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Comprehensive Analysis of Planning Operation and Protection of Microgrid Systems

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Microgrid is a decentralized system in which electrical sources and loads are connected in a way that operates normally in connection with and in synchronous with conventional grid. This system has the ability to work autonomously by disconnecting from conventional grid in island mode. Microgrid offers large number of advantages in power system. Among them, integration of renewable energy sources, reliability, two-way power flow and cost effectiveness are the significant merits of microgrids. Besides its advantages, different challenges are associated with the planning, operation and protection of microgrid systems. Safe two-way power flow, reliable switching of renewable energy, optimal power flow, quick isolation of faulty part from healthy system and incorporation of energy mix modeling are the major challenges behind its real time implementation. In this research, comprehensive analysis is carried out on the planning, operation and protection of microgrid model. A test system is developed in Matlab/ Simulink in which solar power source, wind power source and diesel power source are modelled and connected to residential, commercial and industrial loads. Optimal power flow is achieved through Newton's method. In addition to this, operation of microgrid test system is ensured by the observation of voltage, current and power under steady state and transient conditions of wind based power generation, DC and AC parameters for solar power generation and generation and demand of power in the case of diesel based power generation within acceptable limits. Circuit breakers are installed to ensure protection against faults. Priority is made on the basis of promotion of renewable energy sources. Moreover, realization of microgrid is depicted with its hardware prototype.

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Keywords: Microgrid; renewable energy; power system planning; power system operation; power system protection; Matlab/ Simulink.

1. INTRODUCTION

The reservoirs of conventional energy sources like gas, coal etc. are decreasing with the passage of time. This considered as the major problem in the world and every community needs to think about it with great care [1,2,3,4,5]. Environmental pollution associated with conventional energy sources does not only disturb the world but also causes harmful effects for the living organisms due to which many of the complex diseases occur. Due to environmental pollution and limited quantity of conventional energy sources, world is shifting towards non-conventional energy sources or renewable energy sources. Easy and free of cost way of availability and environmental friendly are the benefits of renewable energy sources. As the initial cost of installation of renewable energy sources based power plants is high engineers and policy makers are trying to encourage the end level consumers to install renewable energy based power generating units at small level to get the benefits of the single time investment. There are many challenges associated with the integration of renewable energy to conventional grids that must be resolved on priority basis. These challenges are associated with the planning, operation and protection of power system [1,6,7,8,9,10].

The consumers which are capable of consuming and generating energy have introduced to the concept of smart-grids and microgrids. A microgrid is a low voltage, a small-scale power grid on distribution side consisting of storage device and controllable loads. There are two modes of operation of microgrids i.e., the islanded mode of operation which operates independently and the grid connected operation which operates with the main grid. Microgrid offers several advantages including increased reliability, improved energy efficiency, transmission loss reduction and most importantly cost reduction. Its significance is increased by proper planning schemes and covering future challenges [6,8,10,11].

1.1 Planning

The main aim in microgrid is to reduce the cost of the operation mode, to reduce the environmental concerns and to increase its output for better efficiency. Different planning schemes are analyzed and methods are put forward for successful planning in literature [12,13,14,15,16,17,18,19]. One planning was carried out by Yan Li in generation dynamics and load dynamics. It was useful as it support in short signal stability analysis. Microgrid has to retain short signal strength under short variations of working conditions of source by generation variations and loads fluctuation. Theoretical division is held on the system values and their corresponding eight vector individually under generation and load. Finally, the competent of matrix perturbation approach for eight solution enquiries are tested via small voltage microgrid model [20,21]. A methodology is proposed for the optimal allocation and economic analysis of an energy storage system (ESS) in microgrid on the basis of net present value (NPV) [22,23]. An analytical approach is developed for determining the amount of storage required to meet a reliable target at a specific load point. Then the method is extended to a more complex islanded microgrid system where initial reliability assessment and final verification of reliability guarantee are performed using sequential Monte Carlo simulations [24]. The necessary component and system models are developed and described and a real life based test system is used to demonstrate the method. The work was performed to determine storage need in order to provide reliable guarantee on an island capable test system grid and a method for optimal storage mix is also developed [25]. Planning of microgrid was also done by using Newton's method and by net metering. Newton's method is developed to obtain different values of power which are produced by renewable energy resources [26]. Per unit costs of solar, wind and conventional power plants are obtained [27].

1.2 Operation

One of the most novel techniques for power flow of standard microgrid is the adapted Newton's Method with Droop control. Other plans are complex and not simple to apply due to the non-presence of slack bus like the dependence of the power on frequency as a result of the droop characteristics. Newton's method provides a simple, and an exact solutions of power flow equations for microgrid [26,27]. The method of successive approximation presents optimal yields and results in the development of the graphical interface which yields better operation by rearranging the equations adequately. The classic way is changed to make adjustment in the specific properties of separately working microgrid. Firstly, a virtual slack bus is defined and subsequently, the microgrid frequency is updated based on the active power flowing through the virtual slack node, then calculated as rearranged equations [28,29,30]. Power flow in a usual distribution arrangement is one directional. Combined effect of power flow in the deployment systems can be bi-directional. Fault current track is dependent on relaying on the site of the fault [31]. For an inverter-based microgrid, an operation is realized by opening the isolating switch which disconnects the microgrid from the main grid. Once the microgrid is isolated, the micro sources feeding the system, are responsible for maintaining the voltage and frequency while sharing the power. During the autonomous working, it is critical to ignore burden of inverters, so it is also significant to assure that variation in load are introduced by inverters in a pre-determination approach. Direct approach is based on a communication link, such as the master-slave method can be adopted in system where mini-sources are linked to common buses situated in close proximity [32,33,34,35].

1.3 Protection

Power flow is unidirectional in conventional distribution circuits. However, with the help of distributed energy sources, the flow can be made bi-directional [36,37,38,39,40,41]. The flow of the fault current relies on the place where fault occurs. The main reasons of protection of a microgrid are bi-directional flow, fault current path, relay setting and short circuit capacity [36,37,38]. In some cases, the fault current is not so high and is not enough to trip the breaker so in such cases under voltage relays are used. Under voltage relays detect the small amount of current and allow the circuit breaker to trip. One of the most important case for the fault is when the diesel generator (DG) starts ride through a voltage disturbance on different section. To overcome this problem, the DG should ride in series in different continuous voltage ratings and it can be summarized as repeating period when the fault is present [42,43,44]. System should be protected from bi-directional flow of current when conventional power source and battery work as a source simultaneously. It is protected by using a variable resistor which doesn't allow the current to pass through it. Whenever circuit is shorted at that moment, current will be maximum [42,45,46,47]. Therefore, in order to protect the circuit from fault current, relays are used. Relay senses the fault and sends feedback to circuit breaker which breaks the circuit [43,48]. If the fault generated is so small and cannot be detected by the relay, flywheel inverter will be used, which allows the increase in the value of the fault current [49,50]. As a result, fault current can easily be detected by the relay module and circuit can be kept safe [51,52,53].

In this research, planning, operation and protection of microgrid are analyzed comprehensively.

2. METHODOLOGY

The proposed diagram of microgrid is given in Fig. 1. In this research, calculation of per unit values from solar, wind and conventional power sources are taken. Then comparison of cost function is done for these three sources. Their priority is set according to their cost, efficiency and their maximum supply. In the portion of self-usage, electricity is used for at consumer ends. If the electricity is not being used, then commercial loads purchase this portion and will be included in the net metering.

Net metering is a charging component that credits sunlight-based vitality framework proprietors for the power they add to the matrix. For instance, if a private client has a photo-voltaic (PV) framework on their rooftop, it might create more power than the consumer's usage during light hours. In the event that the house is net-metered, the power meter will run in reverse to give a credit against what power is devoured around evening time or different periods when the consumer's power usage surpasses the framework's yield [54]. These are three sources which will be used for the accomplishment of this project named as Solar, Wind turbine and National grid.

In solar powered source, solar panel is held to change the energy from the sun to the electricity according to its specific capacity. In wind farm based power source, wind turbine is held through which the kinetic energy of the wind is used to generate electricity. In national grid, conventional power source is utilized. Economic dispatch of microgrid is very difficult because of uncertainty in the obtained data. Hence, accurate model is required for successful planning analysis of microgrid. Cost analysis for energy collecting and sizing of microgrid is used to reduce the initial cost. For power flow analysis during the planning stages for the conventional power system, Newton's method [55,56,57] is used in microgrid [58].

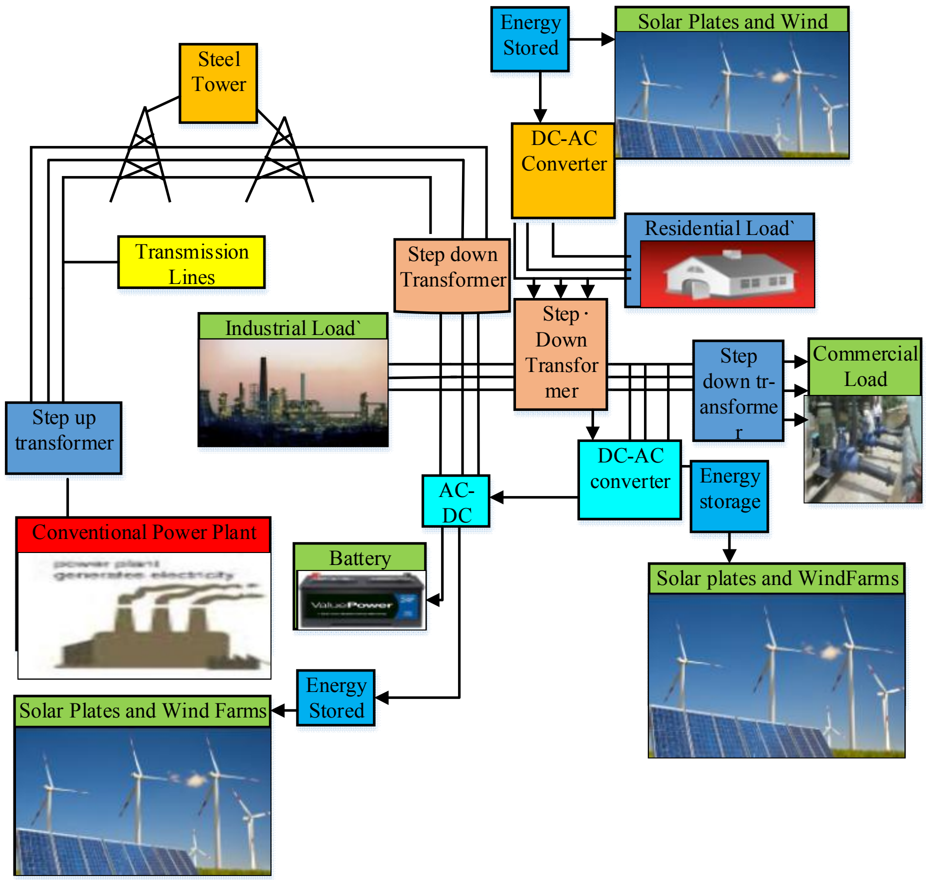


Fig. 1. Microgrid model

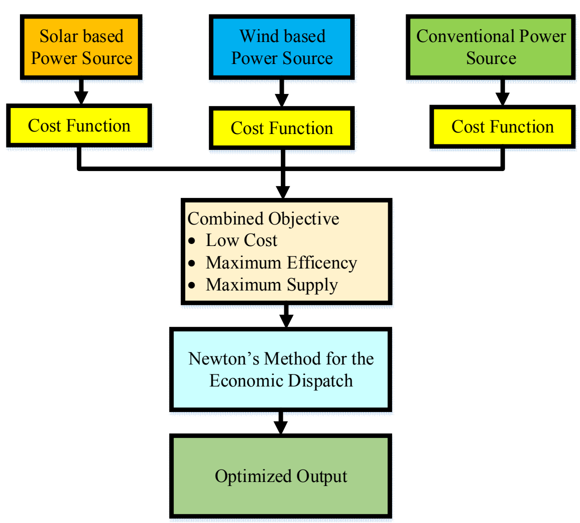


Fig. 2. Planning of microgrid model

Fig. 2 shows the planning of microgrid. Planning aims at reduction of per unit cost of energy supply and consumption. Therefore, cost functions of Solar power source, wind power source and conventional power source are considered and are based on Locational Marginal Prices (LMPs). This LMPs are designed to establish a contract of sale and purchase of energy between consumer and microgrid at a bus of common coupling (say as bcc). The total transaction cost for trading transferrable energy is $C(E(t))$ and is given as:

$$C(E(t)) = \begin{cases} bcc\ (E(t)) & E(t) > 0 \quad Power\ to\ Microgrid \\ 0 & E(t) = 0 \quad No\ Power \\ -bcc(E(t)) & E(t) < 0 \quad Power\ from\ Microgrid \end{cases} \tag{1}$$

Where $E(t)$ is the transferable energy between consumer and microgrid at time t. The main objective is to minimize the fuel cost of diesel generator connected in a test system and transaction cost of transferable energy, given by:

$$\min\{\ (w)[\sum_{t=1}^{T}\sum_{i=1}^{I} C(i)E(i,t) + \sum_{t=1}^{T} C(bcc)E(bcc_t)] + (1 - w)[\sum_{t=1}^{T}\sum_{j=1}^{J} C(b)x(j,t)] + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k} C(k)E(i,t)\} \tag{2}$$

Subject to following constraints:

$$\sum_{i=1}^{I} E(i,t) + Ew_t + Es_t + Ebcc_t = D(j,t) - \sum_{j=1}^{J} x(j,t) \tag{3}$$

$$E_{i,min} \le E(i,t) \le E_{i.max} \tag{4}$$

$$0 \le Ew_t \le W_t \tag{5}$$

$$0 \le Es_t \le S_t \tag{6}$$

$$-Ebcc_{max} \le Ebcc_t \le Ebcc_{max} \tag{7}$$

$$-DR_i \le E(i,t+1) - E(i,t) \le UR_i \tag{8}$$

$$C(k)E(i,t) = \ \alpha_t\beta_k E(i,t) \tag{9}$$

$$C_b(x(j),t) = y(j,t) + \lambda(j,t)x(j,t) \tag{10}$$

Where w is the energy wighting generated and exchanged, $C(bcc)E(bcc_t)$ is the transaction cost for transferable energy at time t; $C(i)E(I,t)$ is the fuel cost of conventional power source i at time t function; $Ebcc_{max}$ is the maximum energy that can be transferred between the consumer and the microgrid; T are the total number of dispatch intervals; I is the total number of sources in the microgrid. $C(k)E(i,k)$ is the treatment cost of the k th class of pollutants, where $y(j,t)$ is the value of United States Dollars (USD) of monetary compesation of customers receives at time t.

Newton's method is applied to obtain optimized values of energy at minimum cost from sources of microgrid.

The operation of microgrid is shown in Fig. 3. Successful operation depends upon the measurement of different parameters i.e., voltage, current, power and losses. It is always desired to have these parameters with in the safe operating limits. In addition to this, reliable and continuous operation is only assured if the circuit has the ability to interrupt any malfunction or abnormal conditions. In addition to this, power factor is monitored so that per unit cost of energy could be maintained at minimum rates.

In order to have reliable system, protection against faults must be installed so that faulty part of system could be isolated from the healthy part of system. Protection of microgrid model is shown in Fig. 4. There are two types of protection associated with microgrids that are: bidirectional power flow and short circuit conditions. In this research, both types of protection are based on the values of current. Circuit breaker with over current relays are deployed to counter short circuit effects in this system. When a current reaches the pickup value of relay, it is sensed by relay and a trip command is sent to circuit breaker for possible action. This over current relay is further supported with direction to ensure bidirectional power flow in the micrgrids.

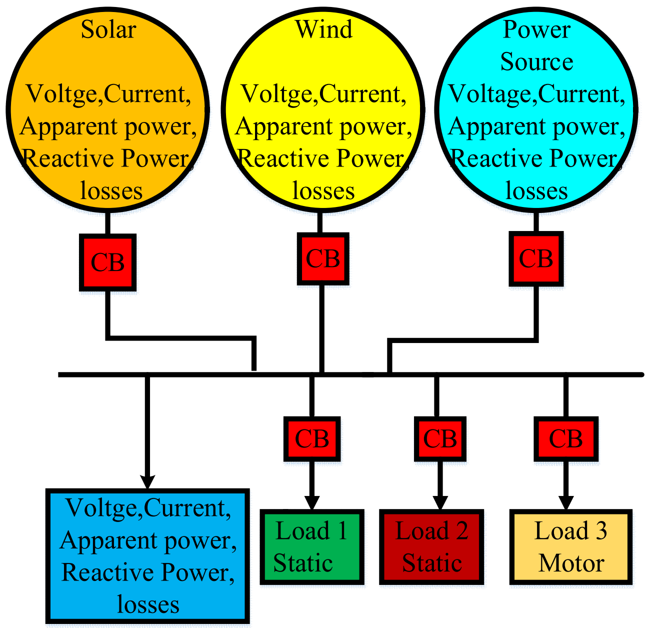


Fig. 3. Operation of microgrid model

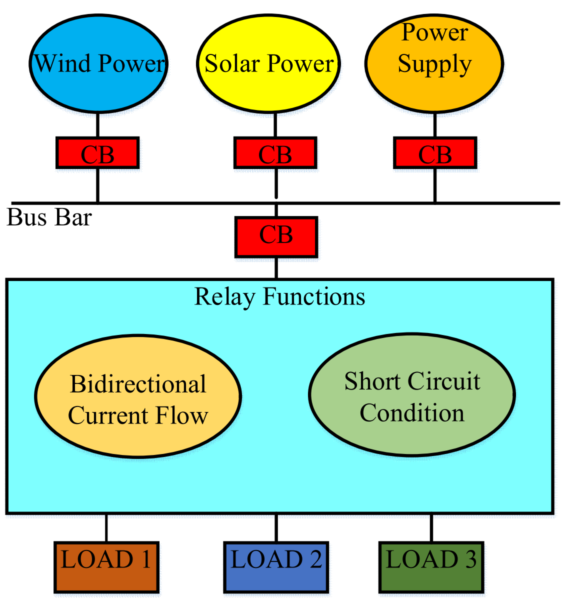


Fig. 4. Protection of microgrid model

3. RESULTS AND DISCUSSION

Matlab/ Simulink is used for the simulation analysis of microgrid test model. Fig. 5 represents the test model of microgrid where three sources are modeled as diesel generation based power source (Wapda), Solar based power source, Wind based power source. These sources are supplying power to three types of load connected to them. Switching operation is designed on the basis of priority set as shown in Fig. 6.

Diesel generator is the union of a diesel motor with an electric generator to produce electrical energy. This is a definite case of engine-generator. A diesel compression-ignition engine is usually made to sprint on diesel fossil, but few types are suitable for other liquid fossil or natural gas. Diesel generating stands are used in sites without linking to a power grid, or in crisis of power-supply. In the case of the failure of the main grid due to more complicate utilization such as peak-lopping, grid strengthen and give it to the power grid. Diesel generator based power source is modeled in Fig. 7. Wind based power source mode is based on wind turbine. In the modeling of wind turbine based wind power source, permanent magnet synchronous machine is used. The output of wind power source is three phase AC power. Wind based power source model is shown in Fig. 8. Pitch angle and wind speed are responsible for the production of mechanical torque for permanent magnet synchronous machine as shown in Fig. 9. Solar power based model is presented in Fig. 10. Since the output of solar power is DC, therefore, power electronic circuitries with PWM based switching is designed to convert DC power to AC power [59,60,61,62]. This model depends on numerical conditions and is depicted through a proportional circuit including a photo current source, a diode, an arrangement resistor and a shunt resistor. The created model permits the expectation of PV cell conduction under various physical and natural parameters i.e., temperature and solar intensity. Integration of renewable energy sources to microgrid enables the application of high voltage direct current transmission and low voltage direct current distribution in power system for bulk power supply and distribution respectively [63,64,65,66].

In this microgrid model, there are three types of load connected to microgrid sources. i.e., residential load (10 kW), commercial load (100 kW) and industrial load (10 MW) as shown in Fig. 11. Each type of load-set consists of five loads. They are connected in parallel as shown in Fig. 12, 13 and 14 for residential loads, commercial loads and industrial loads respectively.

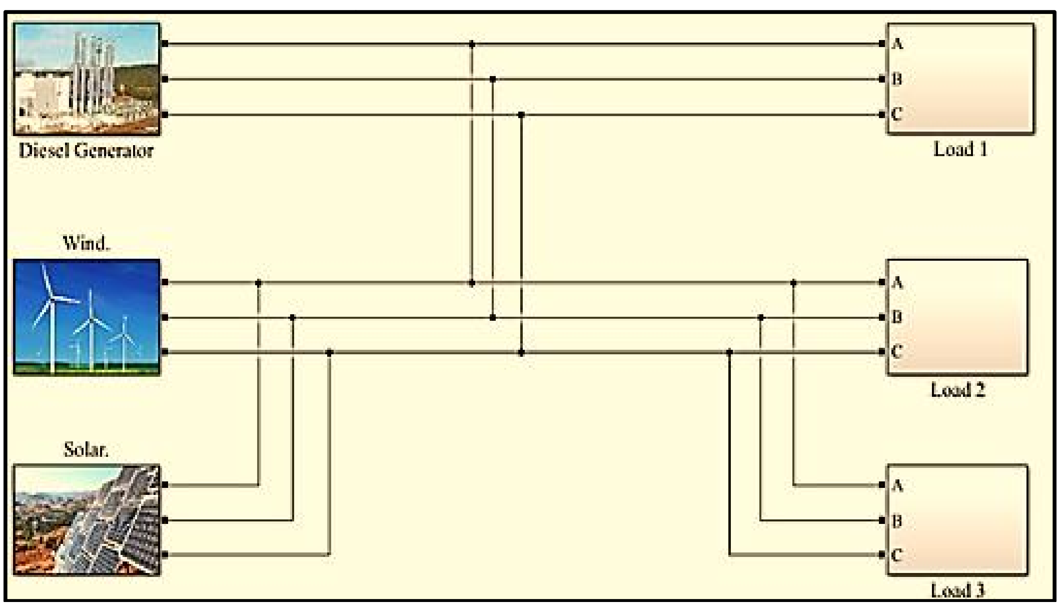


Fig. 5. Test system of microgrid in Matlab/ Simukink

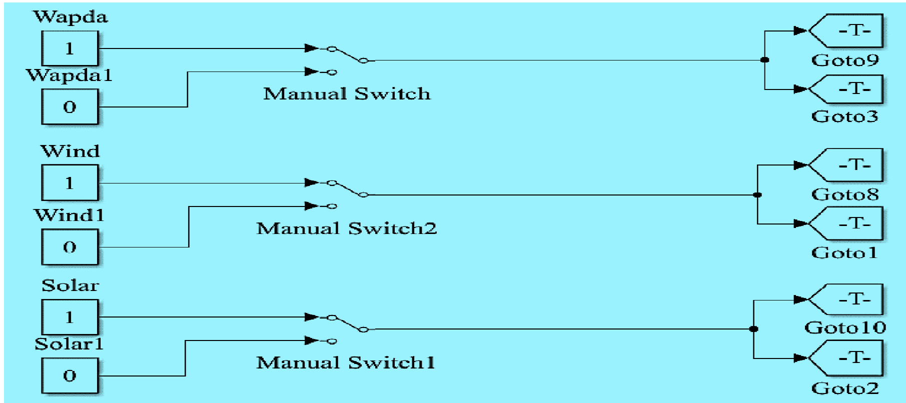
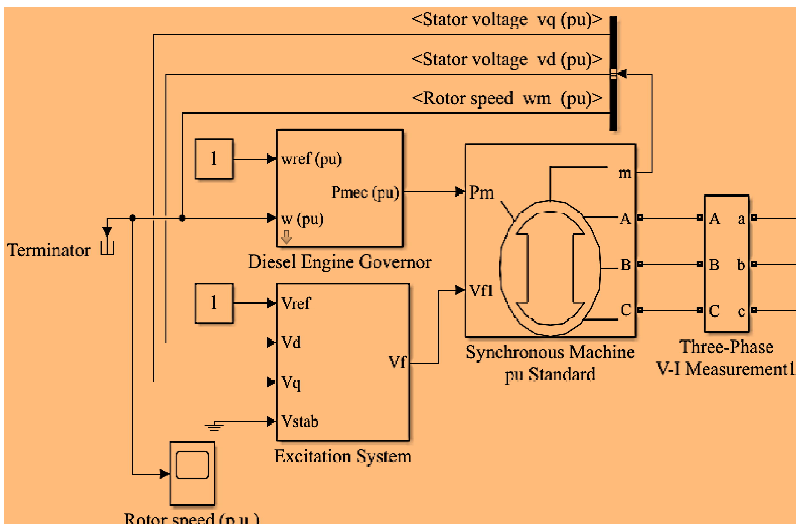
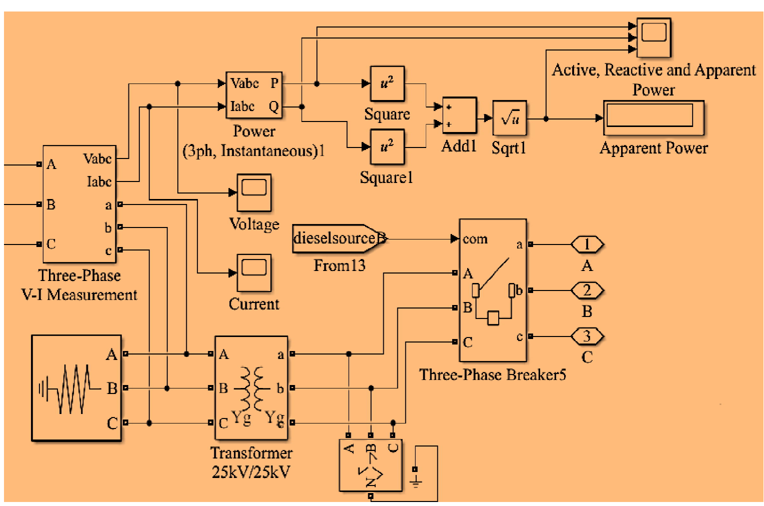


Fig. 6. Switching operation of microgrid test system



(a)



(b)

Fig. 7. Diesel generator based power source model of microgrid test system

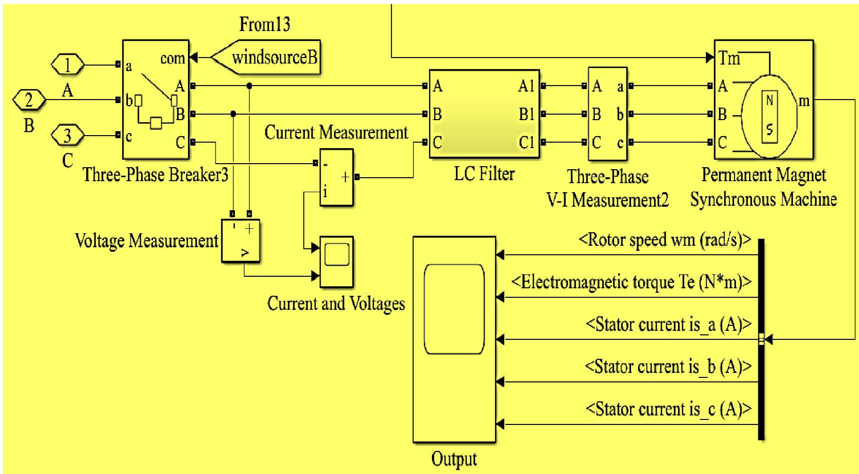


Fig. 8. Wind based power model for microgrid test system

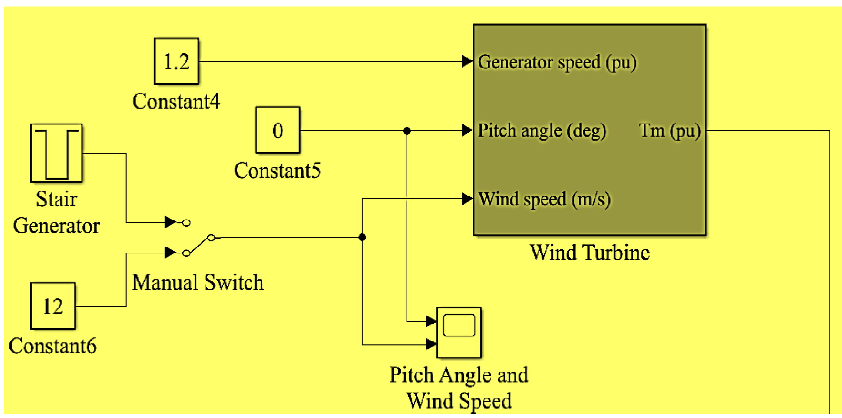


Fig. 9. Wind speed and pitch angle for the production of mechanical torque for wind based power source

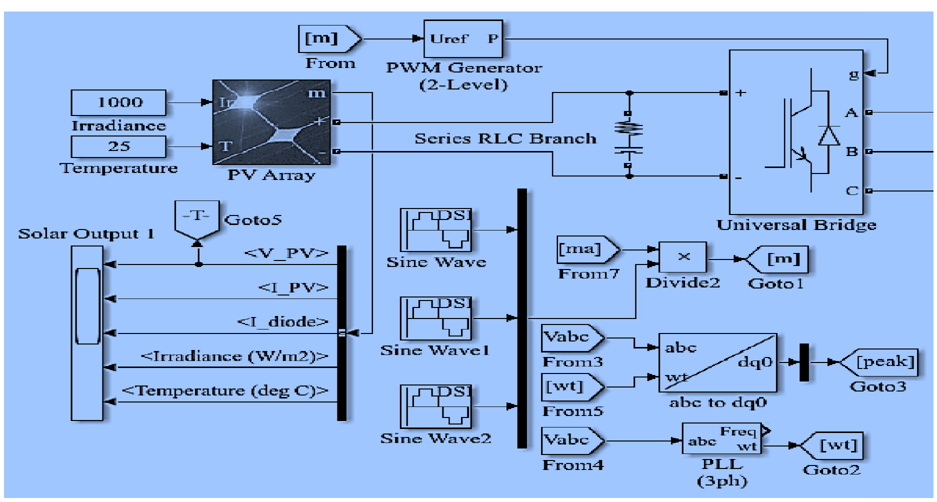


Fig. 10. Solar based power source model for microgrid test system

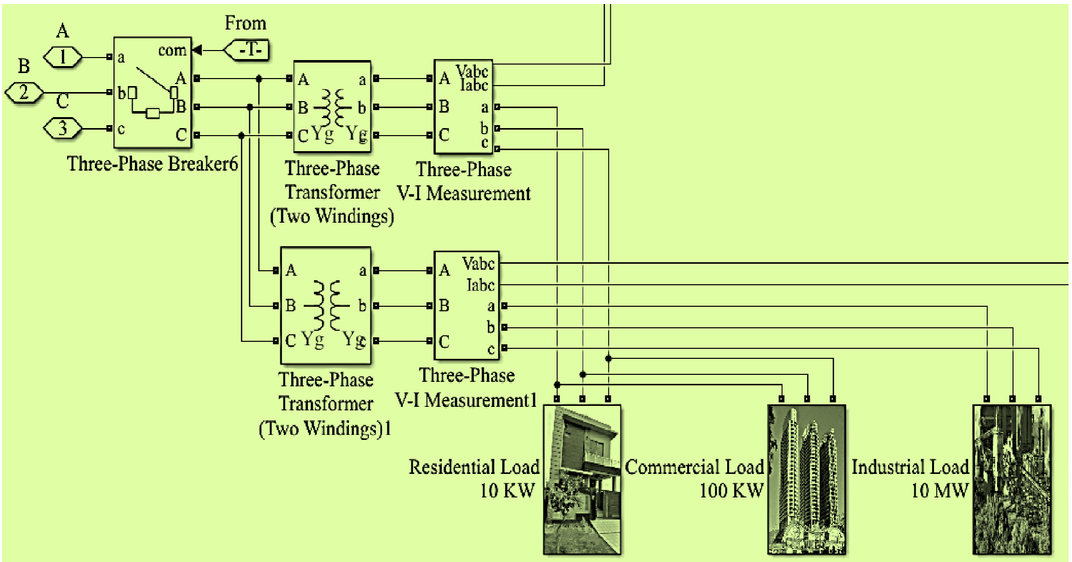


Fig. 11. Types of load connected to microgrid test system

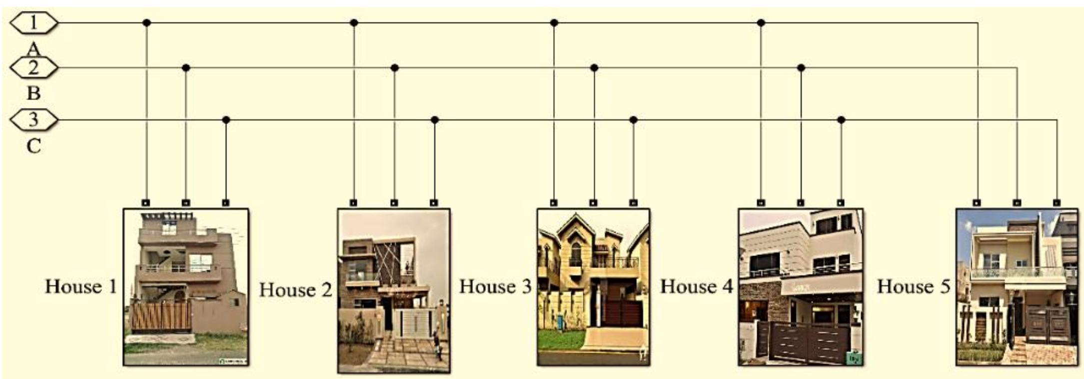


Fig. 12. Modeling of residential load

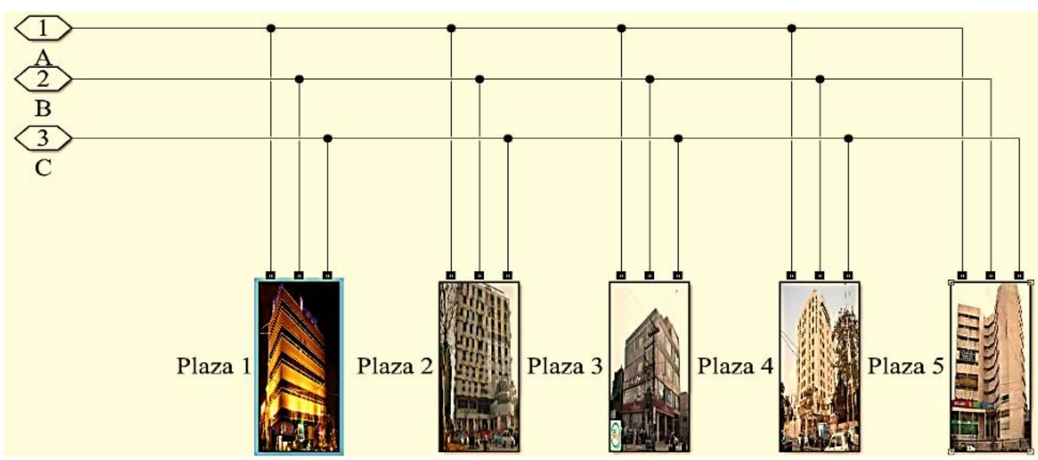


Fig. 13. Modeling of commercial loads

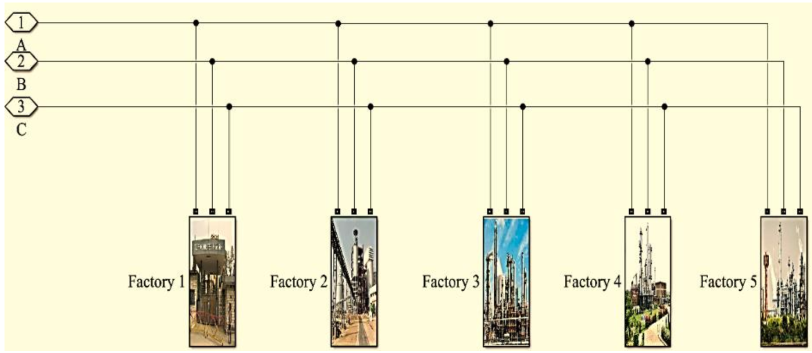
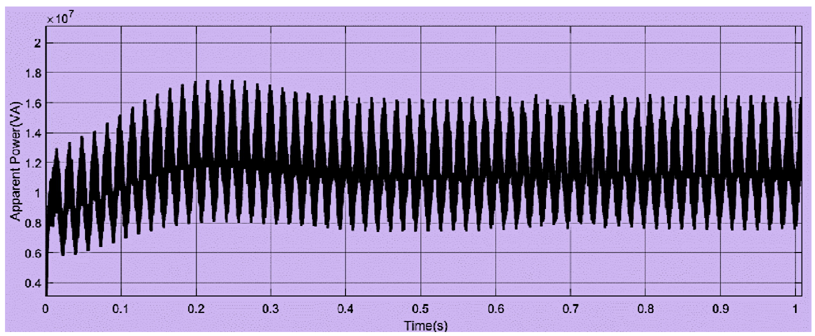
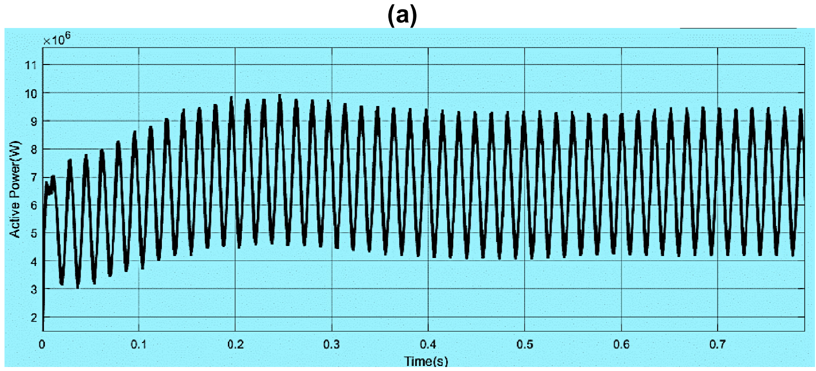


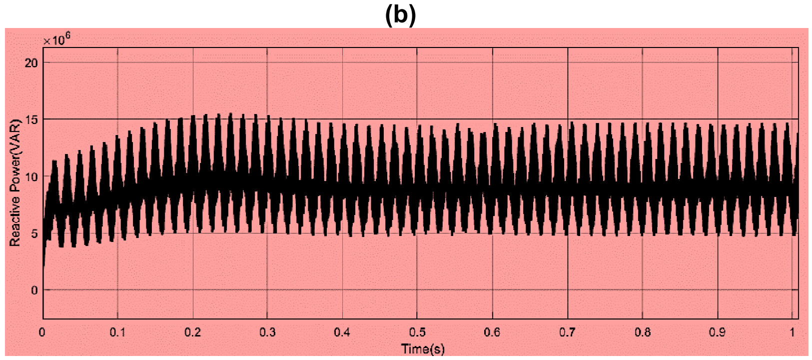
Fig. 14. Modeling of industrial loads



(a)



(b)



(c)

Fig. 1. (a) Apparent power, (b) active power and (c) reactive power generation from diesel based power generation plant

Fig. 15 represents the generation capacity of Diesel power generator in terms of apparent power, active power and reactive power. Similarly, the power drawn from source is dependent upon the energized load. Therefore, under maximum load, power drawn from diesel power generator is shown in Fig. 16.

Wind generator based power source has two states i.e., transient state and steady state. Output voltages and currents are measured in both states to depict about optimal operation of wind based power source and are shown in Figs. 17 and 18.

Solar PV plates give DC output. Therefore, inverter is designed to convert DC to three phase so that there could be no compatibility issues. Output DC voltage and AC voltages are shown in Figs. 19 and 20 respectively.

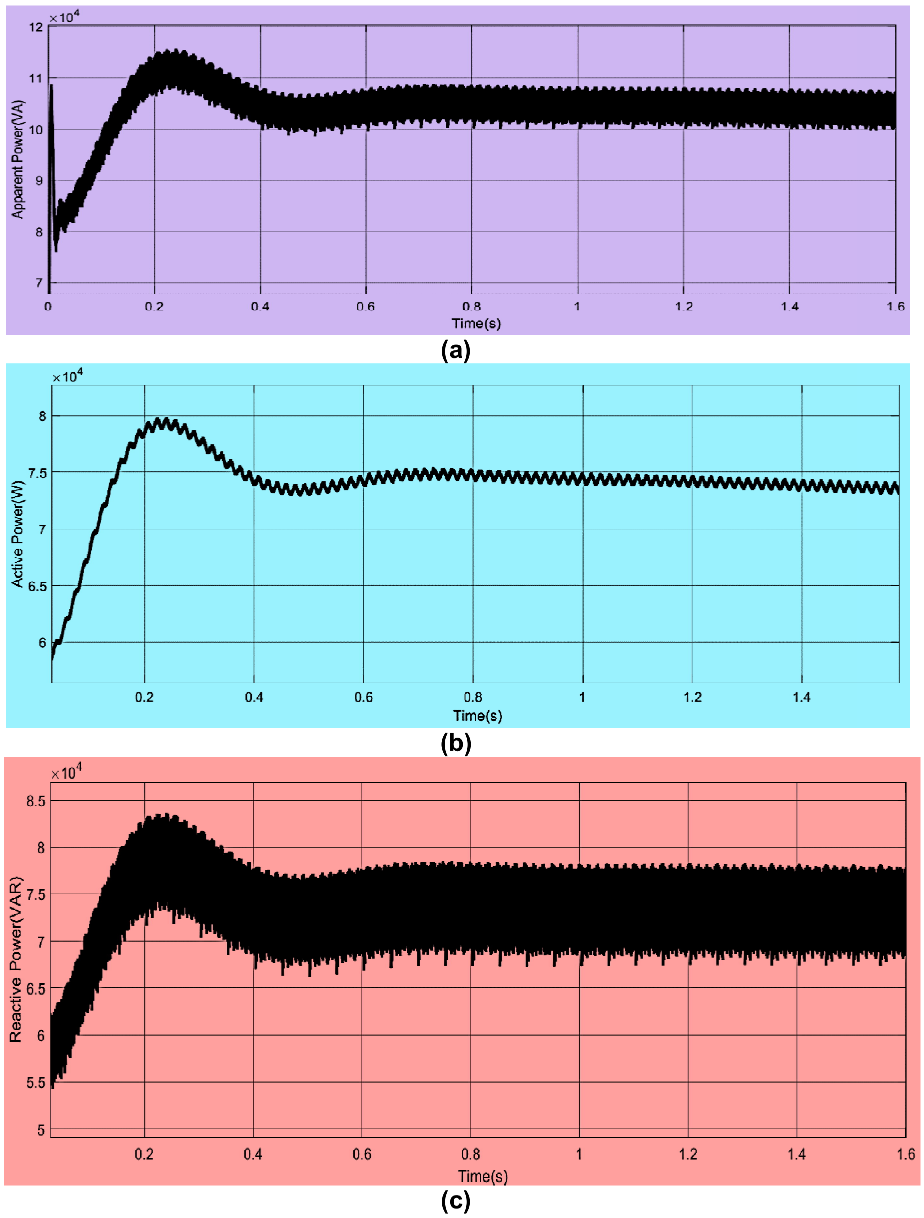


Fig. 2. (a) Apparent power, (b) active power and (c) reactive power drawn from diesel based power generation plant

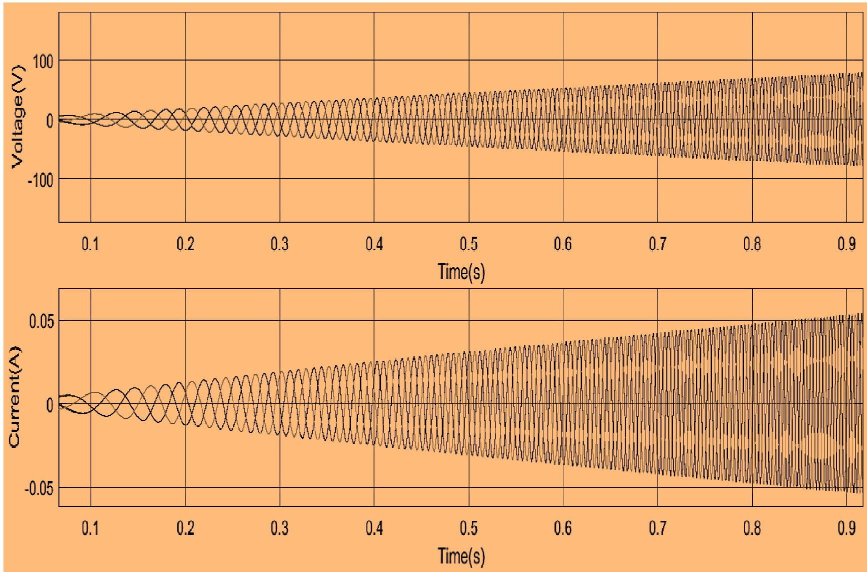


Fig. 17. Output voltages and current generated from wind generator under transient state

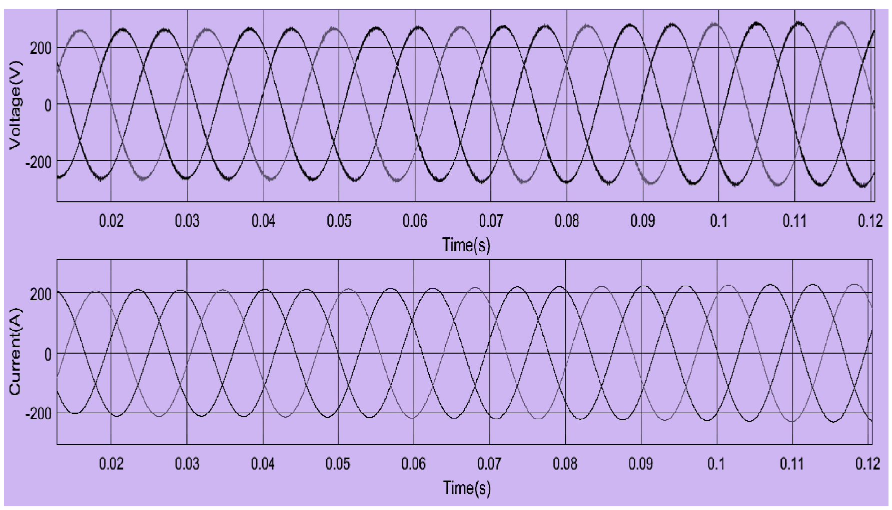


Fig. 18. Output voltages and current generated from wind generator under steady state

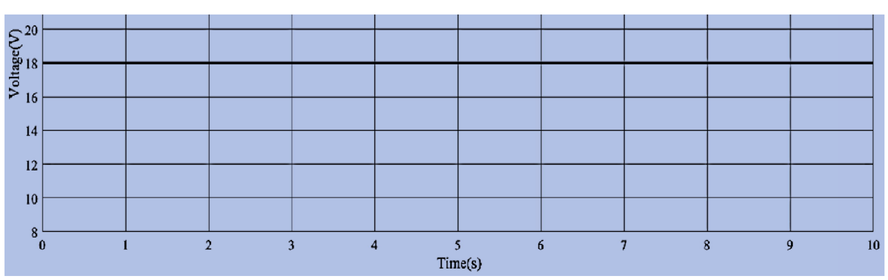


Fig. 19. Output DC voltages of PV plates of solar based power source

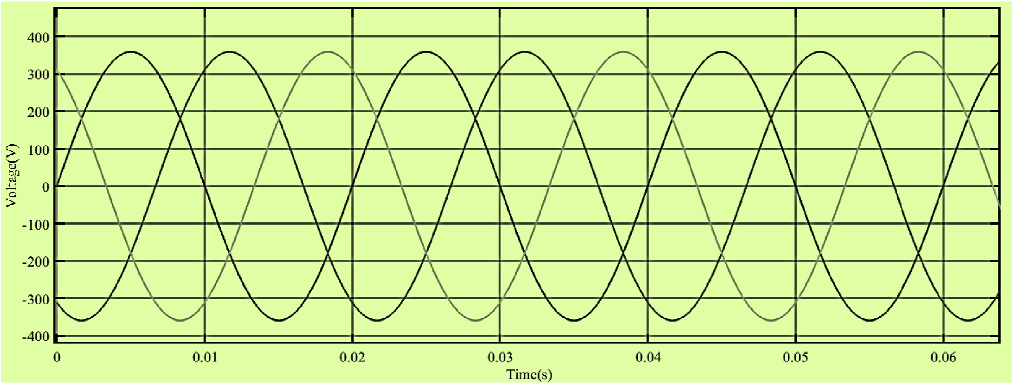


Fig. 20. Output AC voltages of inverter connected to PV plates of Solar based power source

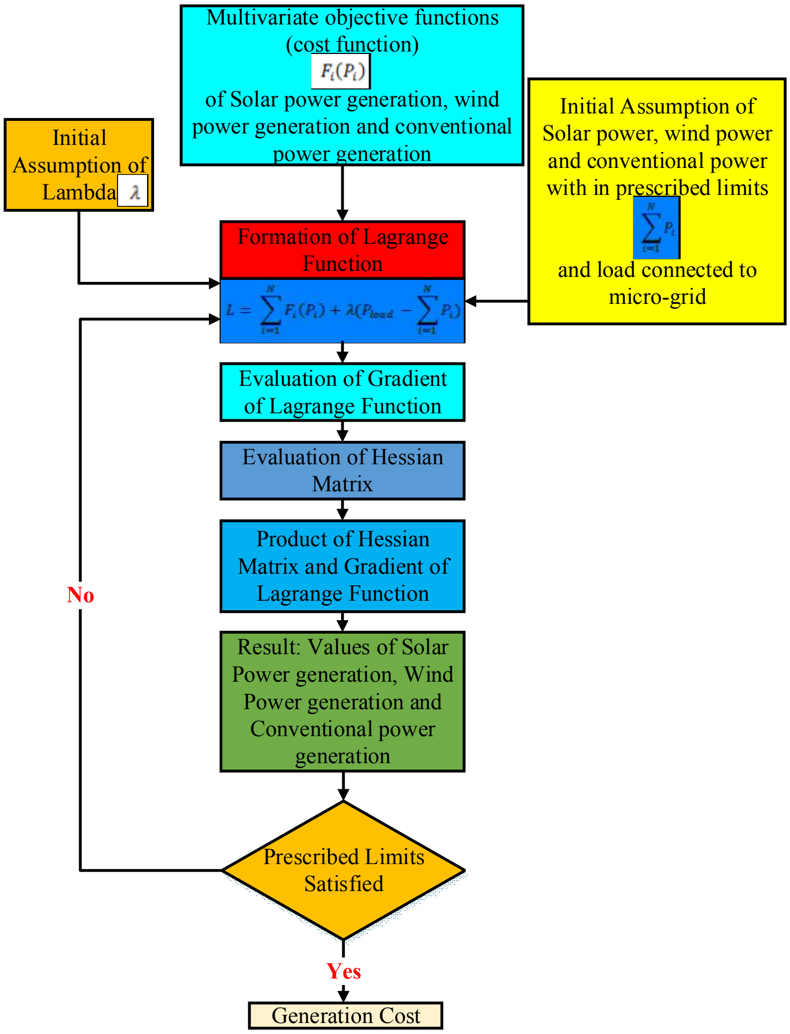


Fig. 21. Newton's method for planning and operation of microgrid test model under optimal cost of generation

Table 1. Optimal cost of generation from solar, wind and conventional power sources under eight hours division of day

8- Hours division	Solar power prices	Wind power prices	Conventional power prices
1	8.85	3.05	17.27
2	8.85	2.06	14.5132
3	8.85	3.003	11.70

Newton's method is applied for finding the optimal cost of generation from renewable and conventional energy sources. Proposed flow chart of Newton's method based on gradient of Lagrange function and Hessian matrix is presented in Fig. 21. Table 1 presents the optimal costs of generation achieved in 8 – hours division per day. This Table shows the variation of wind and conventional power prices because of priority set for Solar power generation.

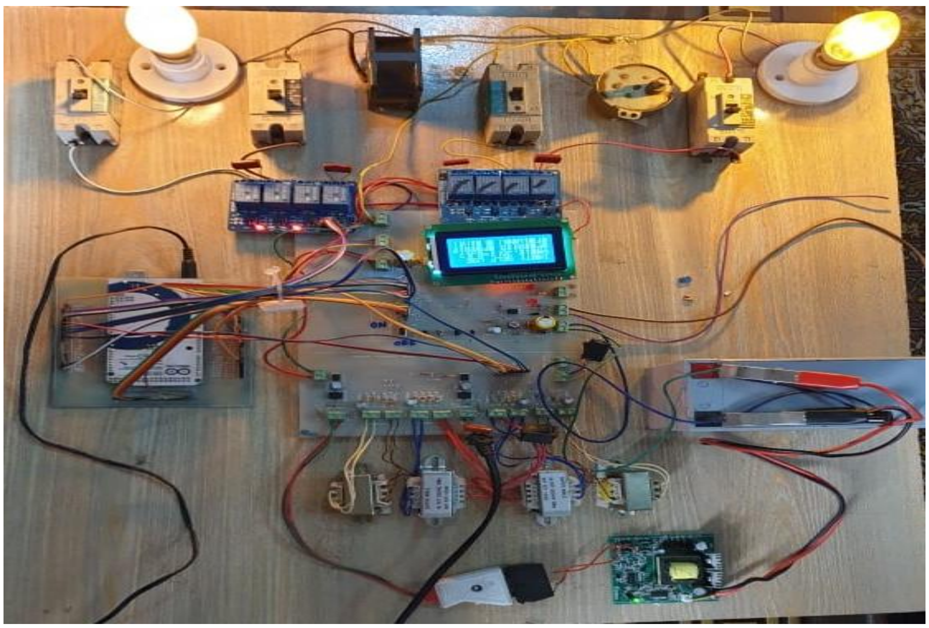


Fig. 22. Hardware prototype of microgrid model

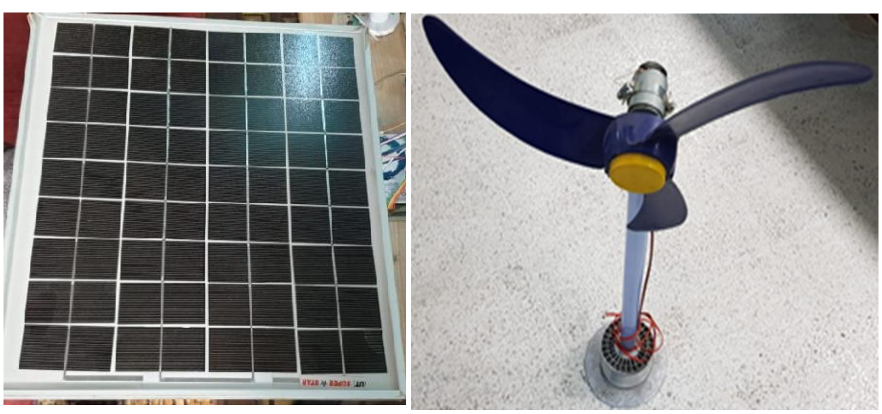


Fig. 23. Hardware prototype of Solar panel and wind farm

3.1 Hardware Development

Prototype of microgrid model is developed as shown in Fig. 22. In this test system, national grid power source (220 V) is switched on followed by switching on of Arduino (12 V) Current will flow and feed the load connected to power supply. Renewable energy sources will supply power only as a backup. In the similar way, when renewable energy sources are feeding the load, national grid power source will not supply power to loads. Potentiometer is installed with the circuit breaker for overload condition. Whenever the load will exceed from the power limit, than the circuit will be automatically disconnected by circuit breaker.

4. CONCLUSION

In this research, planning, operation and protection of test model of microgrid are designed and analyzed. It is found from simulations that microgrid is a wonderful concept for making power supply reliable and cost effective. Further, it has the ability to incorporate renewable energy sources so that future of green energy utilization could be promoted in a wider sense. Moreover, this research enables the consumer to enjoy freedom of energy consumption by the installation of solar and wind farms based power generating units at small level. The concept of microgrid brings revolution in the promotion of small and medium scale enterprises in developing countries like Pakistan. In this research, natural parameters were also considered for development of solar based power source so that realization could be achieved in a more practical way. Successful operation of microgrid relies on adequate planning, reliable operation and an intelligent protection system. This research can be extended by the addition of communication system between prosumers and national grid, by intelligent features of loss and theft detection, by the incorporation of cyber security features for the protection of microgrid against intruders and by the addition of charging systems for electric vehicles.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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