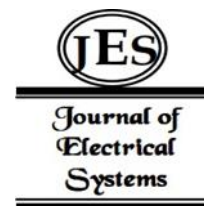


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Decentralized Energy Solutions for Hybrid Microgrids with Trading and Power Management



Abstract: - Renewable energy sources (RES), such as solar and wind power, received extensive interest since the outputs promise to reduce carbon content with the open allowance of renewable energy utilization. However, one of the most crucial setbacks of RES is that it makes dependant grid stability and energy management impossible. To address these challenges, the Indian government has announced several policies to strengthen renewable energy and help spur growth in the sector. The promising solution that will be brought forward is to provide peer-to-peer, or P2P, energy trading opportunities between small-scale producers and consumers themselves. This will help democratize the energy sector, reduce transmission and distribution losses, and help in increasing renewable energy as part of the energy mix. This research paper discusses possible prospects of P2P energy trading in India by exploring several advanced intelligent techniques including optimization of energy pricing, market dynamics analysis, and regulation framework evaluation. Through this, the research will investigate some of the key directions so as to contribute to the development of a more sustainable and efficient energy system.

Keywords: Hybrid Microgrid, Renewable energy resources, P2P trading, Power flow control

I. INTRODUCTION

Indian energy landscape is changing at a galloping pace, and it remains the world's third-largest energy consumer, wanting spirals of energy demand to increase ever more. Although fossil fuels, including coal, form its long energy mix, the government has been drastically moving to diversify its energy resources and reduce dependence on carbon-intensive fuels. Renewable energy has grown quite quickly and rapidly to become the biggest leader in India's energy transition, dominated mostly by solar and wind power. It has taken off due to governmental supportive policies and ambitious targets toward growth, including challenges toward achieving a stable grid as well as proper energy management.

In this regard, P2P energy trading becomes the answer to those hurdles and unlocks full potential of renewable energy. It has truly empowered direct energy exchange between producers and consumers, democratized the energy sector, reduced T&D losses, and optimized the energy price. This paper takes the concept of P2P trading in India to its potential and touches upon advanced intelligent techniques to optimize pricing and analyze market dynamics, coupled with getting into the regulatory framework. In this sense, understanding these aspects together brings it all together to contribute to a more sustainable energy future for this country.

II. INDIAN ENERGY MARKET

It is revolutionizing the energy sector in India. For a very long time, fossil fuels had stayed atop the energy mix with coal, whereas the country today is rapidly propelling forward toward clean energy supply with renewables, nuclear, and natural gas. Rising progressive government policies toward the use of solar and wind power, nuclear, and natural gas are on the rise. The National Solar Mission and the National Wind Energy Mission have been significant drivers in accelerating the growth of these renewable energy sectors. The expansion of renewable energy capacities in India has seen huge improvements, with solar and wind power on the forefront of making up major parts of the total energy mix.

Table 1: Electricity Market Structure: Challenges and Advantages

Market Structure	Challenges	Advantages
Completely Peer to Peer Market	Investment and maintenance cost is high with fully ICT structure.	No obligation. Autonomous. Easily available energy as per preference

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		To maintain the reliability and quality power supply for 24*7	
Community based Market	P2P	To fulfill the requirement as per need of community members without any biasing	Sharing of energy, Active participation of members.
Hybrid Market	P2P	To maintain the coordination between members, energy manager and other nodes.	ICT infrastructure, compatible with system, better than above two.

Renewable energy is becoming the best addition to nuclear power and natural gas in the scale of India's energy landscape. Increasing the share of nuclear power in the mix while promoting natural gas as a cleaner source of energy in preference to coal - these are the twin objectives of the government.

The said improvements notwithstanding, there are still significant challenges facing India's energy sector. These include infrastructure, financial, grid integration, and regulatory issues with regards to the sector. Overcoming these is crucial to ensuring that there is a reliable and sustainable supply of energy for the country. Figure 1 represents the average load profile of a town over year on daily basis.

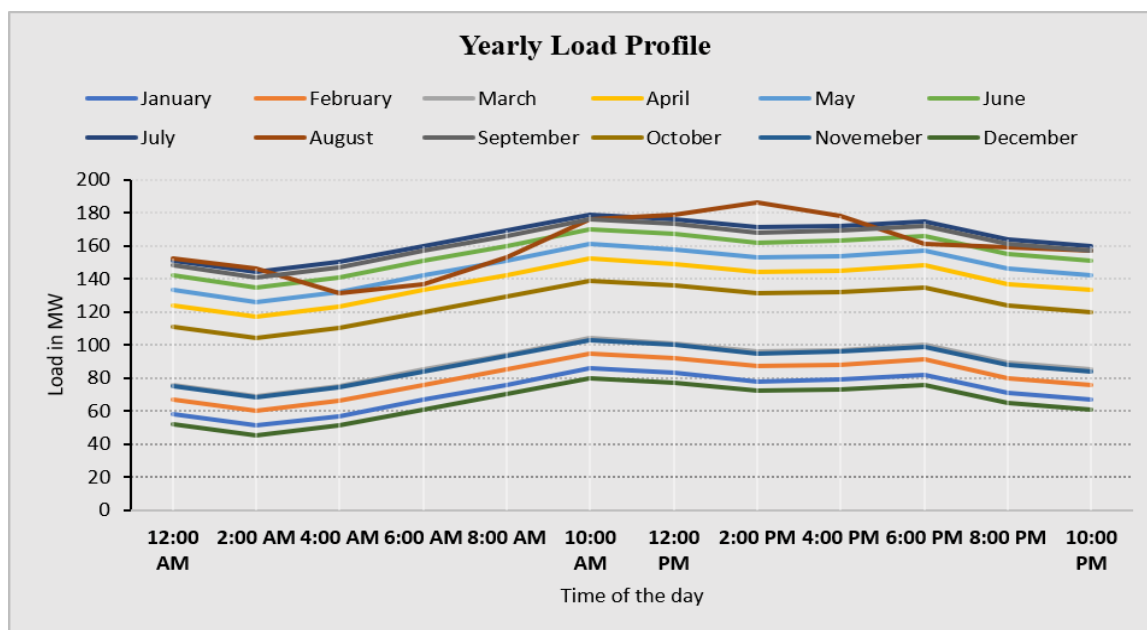


Figure 1: The load profile of the town on daily basis

Advanced technologies and smart techniques are in development in order to overcome such challenges so as to optimize energy consumption. P2P trading is potentially the best method for this purpose. It involves direct energy exchange between the energy producer and consumer over a grid, maximizing the efficiency of energy use, reducing losses in transmission and distribution lines, and helping consumers manage better their consumption. This paper contributes to the research in P2P energy trading as it covers advanced intelligent methods for pricing optimization. The challenge resulting from P2P energy trading - the lack of proper pricing-improves overall efficiency and sustainability in India's energy sectors as a result of this study.

III. FOUR-AREA MICROGRID WITH PRICING MECHANISM FEATURE

The growth of microgrids will increase the demand for sustainable and reliable sources of energy. To put it simply, a microgrid is essentially a localized electrical grid, which can power itself or be synchronized with the main grid. Including RES, particularly solar and wind, in such systems reduces carbon emissions and improves security in energy supply. An interconnection of several microgrids with a central controller can be one of the interesting designs capable of forming a multi-area microgrid system. Such a configuration provides increased reliability, good power quality, and resource utilization efficiency.

Consider, for instance, a four-zone microgrid system (Figure 2). In each zone diversified mix of renewable sources, energy storage systems, and conventional generators are there. The system can operate in offline and online modes. In online mode, the main grid is connected to the micro grid. There is a two-way power flow and sharing of resources. In offline mode, the microgrid can operate independently, providing uninterrupted power supply to local loads even during grid outages.

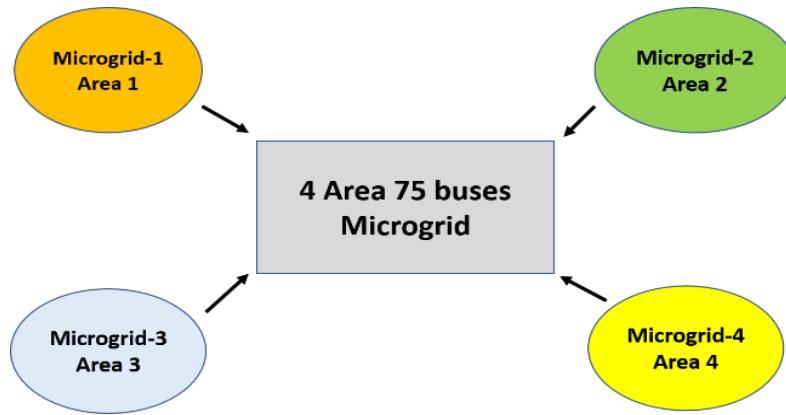


Figure 2: Four area control for 75 bus system

Hence, some advanced control strategies are required to be developed for smooth operation in both modes of microgrid. Those strategies will point out prime areas that include voltage stability, frequency regulation, and power quality. The techniques that are likely to be selected for optimization of the performance of the microgrid system are MPC, AI, and ML. For instance, it will help predict the future generations and demands in the system to provide proper controlling actions towards stabilization of the system. AI and ML algorithms can draw patterns from historical data to optimize strategies of energy management. In addition, advanced communication technology enables information to flow smoothly between regions and the central control area.

P2P energy trading pricing mechanisms may be divided into two parts: namely, energy pricing and network service pricing.

A pricing mechanism is a guideline for how the value of commodities or services traded should be determined. Energy pricing determines the price meant to meet market objectives; network service pricing determines the cost related to using network infrastructure and ancillary services in the background to enable trading. Such transactions in P2P energy trading can be verified on the basis of energy production and consumption and may have regulation through several factors that can change the strategy in a trading scenario. Depending on the approach taken in pricing energy, say for a Pool-based market, trading strategy may be functionally related only to energy production and consumption. For bilateral contracts, trading strategy can actually depend on the counterparty. Figure 3 illustrates how strategy might be employed in determining a classification for pricing mechanisms; methodology on how such pricing mechanism could be implemented is also presented.

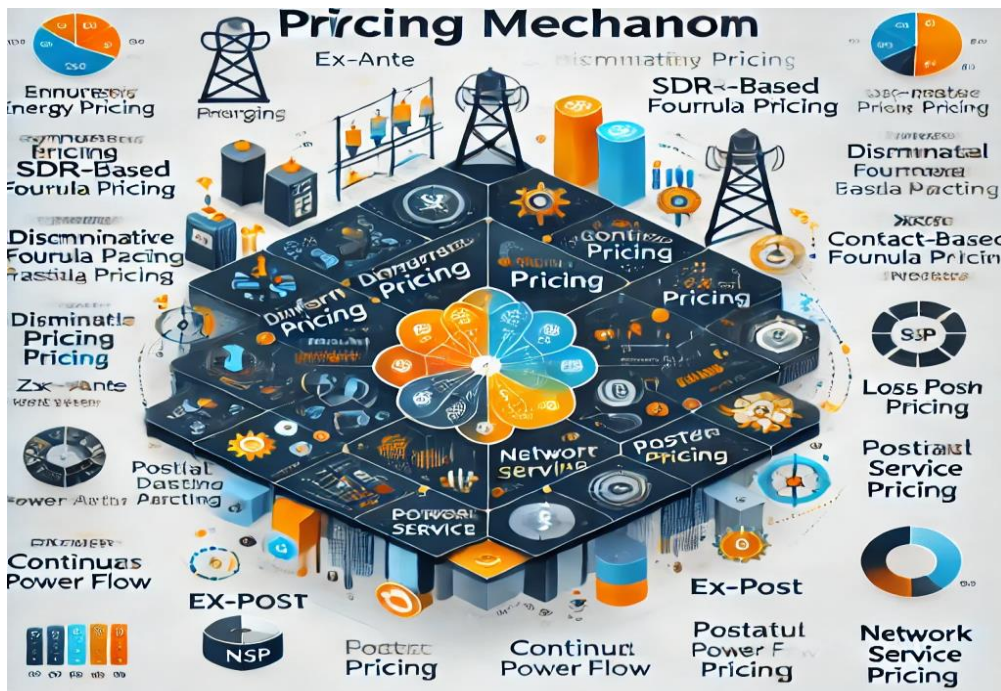


Figure 3: Pricing Mechanism of Microgrid

Such emerging technologies embedded within the four-area microgrid system can therefore further enable it to be better resilient and responsive to fluctuating energy demands and grid conditions, thus contributing to achieving a more sustainable and reliable energy future.

IV. MODELLING AND SIMULATION

Suppose N MGs and one power plant are assumed to exist in Local Area. Within each MG, renewable sources and ESSs with active loads.

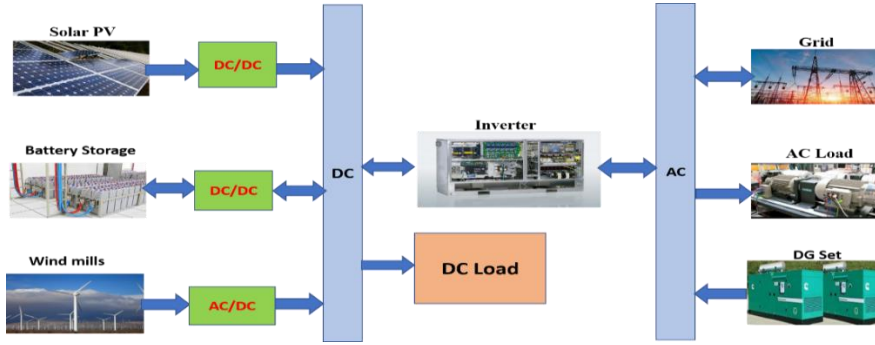


Figure 4: Block diagram of Hybrid Microgrid connected with a controller

The microgrids are mainly dependent on to them through the renewable energy generation and battery bank (or storage system). Local energy demands; however, since the energy source is intermittent. They must exchange energy with each other from renewable energy, other or power plant to balance generation and demand at that particular time. as depicted in Figure 4.

The authors design the multi-level optimization statement to enhance the proposed microgrid by focusing on four objectives, each assigned a specific weight. [14]

$$Objective = w_1 \cdot TFC + w_2 \cdot TOC + w_3 \cdot TDG + (1 - w_1 - w_2 - w_3) \cdot TGE \tag{1}$$

here

$$TFS = \sum_{i=\{pv,wt,bg\}} \left[N_i \left(\frac{IC_i}{T_i} + OM_i \right) \right] + \frac{IC_{bat}}{T_{bat}} \cdot \frac{\sum_{i=1}^{24} \sum_{m=1}^{12} CP_{bat}(t,m)}{12 \cdot ES_{bat}}$$

$$TES = \sum_{i=\{pv,wt,bg\}} \left[\frac{N_i \cdot GE_i}{T_i} \right] + \frac{GE_{bat}}{T_{bat}} \cdot \frac{\sum_{i=1}^{24} \sum_{m=1}^{12} CP_{bat}(t,m)}{12 \cdot ES_{bat}}$$

$$TDG = \sum_{i=\{pv,wt,bg\}} [P_i(t,m)] + DCh_{bat} - \sum_{All\ type} DL(t,m) - Ch_{bat}(t,m)$$

A. Modelling of Solar PV System

The output power of the solar PV module can be calculated through following equation (2)

$$P_{pv} = \eta_{pv} \cdot N_{pv} \cdot A_{mop} \cdot G_i \tag{2}$$

Table 2: I.F. of the solar modules [15]

Property	Monocrystalline Silicon	Polycrystalline Silicon	Amorphous Silicon-Hydrogen	Amorphous Silicon-Hydrogen Tandem	Amorphous Silicon-Hydrogen Triple	Cadmium Telluride	Gallium Arsenide
Efficiency (%)	15-20	13-16	6-8	10-12	13-15	10-12	18-25
Ideality Factor	1.2	1.3	1.8	3.3	5	1.5	1.3
Cost	High	Medium	Low	Low	Low	Medium	High
Temperature Coefficient	Negative (-0.45%/°C)	Negative (-0.45%/°C)	Negative (-0.2%/°C)	Negative (-0.2%/°C)	Negative (-0.2%/°C)	Negative (-0.2%/°C)	Negative (-0.45%/°C)

Lifetime (Years)	25-30	20-25	10-15	10-15	10-15	15-20	25-30
Light Weight	No	No	Yes	Yes	Yes	Yes	No
Flexible	No	No	Yes	Yes	Yes	No	No
Indoor Application	No	No	Yes	Yes	Yes	No	No

Parameters of equation (2) are constant for global irradiance and efficiency of solar PV modules except the solar PV [13]. For electricity generation, efficiency of the Solar PV is settled by the ambient temperature on that particular hour. On the basis of location and the projection about the geographical point, global irradiation varies about the solar PV plant. Efficiency factor of solar module is determined due to an ideality factor about that particular material also.

B. Modelling of the wind power system

Wind is a form of solar energy. The power generated by wind turbine systems relies on several factors, including the area swept by the rotor, the angle of the rotor, the speed and direction of the wind, and the density of the air. This relationship can be expressed through a specific equation

$$P_{wt} = \begin{cases} \alpha \cdot V^3 - \beta \cdot P_{rat} & , \quad V_{ci} < V < V_{rat} \\ P_{rat} & , \quad V_{ci} < V < V_{rat} \\ 0 & , \quad else \end{cases} \quad (3)$$

Here

$$\alpha = \frac{P_{rat}}{V_{rat}^3 - V_{ci}^3}$$

$$\beta = \frac{V_{ci}^3}{V_{rat}^3 - V_{ci}^3}$$

The total power available for transmission and distribution from wind turbine generators accounts for both the efficiency of the turbines and the necessary converters used in the process.

$$P_{wp}(t) = \eta_{wg} \cdot N_{wg} \cdot A_{mow} \cdot P_{wt} \quad (4)$$

Here η_{wg} is the combined efficiency of wind turbine generators and required converters [16].

C. Modelling of Biogas Power Plant

Biogas is a valuable renewable energy source that offers several benefits over solar photovoltaic (PV) and wind energy systems. One of its key advantages is that a biogas power plant can generate electricity on demand, independent of weather conditions. The energy produced from biogas is transformed into mechanical energy using a gas turbine. The amount of electricity generated by a biogas power plant primarily depends on the total solid waste available for processing. [17],

$$P_{bio} = \eta_{bio} \cdot TS_{bio} \cdot A_{bio} \quad (5)$$

D. Modelling of battery

The ongoing expansion of renewable energy systems increasingly relies on battery bank units, as the output from solar panels and wind turbines is influenced by weather conditions. In a microgrid, these energy storage units can perform several important functions, such as managing power quality, regulating voltage and frequency, smoothing out fluctuations in renewable energy output, providing backup power during emergencies, and optimizing costs. Common types of storage units include flywheels, batteries, and ultra-capacitors, with electrochemical batteries being the most widely used in power systems. These batteries are charged when there is excess energy available or during off-peak times and are utilized during periods of high demand or power shortages. However, accurately determining the state of charge for a battery bank can be quite challenging. The capacity of a battery storage units at any given moment is determined by [18],

During charging

$$C_{bat}(t) = C_{bat}(t - 1) \cdot (1 - \delta) - PE_{DC} \cdot \eta_{bat} \quad (6)$$

During Discharging

$$C_{bat}(t) = C_{bat}(t - 1) \cdot (1 - \delta) + PD_{DC} \cdot \eta_{bat} \quad (7)$$

E. Availability of AC Power

The cost of electricity will go down when we stop wasting energy on unnecessary loads. This means that the amount of power generated should match the total power used by all devices, except for what's stored in reservoirs. While we can't control the energy produced by solar and wind sources, we can optimize the output from biogas power plants and batteries to minimize energy loss.

$$P_T = (P_{pv}(t) + P_{wt}(t) + C_{bat}(t)) \cdot \eta_{inv} + P_{bio} \quad (8)$$

Figure 5 represents the Microgrid power management system. The central controller should try to balance the power with its demand. All the controllers work automatically but depend on specific algorithms and predefined rules to operate. This paper outlines several scenarios that the algorithm handles; it covers scenarios of power plants based on biogas and the storage unit. For one, it determines whether additional power should be bought from the grid.

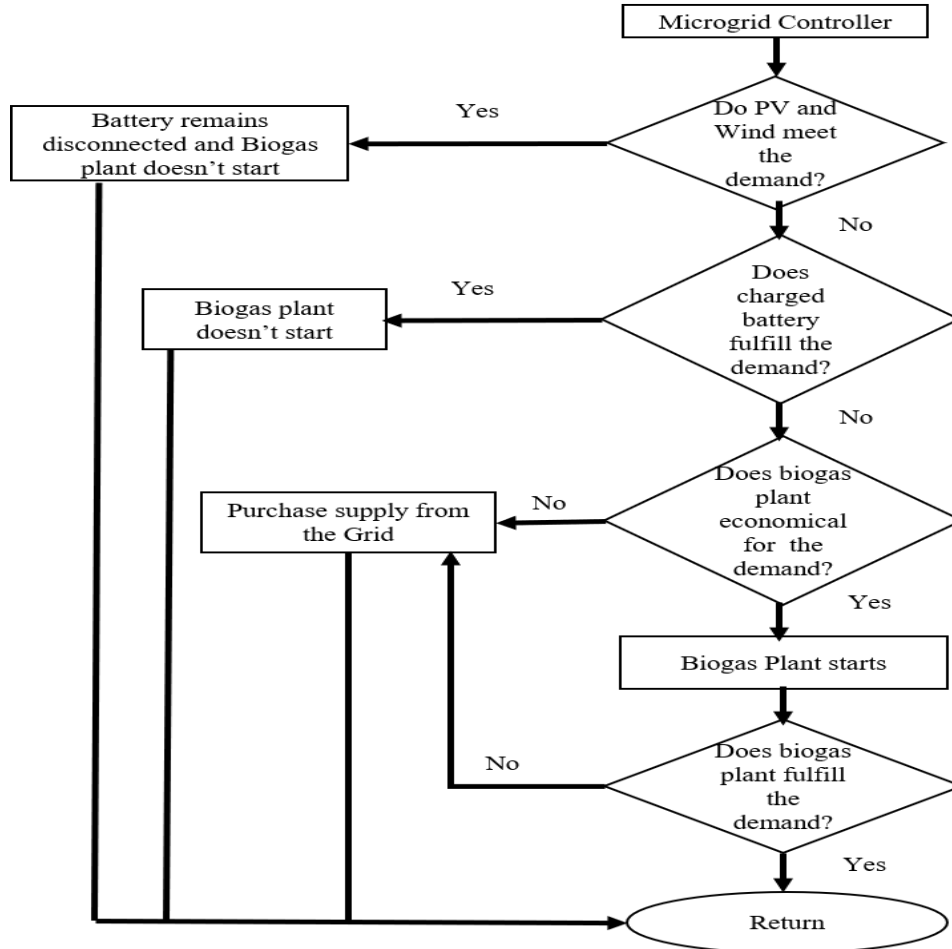


Figure 5: Algorithm to management of power flow in proposed system

V. RESULTS AND DISCUSSIONS

The proposed hybrid microgrid system with RES, ESS, and conventional mix generators was rigorously simulated against different load profiles and possible grid conditions. In effect, the simulations were essentially aimed at appraising the power quality, reliability, and economic viability the system promises in this regard. This hybrid microgrid exhibited good power quality performance since, for example, voltages and frequencies remained within acceptable limits, even for scenarios of high load demand or grid disturbances. The contribution of RES-solar and wind power-to the enhancement process of the power quality of this microgrid is of great importance. The use of the ESS buffer system further enhanced the potential of this hybrid microgrid to reduce voltage fluctuations and frequency deviations even further. With regard to the grid or unexpected events-related outages, the hybrid microgrid system's reliability and sensitivity were analyzed. It could maintain the provision of critical loads for a significant time, and diversification of energy sources and redundancy in the ESS system helped maintain system reliability. After applying the multi-level optimization problem method to the projected microgrid, the author simulates the microgrid system and optimizes the desired all four objectives. The system is ascertained to operate at the lowest cost with emission of the minimum carbon emission. As shown in Figure 6, each point on the Pareto front represents the exclusive and ideal solution to the problem. The Pareto front method is stronger compared to the other methods. The authors' calculations are based on various assumptions levied from their literature review.

Table 3: Optimization function weight management

S.No.	Weight w_1	Weight w_2	Weight w_3
1.	0.25	0.40	0.15
2.	0.30	0.35	0.25
3.	0.35	0.30	0.20

4.	0.40	0.25	0.10
5.	0.45	0.20	0.20
6.	0.50	0.15	0.15

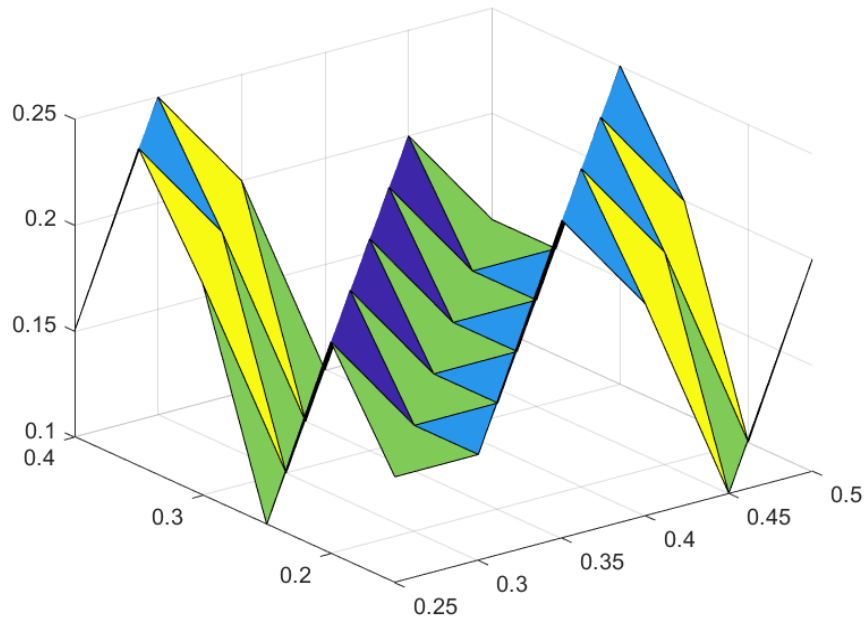


Figure 6: Variation of weights of objective function

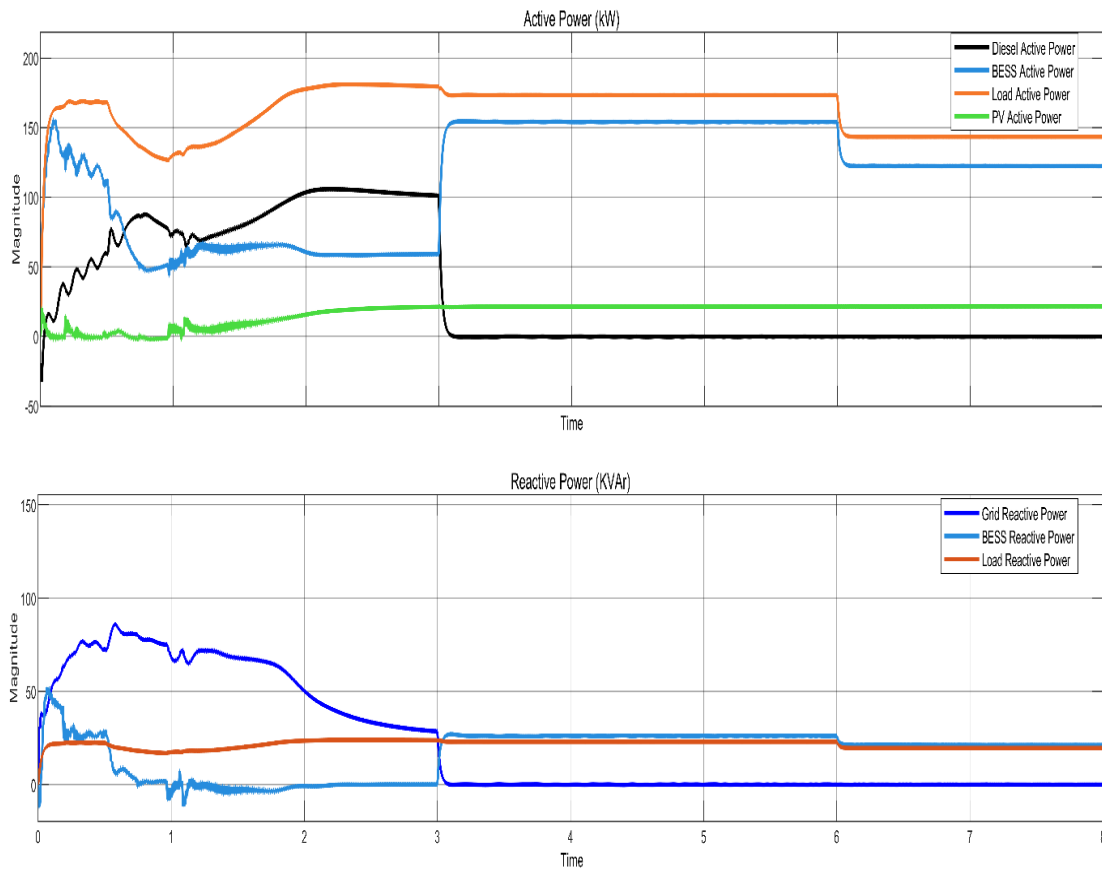


Figure 7 (a): Active and Reactive Power variation when diesel generator is disconnected at t=3 sec

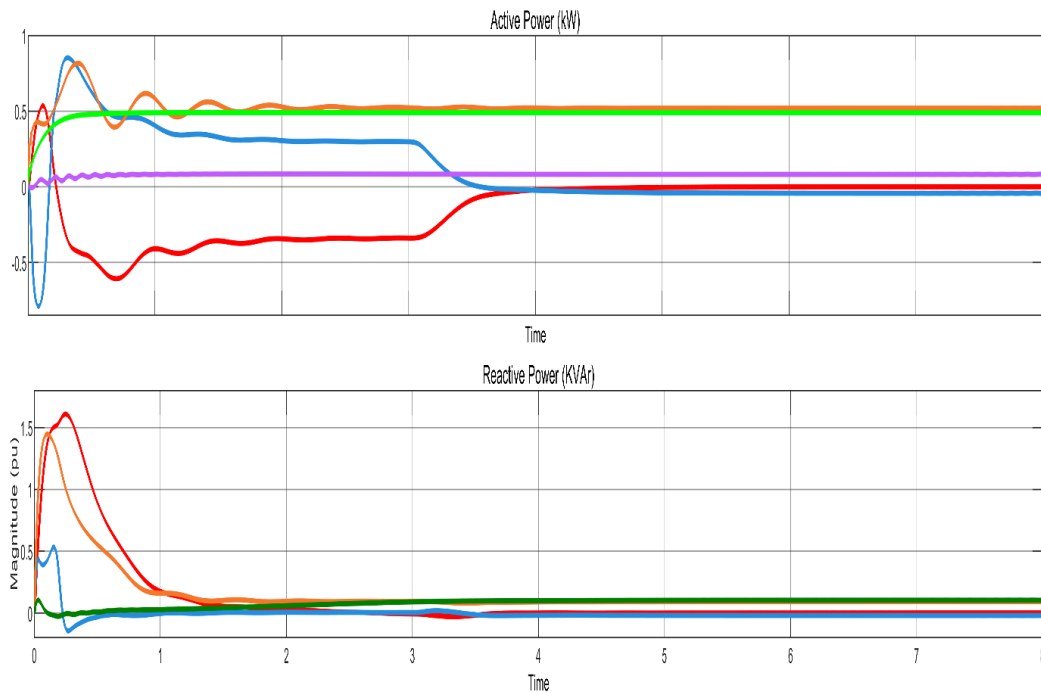


Figure 7 (b): Active and Reactive Power variation when fault occurs in microgrid

The economic feasibility of the hybrid microgrid is always calculated based on a cost-benefit analysis. The result shows that hybrid microgrid significantly offers benefits in terms of low operating costs as well as independence in energy thus allowing for sales of excess power to the grid. Apart from covering the initial capital investment long-term savings may be covered by government policies offering incentives.

VI. CONCLUSION

Results on similar systems in existing literature are further compared with a performance evaluation of the proposed hybrid microgrid. Further, it has been noted that the proposed system outweighs many of the existing systems regarding power quality, reliability, and economic viability. Advanced control strategies, optimum system sizing along with multiple energy sources, all have been truly effective for its performance. Exploratory areas include: Advanced control algorithms to enhance the operational efficiency of hybrid microgrids; the potential influence of emerging technologies: e.g., energy storage devices with significantly increased energy density and power density; more sophisticated economic models for better estimations of the persistent benefits of these systems.

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