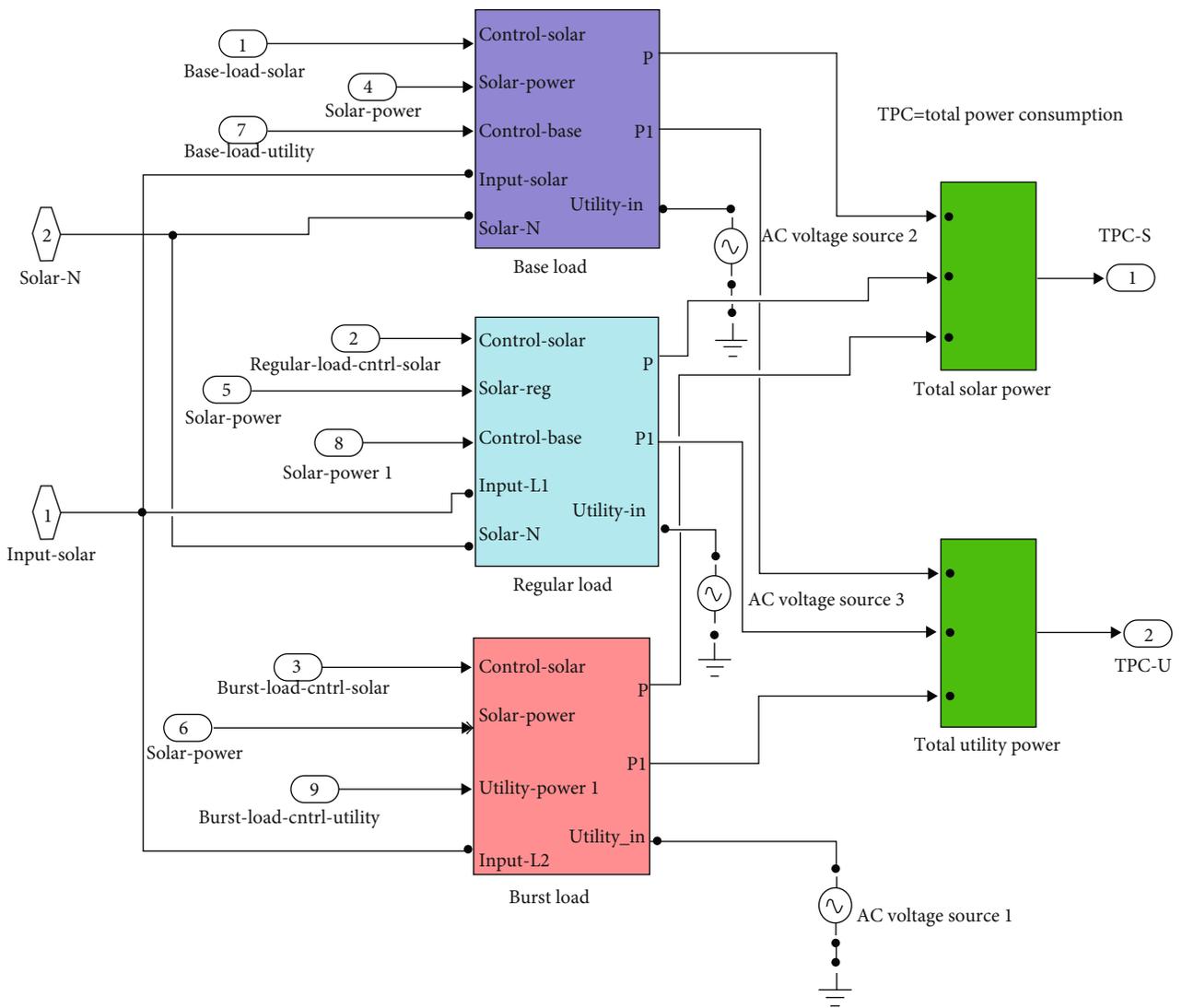


FIGURE 23: Load priority model for proposed scheme.

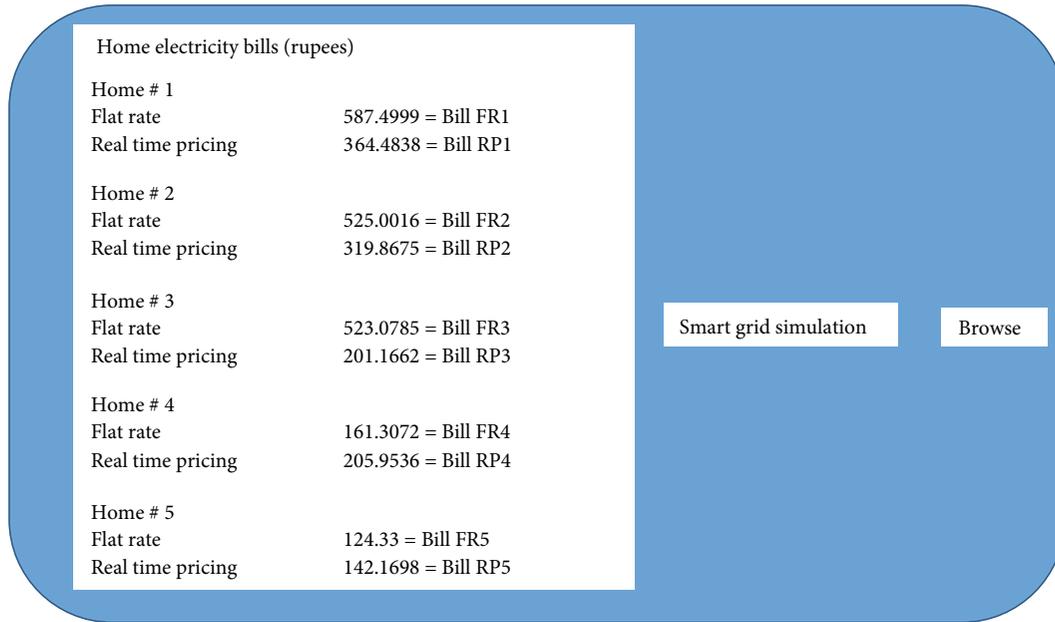


FIGURE 24: Daily electricity bill for five proposed houses.

TABLE 6: Utility tariff set by NEPRA.

S#	Type of tariff	Fixed rates	Variable rates	Tariff rationalization			
				Govt. sponsorship Fixed rates	Govt. sponsorship Variable rates	Surcharges Variable rates	
(a)	Load < 5 kW						
(i)	Up to unit (50)	—	4	2			
	Load Consum > unit (50)			—			
(ii)	Up to 100 units	—	9.25	3.4			
(iii)	Up to 200 units	—	11	2.8			
(iv)	Up to 300 units	—	11	0.80			
(v)	Up to 700 units	—	13.33	—			2.6
	Above 700	—	15	—			3
(vi)	Load < 5 kW & greater						
			Peak/off-peak	Peak	Off-peak	Peak	Off-peak
	ToU	—	15/9.5	—	—	3	3

To calculate the real-time charges of electricity, daily usage for 24 hours is multiplied with real-time price for each hour. Every hour has predefined value of electricity, and other charges are same as mentioned in the above equations.

5. Loss Analysis for Integrated Solar PV Nanogrid

The losses in nanogrid are as below:

- (i) Line loss for AC and DC
- (ii) AC to DC rectification losses
- (iii) DC to AC inversion losses
- (iv) DC to DC conversion losses

The current I_{dc} and line losses LL_{dc} are given in (16) and (17), where V_{dc} is the voltage source in DC nanogrid, P is the power consumption by load, r is for resistance, and l is for unit length:

$$I_{dc} = \frac{P}{V_{dc}}, \quad (16)$$

$$LL_{dc} = 2 \cdot r \cdot l \cdot I_{dc}^2 = 2 \cdot r \cdot l \left(\frac{P}{V_{dc}} \right)^2. \quad (17)$$

Similarly, rms current I_{ac} and line losses LL_{ac} are given in (18), where V_{ac} is the voltage source in AC nanogrid, P is power consumption by the load, r is for resistance, l is for unit length, and $\cos \theta$ is the power factor of the applied ac load:

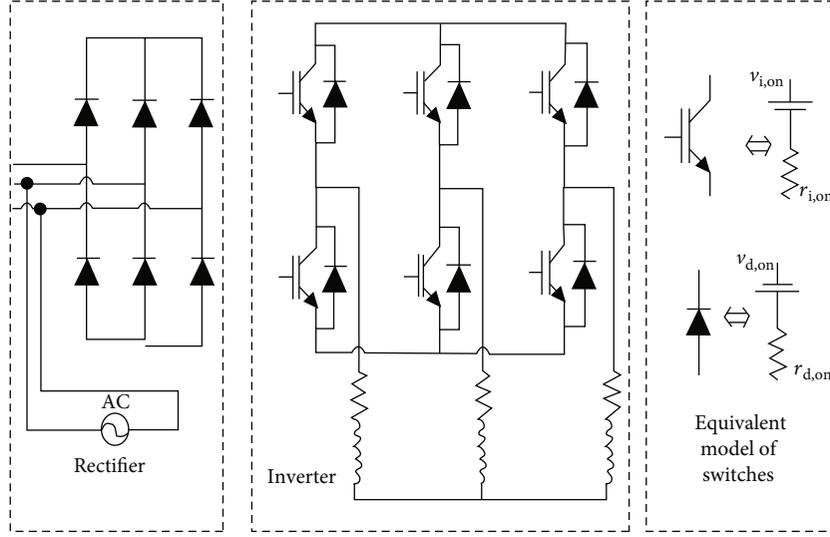


FIGURE 25: Model for AC/DC conversion switches.

$$I_{ac} = \frac{P}{V_{ac} \cos \theta}, \quad (18)$$

$$LL_{ac} = 2 \cdot r \cdot l \cdot I_{ac}^2 = 2 \cdot r \cdot l \left(\frac{P}{V_{ac} \cos \theta} \right)^2.$$

Conversion losses are due to interconversions from AC to DC, DC to AC, and AC to AC; DC to DC voltage level conversions between supply and load; the characteristic of switch device; and the switch frequency. The losses during conversion are given by equation (19), where P_{cond} is conduction losses and P_{sw} is switching losses [152]:

$$P_{conv} = P_{cond} + P_{sw}. \quad (19)$$

MOSFET, SCR, diodes, and IGBT are used for interconversion in electronic switching. The conduction losses for IGBT, diode, and MOSFET are given in equations (20), (21), and (22), respectively. Conduction losses for the power diode and IGBT are modelled as series sum of resistance and voltage sources whereas conduction losses for MOSFET are modelled as power loss across the resistance [153]:

$$P_{i,cond} = V_{i,on} \cdot I_{i,avg} + I_{i,rms}^2 r_{i,on}, \quad (20)$$

$$P_{d,cond} = V_{d,on} \cdot I_{d,avg} + I_{d,rms}^2 r_{d,on}, \quad (21)$$

$$P_{m,cond} = I_{m,rms}^2 r_{m,on}. \quad (22)$$

The subscript for IGBT is *i*, diode is *d*, and MOSFET is *m*.

On-state voltage is V_{on} , rms value of current is I_{rms} , average value of current is I_{avg} , and on-state resistance is r_{on} . Losses during switching for DC to DC conversion and AC to DC inversion are associated with switching frequency

f_{sw} , for IGBT, diode, and MOSFET are $P_{i,sw}$, $P_{d,sw}$, and $P_{m,sw}$, respectively, as below [154]:

$$P_{i,sw} = f_{sw} \cdot (E_{i,on} + E_{i,off}), \quad (23)$$

$$P_{d,sw} = (E_{d,on} + E_{d,off}) \cdot f_{sw} \approx E_{d,on} \cdot f_{sw}, \quad (24)$$

$$P_{m,sw} = (E_{m,on} + E_{m,off}) \cdot f_{sw}. \quad (25)$$

Three types of loads are used for analysis of the residential load, such as independent loads, DC loads, and AC loads, where independent loads could run by equal AC and DC [155]. Three subintervals such as 1st day, 2nd day, and during night hours are categorized during variations for the whole day. The line conversion losses, distribution losses, and efficiencies for the system are analyzed for both AC nanogrid, DC nanogrid, and hybrid AC/DC nanogrid with different conductor sizes and load distribution at different time intervals. The hybrid AC/DC nanogrid is studied for 100 m length of 220 VAC/240 VDC distribution wire in the residential area. Power factor 0.95 is considered for AC loads.

Z inversion topologies and three-phase rectification in [155] are presented in Figure 25. P_{rec} is rectification losses for AC/DC and given by

$$P_{rec} = 2VD \cdot \frac{P_{ro}}{V_{dc}}, \quad (26)$$

where VD is the forward voltage drop across the diodes, P_{ro} is rectifier power, and V_{dc} is DC link voltage. P_{inv} is inversion losses for DC/AC given by [156]:

$$P_{inv} = \frac{2\sqrt{2}V_{on} \cdot I_{rms}}{\pi} + I_{rms}^2 \cdot r_{on} + \frac{2\sqrt{2}I_{rms}}{\pi I_{nom}} (E_{on} + E_{off}) \cdot f_{sw} + E_{d,on} \cdot f_{sw}. \quad (27)$$

TABLE 7: Load during different time intervals [158].

Intervals	Durations	Loads (kW)			Total loads (kW)
		AC	DC	I	
Day 1	07:00-12:00	0.76	0.48	0.44	1.68
Day 2	16:00-1:00	1	1.02	0.67	2.69
Night	1:00-07:00	0.3	0.1	0.15	0.55
Average	00:00-23:59	0.68	0.53	0.42	1.63

$V_{i,on} = V_{d,on} = V_{on}$, $r_{i,on} = r_{d,on} = r_{on}$, nominal current is I_{nom} , and switching loss is I_{rms}/I_{nom} .

MOSFET-based DC-DC boost converter MPPT is used, and losses can be found using (20), (21), (23), (24), and (25) with the following current output characteristics [157]:

$$I_{m,rms} = \sqrt{D} \frac{P_{in}}{V_{in}} \cdot I_{d,avg} = (1-D) \frac{P_{in}}{V_{in}} \cdot I_{d,rms} = \sqrt{1-D} \frac{P_{in}}{V_{in}}, \quad (28)$$

where converter input power is P_{in} , converter duty cycle is D , and input voltage is V_{in} .

The total load demand for an entire day for the independent load, DC load, and AC load is obtained from Table 7 to determine the distribution line losses. Equations (27) and (28) are used to calculate line losses for DC nanogrid, AC nanogrid, and AC/DC hybrid nanogrid as shown in Figure 26. DC power is used for independent loads for AC nanogrid, DC nanogrid, and hybrid AC/DC nanogrid.

DC power is being used by independent loads in both AC nanogrid, DC nanogrid, and AC/DC hybrid nanogrid. Independent loads are to be run on AC or DC depending on the altering building load, grid power availability, state of battery, and PV generation. Switching and conduction losses for conversion losses are calculated for AC nanogrid, DC nanogrid, and hybrid AC/DC nanogrid in Figure 27. It is observed that due to AC to DC and DC to AC conversion in AC/DC hybrid nanogrid, they have higher efficiencies and less losses during conversion as compared to AC nanogrid and DC nanogrid.

Results show that during night hours, overall efficiency is very low as conversion losses are very high for low loads. Therefore, at this time, the efficiency drops as overall load is very low. Therefore, using hybrid AC/DC nanogrid, conversion efficiency of 97% is achieved even when the load is very low during night hours.

Figure 28 shows the overall system losses and efficiencies. Losses in hybrid AC/DC nanogrid is 63% less than AC-only nanogrid and 18% less than DC-only nanogrid. Efficiency for the proposed architecture is validated using hardware implementation of AC/DC nanogrid.

The nanogrid power consumption with or without EMS can easily be evaluated by observing Figures 29 and 30.

Table 8 gives us a clear idea of how the power consumption is reduced if the nanogrid is working with EMS or without it. The system was installed in Kharian, Pakistan, and the values are calculated in the summer season. The nanogrid with EMS has a drastic reduction in power consumption hence increasing the efficiency and reliability of the system.

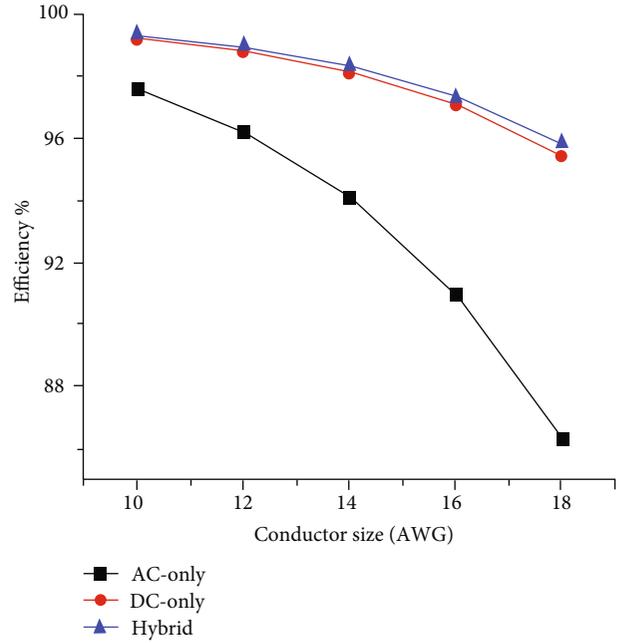


FIGURE 26: Distribution line losses and efficiency.

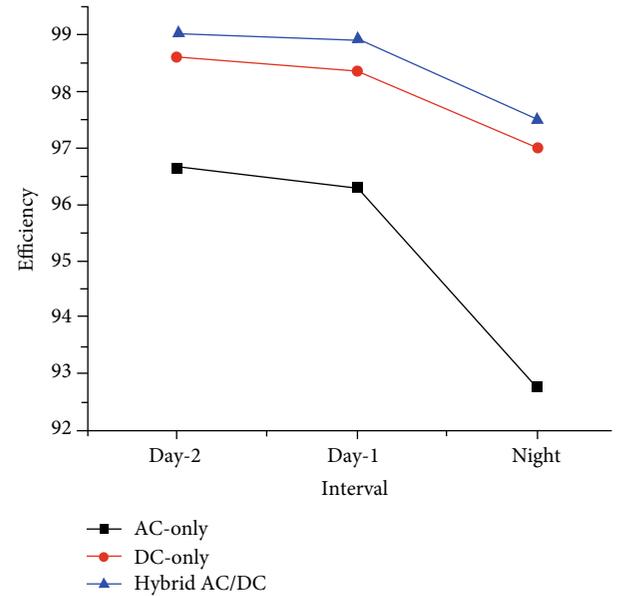


FIGURE 27: Conversion losses for 1st day, 2nd day, and night interval.

6. Simulation Results

All the results presented here are for the summer season. The simulation results for five houses are shown below by house rank. Houses 4 and 5 have installed solar capacity while houses 1, 2, and 3 do not have any solar system, but they have controllers to save the electricity in peak hours.

6.1. House No. 1 Load Profile. The total load of house no. 1 is 9400 watts. The load is categorized as basic, regular, and

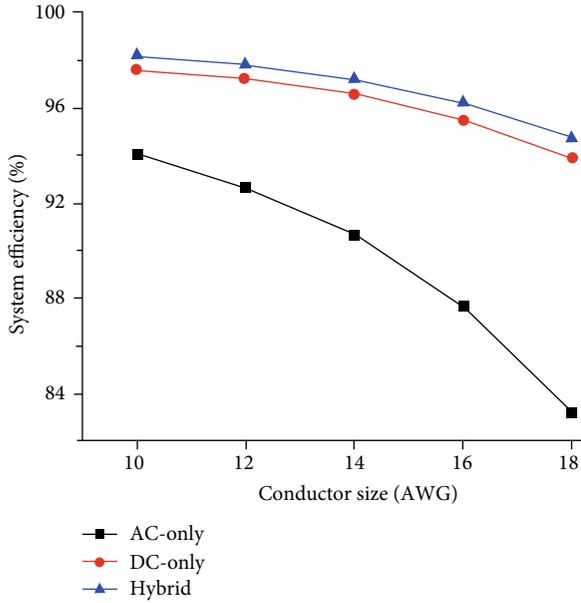


FIGURE 28: Overall system losses and efficiencies.

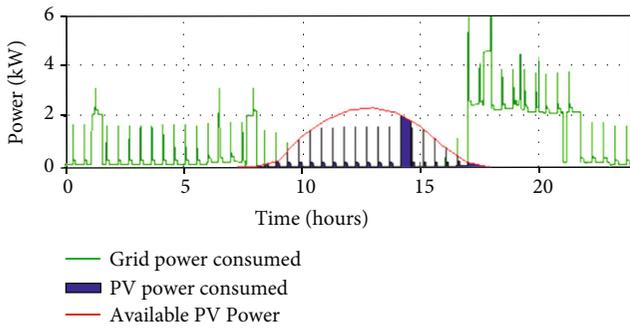


FIGURE 29: Nanogrid power consumption without EMS.

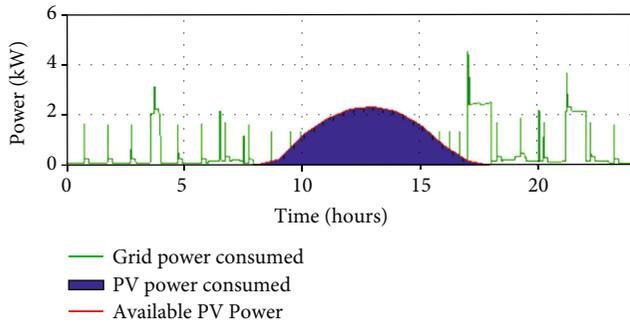


FIGURE 30: Nanogrid power consumption with EMS.

burst loads. In Pakistan, peak hours are defined by the utility company. Peak hours are shown in Table 9.

The load profile of each load is shown in figures. The investigation from load profile in Figure 31 is that the load is switched off after midnight, but there is a manual control that the user can use to switch on the load. But in peak hours,

TABLE 8: Nanogrid power consumption comparison without EMS and with EMS.

Home	Nanogrid without EMS	Nanogrid with EMS	Reduction (%)
1	19.78	13.89	29.76
2	18.31	11.31	38.25
3	32.72	25.39	22.38
4	15.75	8.89	43.54
5	15.94	8.89	44.21

TABLE 9: Peak/off-peak timing.

Sr.no	Period	Peak hours	Off-peak hours
1	Dec-Feb	5 pm-9 pm	20 hours
2	Mar-May	6 pm-10 pm	20 hours
3	Jun-Aug	7 pm-11 pm	20 hours
4	Sep-Nov	5 pm-9 pm	20 hours

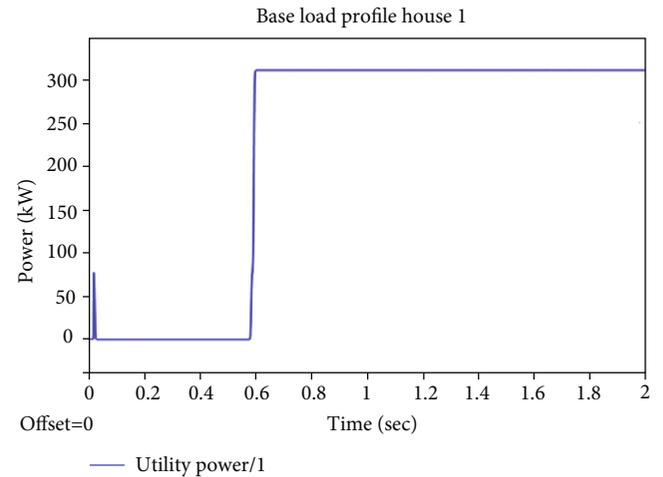


FIGURE 31: House one base load profile.

the base load is in the active state. The profile of the regular load is shown in Figure 32; here, all the load is in the active state even in the peak hours.

Load profile of the burst load is shown in Figure 33. During the peak hour, the burst load is deactivated and overall load profile can be seen in Figure 34. Simulation is scaled in 24 hours, so 1 hour is equal to 0.083.

House no. 2 and house no. 3 have similar results like house no. 1. The only purpose behind showing five houses is to compare the electricity cost using real-time pricing and flat rate.

6.2. House No. 4 Load Profile. Load profiles of house 4 are shown here. When solar power was enough to derive the load, then basic, regular, and burst loads are shifted on solar power through the local controller. But when the solar power was not enough to derive the certain loads, it shifted towards

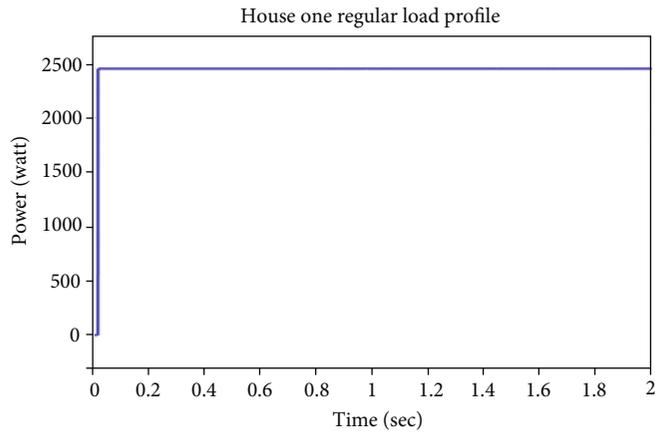


FIGURE 32: House one regular load profile.

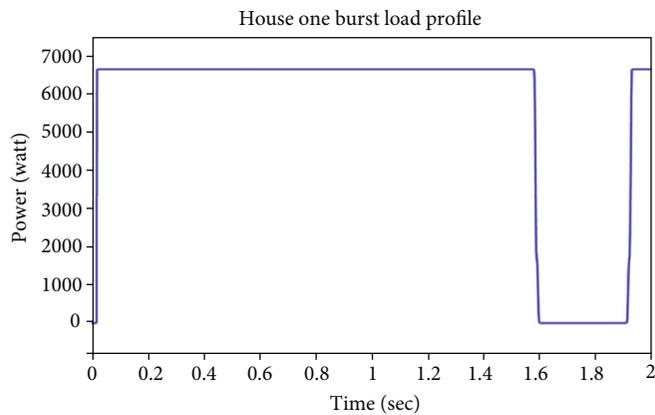


FIGURE 33: Burst load profile of house one.

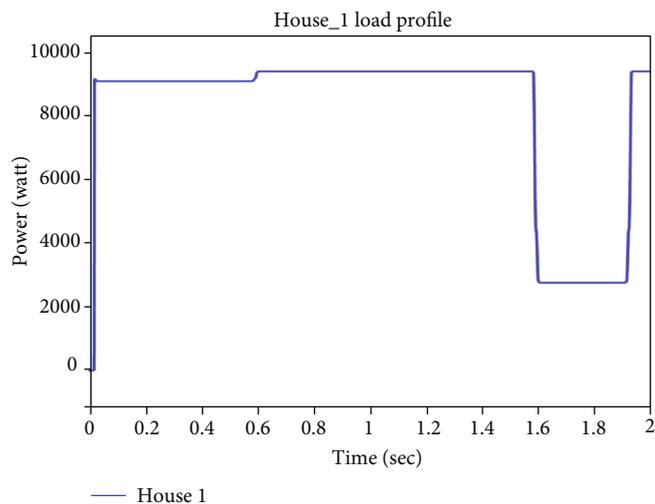


FIGURE 34: Total load profile of house one.

the utility. All the results of basic, regular, and burst loads are shown in Figures 35, 36, and 37, respectively.

6.3. *House No. 5 Load Profile.* House no. 5 load profiles are different from previous houses because solar power is not sufficient for all the loads. Solar power is fully capable of

operating the basic load and regular load but is insufficient for the burst load. Therefore, this load is shifted on to the utility. All load profiles are shown in Figures 38–40.

6.4. *Pricing Mechanism.* To observe the flexibility and reliability of the system, real-time and flat rate pricing

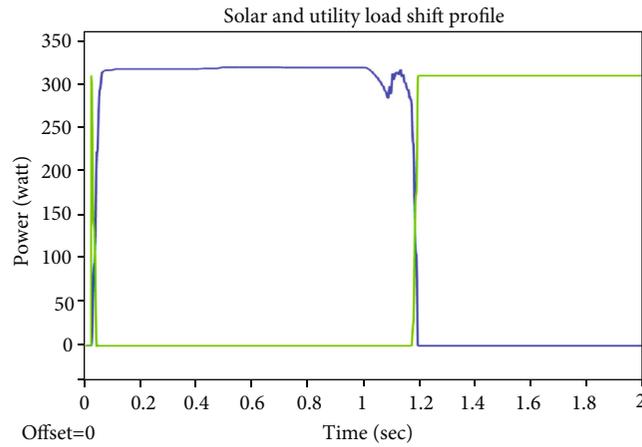


FIGURE 35: Basic load profile of house 4.

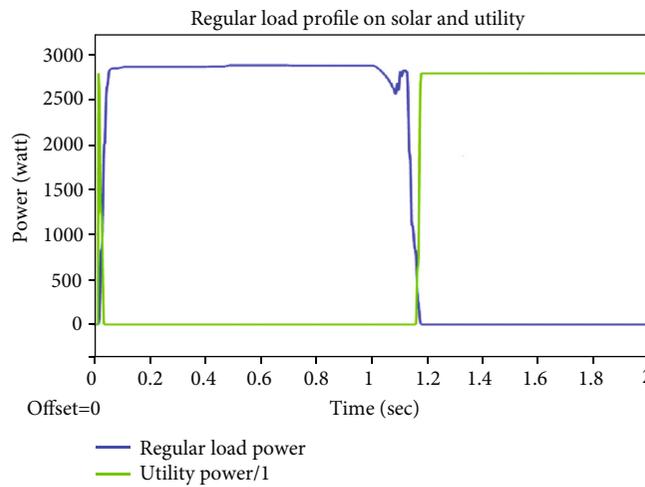


FIGURE 36: Regular load profile of house 4.

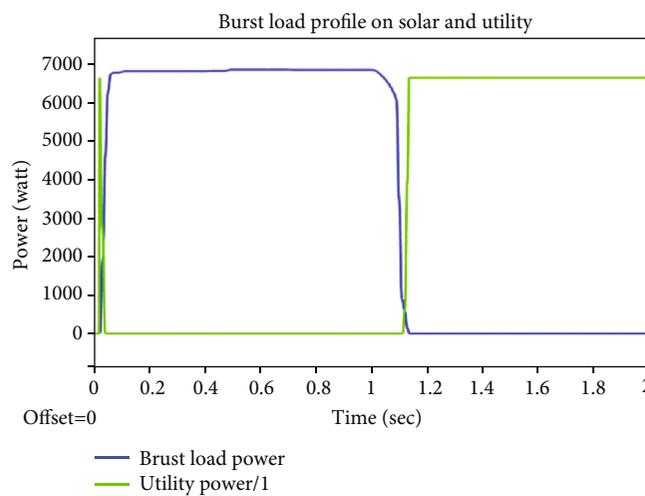


FIGURE 37: Burst load profile of house 4.

mechanisms are used. When the first three houses are under consideration, real-time pricing is beneficial to the consumer as well as supplier, but when we consider

houses 4 and 5, the flat rate is more economical than real-time pricing. The electricity billing comparison is shown in Table 10.

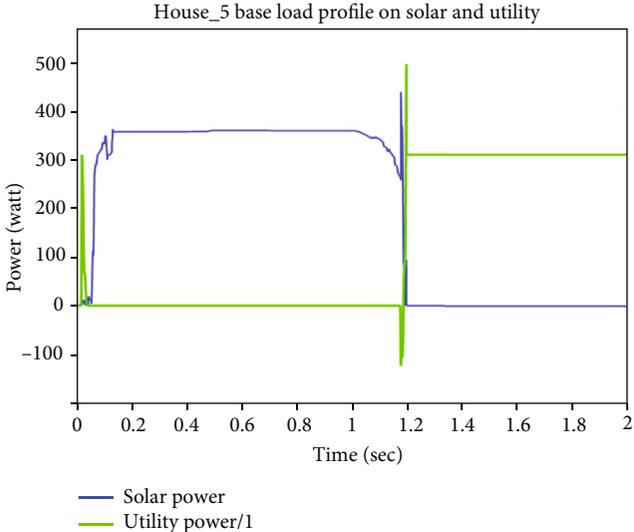


FIGURE 38: Basic load profile of house no. 5.

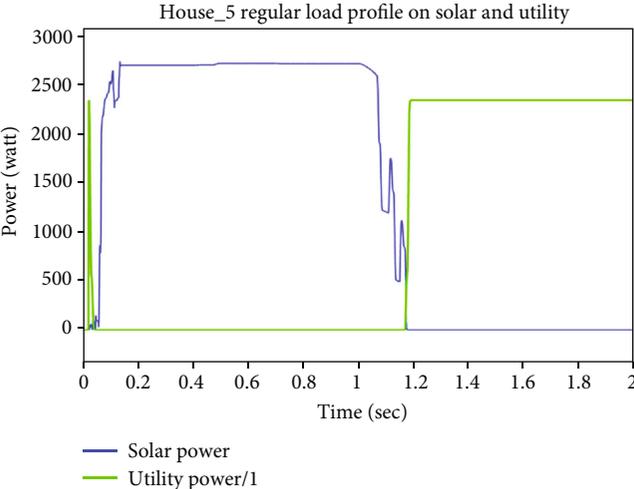


FIGURE 39: Regular load profile of house 5.

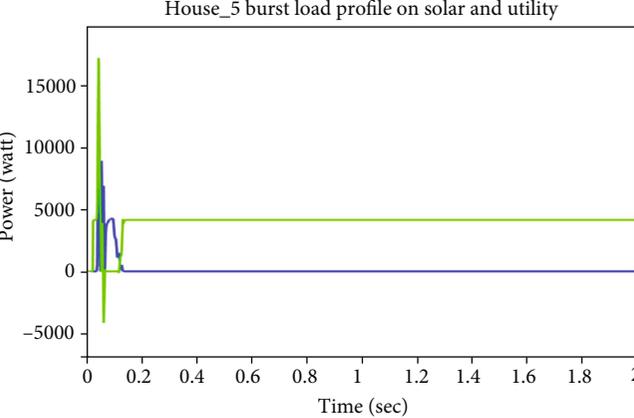


FIGURE 40: Burst load profile of house 5.

TABLE 10: Real-time pricing and flat rate comparison.

Sr.no	Home no.	Real-time pricing (PKR)	Flat rate (PKR)	Saving
1	House#01	364.4838	587.4999	223.0161
2	House#02	319.8675	525.0016	205.134
3	House#03	201.1662	523.0785	321.9123
4	House#04	205.9536	161.3072	44.6464
5	House#05	142.1698	124.33	17.8398

The AC/DC nanogrid is a remarkable achievement of feat of modern engineering, capable of delivering continuous supply of power for end users. In spite of its innovation, there are often new challenges, unforeseen consequences, and room for improvement. The proposed system was successful in efficient load management and its proper scheduling to ensure maximum utilization of solar energy. Demand-side load management is well demonstrated practically in domestic electrical loads and is driven by the solar PV array and DLC techniques in the smart domestic self-designed grid. It resolves the problem of load shedding and further boosts the efficiency of the whole system by decreasing the running cost of batteries and increasing the reliability of continuous power supply all day long.

The use of nanogrid technology helped in resolving the issue of load shedding and hence the load management in an intelligent manner without putting the physical stress on the system or the financial stress on the consumers.

The different load management techniques and load classification utilizing maximum solar energy helped in managing the existing solar PV system in an intelligent and cost-effective manner. The basic, regular, and burst loads initially categorized were further defined in an effective manner. The inclusion of DC-based load in basic load, DC inverter load in regular load, and scheduling of the burst load during the hours of maximum solar PV generation brought novelty in this work. About 42.5% of the regular load was decreased when replaced with the DC inverter load. The proposed architecture reduced the AC/DC conversion losses by assigning AC and DC power to AC and DC loads separately.

Research into the use of AC/DC nanogrids, load classification technique, and interconnected nanogrid networks is represented in literature, creating a strong knowledge base of successful implementation and potential for improvement. It is demonstrated that the proposed smart schemes manage both DC and AC loads together with optimum storage, in terms of maximum 34% economy, 54% of more reliability as compared to AC or DC grid individually.

This work also demonstrates the remote access of individual appliances during power shortage and self-shifting of excessive load to the alternative source during scheduled hours of usage. Load shifting and load reduction enables uninterrupted and frictionless exercise of demand-side load management. It proposes a technique for load shifting which smoothens the load demand curve more adequately than conventional load shifting. With the deployment of both distributed generation and continuous flow of power supply, replacement of existing load to energy-efficient load and

remotely shifting of load can provide significant fruitful impact.

It also presented a smart load management scheme for domestic use fed by local distributed generation of solar PV array. Loads were classified according to their priority, switching through wireless switches on feedback from weather forecast. DC loads were directly fed through battery storage during unavailability of solar energy during cloudy hours or nighttime and simultaneously from PV array during maximum daylight, which enhances the overall efficiency of the system. The storage is directly charged by smart DC PV array during daytime and efficiently used during night hours.

The goal of this work is to justify the efficient use of DC appliances to minimize the losses during conversion from DC-AC-DC for solar PV array. Generalized equations for solar PV and battery sizing have been derived using experimental results. A technique was developed to prevent the total blackout in system and by using the priority load without affecting the backup time of storage at night hours. It was demonstrated that the proposed smart scheme can be useful in efficiently managing the various DC and AC loads together with priority switching and proper sizing of storage and PV array, hence leading to the cheaper solution for domestic loads.

Resistive loads like electric irons, toaster, and heaters have maximum efficiency when operated on AC supply instead on DC supply. DC load is to be run directly on DC; resistive loads have maximum efficiency of up to 100% on AC instead on DC, so they need to be run directly on AC supply.

EMS along with solar PV distributed generation is implemented successfully at the domestic level for a specific home situated in an irregular load shedding area of Punjab, Pakistan. The mentioned techniques decrease the abrupt power shutdown during load shedding hours. Load shifting techniques during peak load demand helps the user to reschedule maximum power-consuming tasks during hours of maximum PV generation, with a positive intension of reducing utility tariff and generator fuel consumption. Intelligent appliance communicates with EMS further presenting an approach for power scheduling at the local level. The implemented work confirms massive reduction in terms of running cost and peak load for both utility and users. It demonstrates the real application of the DC-AC network with existing infrastructure. The resulting outcomes are satisfactory and implemented along with the concept of the smart grid. Also, the same strategy can be proposed and implemented to other consumers.

When multiple consumers switch on their loads during peak hours, a huge demand of electricity is produced. To balance the demand and supply, demand-side management (DSM) with distributed generation was introduced. In this proposed scheme, initially, five houses were considered to investigate the supply and demand requirement from the utility. Every house had an individual load priority with solar and utility to switch on or off load. Through simulations on Simulink, it is verified that houses one, two, and three had individual energy management units which switch the load on or off during peak hours. Similarly, house four and five

are solar PV installed. These two houses had load priority with solar PV and utility to see the effect of DSM. This effect was observed by introducing pricing mechanisms like real-time pricing and flat rate. The comparison was determined over these five houses. When DSM is applied to houses one, two, and three, real-time pricing is economical. At the same time, by implementing DSM with distributed resource like solar power, real-time pricing is not economical as compared to flat rate. So demand-side management was really used to overcome the high demand of electricity as well as to save the electricity bill of consumer. Therefore, demand-side management with distributed resource is economical for the present tariff system in Pakistan.

The proposed system has the highest preference on the distributed resource. The pricing mechanism is used in order to check the saving by the proposed system whenever flat rate and real pricing is introduced. This work had a huge positive impact on the batteries too as it was observed that battery storage is not discharged below 59% for the basic load and 54% for the regular load; the combined load management can reduce grid power utilization by 43.5% as compared to an uncontrolled nanogrid. ROI is about 20 months which is highly appreciable. Losses in hybrid AC/DC nanogrid is 63% less than those in AC-based nanogrid and 18% less than those in DC-based nanogrid.

In the future, addition of practical wireless control is recommended and message should be sent to the consumer via GSM to switch off the load during peak hours. There is also a possibility for the flexibility of the system to add another resource of renewable energy like wind, geothermal sources, and biomass so that battery cost can be removed from the overall investment. Extra generated energy can be sold to the grid, and the consumer can get benefit. This concept is encountered in net-metering.

With the implementation of the proposed energy management system, we are able to enhance the working of the existing energy system. In addition to increasing the comfort level of the consumer, the proposed system has given the consumers a major relaxation in their electric bills. Also, the efficient management of the system helps in increasing the life of the system installed with minimum management cost.

7. Conclusion

In this paper, we have investigated the hybrid AC/DC nanogrid that helps in managing the load and allows us to benefit from the PV system installed with maximum efficiency. Simulations are provided for various values of the parameters encountered in the proposed approach to show that the real-time pricing is more economical than the flat rates whereas for the houses where DG are involved in the nanogrids, the flat rates are more economical. If only flat rates are used for DG instead of real-time pricing, it is observed that up to 12.67%-21.46% saving is achieved. A novel utility function was proposed, and the consumers are able to save electricity bill up to 56% in summers and 41.2% in winters in addition to getting rid of the acute blanket load shedding. The term "nanogrid" was defined in a concise manner using various characteristics from the already published literature.

The nanogrid was hence defined as the following: "The nanogrid is a single unit power distribution system which is capable of connecting or disconnecting with other power units through the gateway. In this system, the local loads are powered by the local power production and can even opt to utilize a control system or the energy storage."

Data Availability

The underlying data is related to my submission.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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