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Analysis and simulation of optimized micro-grid

Saqib Ali [*], Muhammad Usman, Shahzad Aziz, Muhammad Kamran Liaqat Bhatti, Safdar Raza

NFC Institute of Engineering and Technology, Multan Pakistan

[*] Corresponding author: Saqib Ali, Email: saqib.ali@nfciet.edu.pk

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KEYWORDS

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ABSTRACT

The centralized power grid bears a heavy burden in a time when consumers expect an uninterrupted reliable power supply, a reduction in carbon emissions, increased efficiency within the national grid, and power supplied to remote communities. One such structure is used to implement this type of control that is based on small-scale Distributed Generation (DGs), at a single house or a small building level: micro-grid (μG). A μG is an autonomous, sustainable hybrid framework that uses renewable and non-renewable energy resources to supply continuous electricity to the load. Taking this scenario into account, the three sources of generation that have been utilized in the proposed μG are Photovoltaic (PV) array, Fuel Cell (FC), and Wind Turbine (WT) in this research paper. The active and reactive power of all three generation resources has been controlled using various controllers, i.e., integral, proportional-integral, proportional derivative, proportional integral derivative, fractional-order proportional-integral, Fractional Order Proportional Integral Derivative (FOPID), and Sliding Mode Controller (SMC). An advanced optimization technique based on a Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm has been utilized to optimize all these controllers. The integral square error has been taken as the objective function for both optimization algorithms. Finally, a graphical and tabular comparative analysis of all optimized controllers along with their control parameters and performance indexes has been evaluated to find the best optimal solution using MATLAB/Simulink. The performance of SMC has been surpassed the performance of all other optimized controllers for the power stability analysis. Moreover, a smart switching algorithm has been introduced for switching between the generation resources following the load demand and cost of the system to operate the μG more economically. Finally, a case study has been performed in which the smart switching algorithm has been utilized to switch to the best available generation resource in case of any fault at the generation side to provide uninterrupted power to the attached loads.

1. Introduction

The usage of sustainable power sources in power networks is getting recognition due to ecological issues. The over-consuming of non-renewable sources to produce electrical power along with its infrastructure development are dealing with several adversities i.e., ill-equipment. These types of issues are faced mainly due to the usage of long-distance transmission lines while supplying electricity to the customers.

One other leading problem is that approximately 1.2 billion individuals throughout the world don`t have accessibility to electrical energy [1]. Among these 1.2 billion people, mostly living in rural or separated communities, and expanding the grid to such a community is usually regarded as uneconomic. For the societal, ecological, and financial factors, these types of inadequacies urges must be resolved and that remedy under research is distributed generation. One practical solution to the said problems is micro-grid (μG) technology that's the independent power system.

By using power converters, sustainable resources could be linked straight to the network of distribution and can relate to some other localized loads and generators to develop a self-sustaining power network. A μG is probably to be smaller in size as compared to a smart grid, having a capacity in the order of 40-100 kW as it is focused on electrically isolated areas [2]. Moreover, a μG works as both types of electricity supply i.e., DC well as AC. These are dependent on power electronics converters to connect sources, storage, and loads in a mannerly ordered according to the required system. Different types of converters work at various voltages to utilize bi-directional energy to and from the μG [3]. Various μG techniques for these types of electronic converters have been offered by researchers. However, the leading control problem in the field of μGs is to provide the sustainable and stable provision of electricity by utilizing various types of sources, storage, and loads. Fig. 1 depicts the proposed μG that utilizes renewable and non-renewable sources, energy storages and number of loads that are connected to the external utility grid. There all sources, storages and loads controlled by the proposed μG controller to provide an optimized and stable electricity.

The key control problem in a μG is keeping the power stable in the grid that faces the varying power sources. Electricity provided by renewable power supplies fluctuates greatly because of the stochastic behaviour of its power supply. The control strategy may include load-side as well as source-side management [4].

Loads having the least priority decrease the peak demand could be stripped out, averting the non-renewable sources to operate online for generating spikes of the transient in load. In a renewable-based system, the conventional approach of implementing a source-side control scheme is for using the centralized controller that scheduled every source through links of communication [5].

The network thus is based on links of communication as well as centralized controllers. Redundant controllers must be used at a surcharge to ensure the reliable function of the network. A distributed management technique increases system performance by distributing the control functionality all over the network. Nevertheless, for proper operation, the device is still based upon links of communication. The transmitting system itself could be utilized for conveying network information to minimize dependency on the communication links. Simulation tests have demonstrated the ability to use a DC transmission network's voltage level to transmit load-side control information within a network with an optimal transmission system [6].

1.1 Literature Review

Renewable Energy Sources (RESs), Distributed Generation (DG), and Distribution Systems will be deployed soon in power systems leading, among others, to significant changes in the way distribution networks are currently operated, one such distributed generation is μG [7].

The majority of the μG focuses on the control and the hardware, with a variety of algorithms and power converter topologies being discussed [8].

The control of the μG implemented by the μG controller is what gives the system ability to coordinate multiple sources and optimize power production and consumption. There are two categories for control one is supply-side management (SSM) and the other is demand-side management (DSM). Several control topologies can be used to implement SSM and DSM with various levels of success. Using μG control topologies, the implementation of supply-side management has been presented [9].

A centralized control had been used that acts on information from sensors measuring the power production and consumption of the system [10].

All control decisions are made from a central location. The central control measures parameters in real-time, making the system fast when implementing control. The disadvantage to this topology is that if a fault occurs in the controller then the whole system was shut down and the system was no longer could implement control [11].

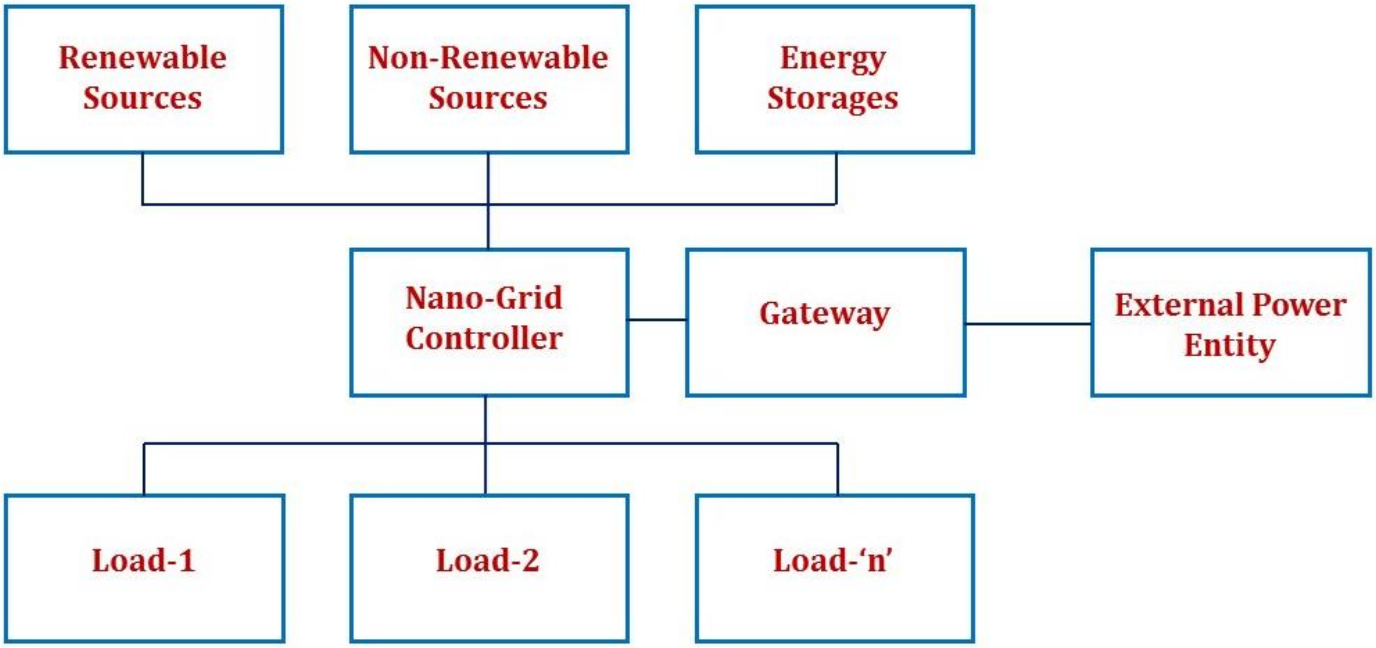

Fig. 1. Block diagram of proposed micro-grid

Another controlled method is defined that is distributed control which takes the decentralized topology and adds communication between nodes via communication lines as in central control. The distributed system adopts certain characteristics of both the systems distributed as well as central [12].

In the past, a hybrid distributed control model was explained, the nodes can communicate creating a cohesive control strategy. This method was to improve the distributed control topology by avoiding the need to use a communication line, it does so by utilizing the DC bus/supply lines to communicate between lines [13].

N. Liu et al. [14] presented a partially distributed architecture, in which peer-to-peer electricity sharing was enabled by GSM-based through power management units.

Similarly, C. Cecati et al. [15] proposed a PV/battery-based central generation and distributed storage architecture, with the provision of local batteries in individual households.

Distributed control, exhibits characters that are present in decentralized and centralized control technology, have an external surplus communication link without any central controller [16]. Distributed power allows the execution of a control law as with central control. The control law is executed by embedding the section of the control law related to the operation of every source in the local controller of the source. Every controller of the source communicates with the other nodes that influence its operation to decide its operation of mode. A distributed control topology has been proposed for a hybrid wind-diesel network [17].

The major benefit of having distributed control over centralized control is that system stability is improved as the network becomes independent of the centralized controller. With the control function spread over the network, system operation is still feasible when a control node fails [18]. A hierarchical topology is hybrid central control, a combination of centralized and decentralized control. Decentralized control can be used for immediate, source-level power-sharing to reduce the control pressure on the centralized controller [19].

The centralized controller role becomes one of each node's central planning, rather than real-time control. A management regulation can be readily applied due to the presence of a central controller [20].

To boost the control strategy's reliability, redundant controllers and communications connections must be included at an additional cost. Nonetheless, hybrid centralized control typically offers the best compromise between reliability and performance, and this hierarchical topology is widely used to manage the traditional 50/60 Hz conventional AC system [21].

The hierarchical control method was also applied to the management of small renewable resources, suitable for managing the traditional power grid [22].

Decentralized control has excellent reliability and low cost of implementation but does not provide for source scheduling under supply-side control law [23].

Distributed control is a potential candidate for supply-side control topology because it allows a Demand-side control law to be applied and offers enhanced flexibility over central control [24].

Energy-saving becomes one important action as a solution for global warming. Energy Management System (EMS) is one of the most important actions for energy saving. Building Energy Management System (BEMS) is one example of EMS, and the concept of EMS mainly focuses on total energy monitoring, control of air-conditioning or lighting [25].

In the same way, Home Energy Management System (HEMS) is used for a small power customer that aims to control electric devices efficiently [26].

Control of the power of a household is difficult because the amount of household energy consumption depends on the customer's behaviour. Moreover, isolated, and stand-alone management of one household is not so effective because of the limited control margin that comes from its small scale. From this viewpoint, both power control prediction of each consumer and integrated multiple energy management are indispensable [27].

H. Kumar et al. [28] proposed distributed demand-side management (DSM) system for a household by using Keio University Network oriented Intelligent and Versatile Energy-saving System (KNIVES) and a smart circuit breaker box. Keio University Network-oriented Intelligent and Versatile Energy-saving System is an information control technology-based DSM and controls electric power by using distributed and cooperative power control algorithms. As approaches from the demand side, DSM is mainly developed with the concept of energy-saving and cost reduction in large-scale customers. In addition, DSM-able electrical devices in the home have been proposed to define what is appropriate for each device [29].

1.2 Research Gap and Motivation

Wind Turbines (WTs) and Photovoltaics (PV) are sustainable energy sources. These can be used in remote as well as isolated areas for supplying power where the conventional power grid is not available or connecting these areas with conventional grids is uneconomical. In this perspective μG offers the best possible solution that is economical, and the power supply is reliable and uninterrupted. Additionally, the remote areas or the isolated houses which do not have the facility of power from the conventional grid could utilize these sustainable sources connected with the μG.

1.3 Scope of this Research

The load-side-management strategy should be followed as the major mean of sustaining the electrical energy balancing in the network for avoiding the load from being at risk to the variations in the result of sustainable sources. With the advancement in power electronics technology, newer kinds of electrical power systems are growing. A variety of choices are presented for the use of renewable sources, such as μG that are entirely dependent on switching-converters. Traditional techniques for managing AC systems are usually followed while many research works concentrate on maintaining and balancing the network layout of effective power converters. This paper inspects attributes of the renewable energy sources depending on μG and suggests solid, effective, and cost-reliable ways of functioning and managing or controlling the system utilizing newer choices made feasible with the usage of power electronics.

1.4 Problem Statement

To provide uninterrupted power from the μG to the local loads by optimizing various controllers using intelligent algorithms to improve the power quality and stability along with the control of voltage, current, and frequency through various control strategies.

1.5 Aim and Objective

The Aim and objective of this paper are to satisfy the load by producing optimized uninterrupted power from the optimized controller having intelligent algorithms in terms of power system stability and reliability. The system has been implemented using Simulink / MATLAB. The system should be more efficient and robust in satisfying the load by controlling and management of energy in the system that should more reliable than the previously available systems. The designed system output has been justified by comparative analysis with multiple controllers.

1.6 Research Contributions

To provide uninterrupted power from the μG to the local loads by optimizing various controllers using intelligent algorithms to improve the power quality and stability along with the control of voltage, current, and frequency through various control strategies.

This research presents following contributions.

1. Sliding mode controller to control and stabilize the output power under varying load or environmental conditions.

2. Optimization of the controller using GA and PSO algorithms.
3. Comparison of the performance GA and PSO algorithms.
4. Control of all five parameters (i.e., active power, reactive power, voltage, current, and frequency).
5. Smart switching algorithm to switch between generation sources following the load demand and cost.

1.7 Organization of this Article

The rest of the article is organized as section-2 presents the research methodology, section-3 simulation, and results and section-4 presents the conclusion and future work.

2. Research Methodology

The main control problem of the μG is to maintain a power balance in the system in the presence of variable power loads and supplies. A supply management scheme must be adopted as the main means to maintain a power balance in the system to avert the load from becoming sensitive to fluctuations in the production of renewable energy resources. The purpose of the supply-side management system has been to plan the sources present in the μG following supply-side control laws that minimize the system's operating costs. The control method of supply-side topology makes sure that the usage of renewable energy has been maximized because the fuel price of the energy source is insignificant. Renewable energy provides a basic demand load, and surplus energy has been utilized for charging the backup storage devices as well as for net metering. In case of the shortage of energy of the renewable source, energy is extracted from backup storage devices or the grid. When storage devices are exhausted due to a long-term lack of renewable energy, the backup generation has come online.

Several control topologies can be used to control the sources present in the μG. The main criterion to choose a control technique is its ability to perform source planning according to the control laws of source and loads. The selected control technique must have to maintain modularity and reliability in a distributed network of the system. Moreover, it must be economical for implementing reliably to help for increasing the economic viability of the network.

The proposed layout of the whole system is shown in Fig. 2 which shows that three sources are connected and inter-linked at the AC bus. In the PV array, 23 strings are connected in parallel and there are 5 connected modules per string in series. The maximum power from one cell that can be extracted is 305.226 from that we have a PV array having a capacity of 35 kW from that we just extracted power of 20 kW. P & O MPPT technique has been implemented with the PV array and then there are two types of converters have been used. The first converter that has been used is the Buck-Boost converter that is attached with the storage batteries. The buck converter is used to store the power in batteries while in absence of power from the PV array that power is extracted through boost and fed to an inverter for the demand of the load. The DC-DC boost converter is used in the next stage of that wing, and it just levels up the voltages produced from the array.

The WT is the second source that has related to the micro-grid. The generation of the WT is 20 kW having a power factor of 0.8 the reactive power that has been produced by the WT is around 12 kW. The speed of wind is not nominal or ideal. The wind speed is variable just like in the real-life case. The three-phase Permanent Magnet Synchronous Machine (PMSG) relates to the WT. In the next stage, the generation of a WT is rectified into DC. The reason for converting the AC into DC is to smoothen the power and store the power in batteries with Buck-Boost converter and it can be used in absence of power from the sources.

There are many types of fuel cells (FC) but due to their efficiency, Solid Oxide Fuel-Cell (SOFC) is used in this proposed model. The SOFC converts chemical energy into electrical energy directly and its conversion efficiency is 65%. The main advantage of SOFC is that its by-product is high-temperature steam, which is used for different purposes. Their disadvantage is its slow response time. DC power is fed to a DC bus. DC bus has a constant DC voltage because the inverters operate on the constant input voltage.

A battery is a better way to store energy and it also provides energy for a long time. Integrating a battery with a hybrid power system makes it a more reliable source of energy. Similarly, the integration of super-capacitor in micro-grid makes it efficient during transients in load. It becomes very costly when the battery or super-capacitor acts as a primary source because it has required a large storage system. It is better and cheaper to use them during peak time, rapidly changing load, or during cloud cover in case of PV arrays and when there is no wind in case of the WT.

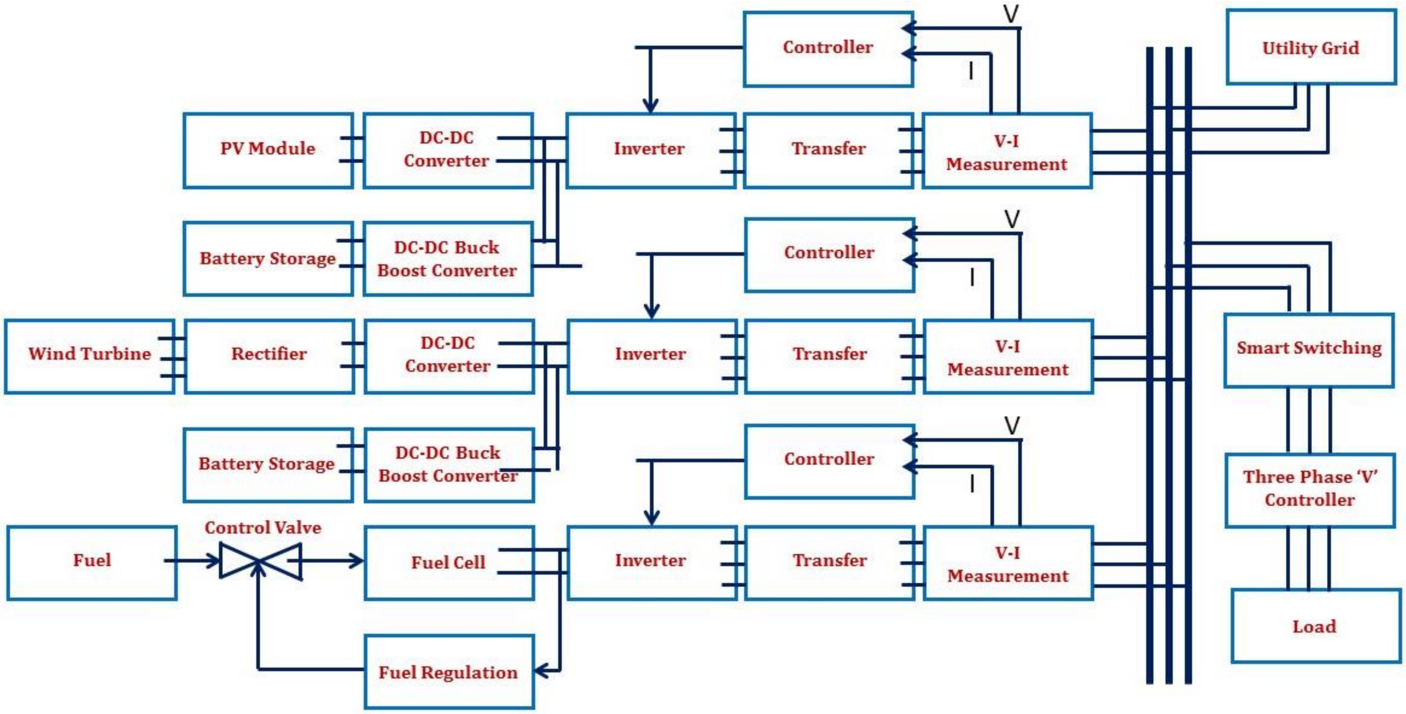

Fig. 2. Proposed layout of smart micro-grid

3. Simulations and Results

This section incorporates all the simulation results of the proposed hybrid μG system and proposed power management system (PMS) in hybrid μG. The first source PV array has 20 kW as it is the primary source of hybrid μG. PV power depends upon solar irradiance and atmospheric temperature but in this proposed technique ideal situation of irradiance and temperature has been taken. The reference real power of 20 kW and output real power of PV array has been shown in Fig. 3.

The second primary source of the proposed μG is the WT. From the optimized controllers and algorithms sliding mode, the controller provides the optimized controlled power and has the least steady-state error and least settling time in comparison with other controllers there are transients in other controller's output. The WT is the secondary source of hybrid μG. It generates the 20 kW of real power that is shown in Fig. 4. The FC is the third source of the proposed hybrid μG. The FC is the tertiary source in switching smart algorithm that if the demand of load is exceeding from the generation of primary and secondary source of WT than the fuel is switched in to provides the power to load. The FC has the fuel flow rate controller having installed PID to the controller flow rate of fuel towards the FC by sensing the changing of current. The flow rate of fuel in the FC varies from 1 mL/min to 81 mL/min. Sensing the current and changing flow rate of control can control the transients of the system. The inverter control of the μG has installed a sliding mode control and gives the optimized output power. The generation of real power is 20 kW of the FC which is shown in Fig. 5. The load is variable, and the demand of load is changing hourly. The load which is attached with AC bus is variable that the demand of load is started from 15 kW, and it changes with every hour and approaches at the peak demand of load is around 58 kW that is why the smart switching is considered that will connect or disconnect the sources towards the load according to the demand of the load. The load curve or the demand of load with time is shown in Fig. 6. The sources relate to load via smart switching algorithm and three-phase voltage controllers. The purpose of the smart switching algorithm is to connect the sources with load according to their demand. When the demand is low from the smart switching algorithm only one source is connected, and the other sources will connect with the load when the demand of load exceeds the rating of that source. This algorithm connects from one source to three sources with load through the algorithm. The real power of load with reference is shown in Fig. 7.

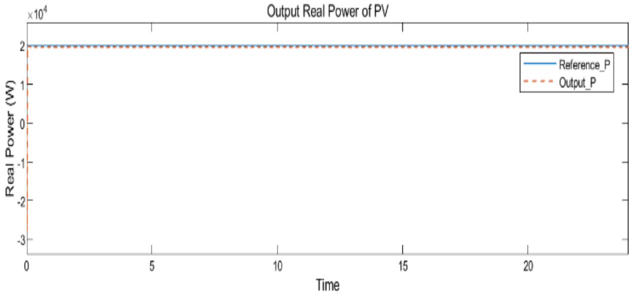

Fig. 3. Output real power of PV with reference

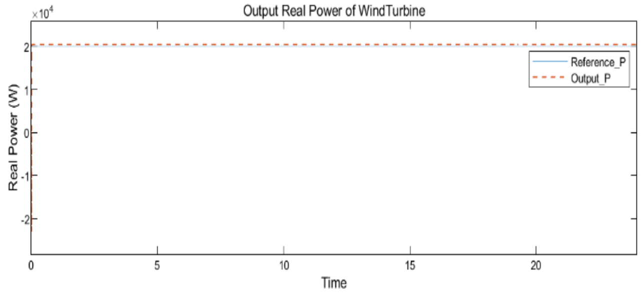

Fig. 4. Real output power of wind with reference

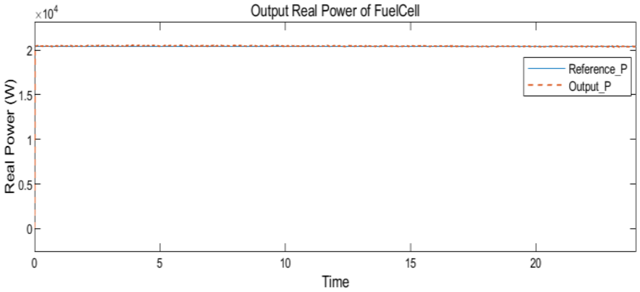

Fig. 5. Real output power of FC with reference

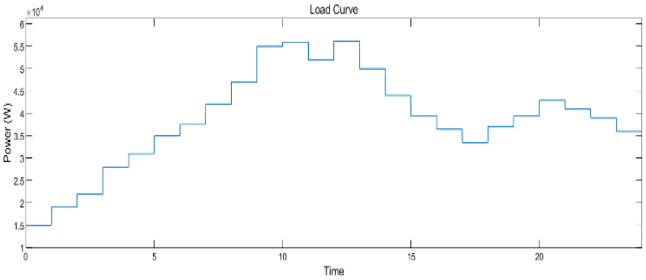

Fig. 6. Load curve of the connected load

The frequency is the important parameter of the system that when the demand of load changes it has effects on the frequency as well. The transient in the frequency shows the changing of load that is why the frequency controller is used to control the frequency in case of changing load the frequency of the system should not have transients in it. The steady state is reached after 0.096 s and the variations at that time are within 0.1% of the desired frequency, which is within acceptable limits of the applied constraints. The frequency of the system is shown in Fig. 8. A three-phase voltage controller is utilized at the load end that when the demand of load changes the level of voltage should not exceed or decrease from its level that is why the PID controller is used to minimize the error and keeps the voltage at its level to save the sensitive load. The RMS voltage of the load is shown in Fig. 9.

Fig. 10-11 is shown that the primary source of system PV is turned off due to fault or switching algorithm at 6 hours and turned on at 7 hours. In that time the smart switching will be done its work to switch the sources according to the demand of the load.

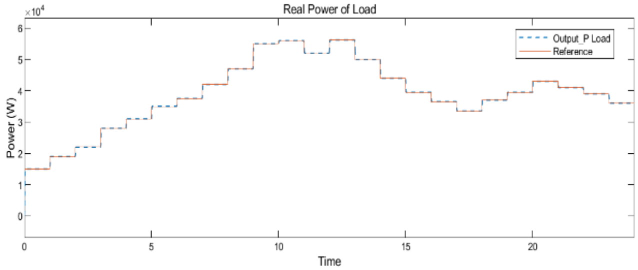

Fig.7. Output Real power of load

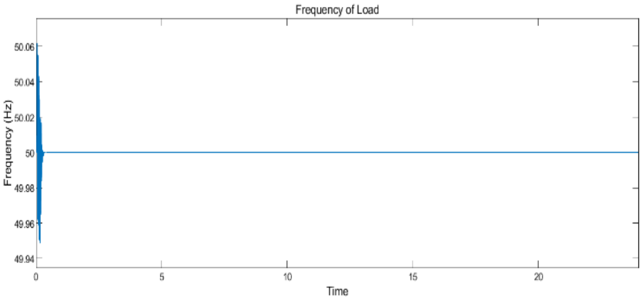

Fig.8. Frequency of load

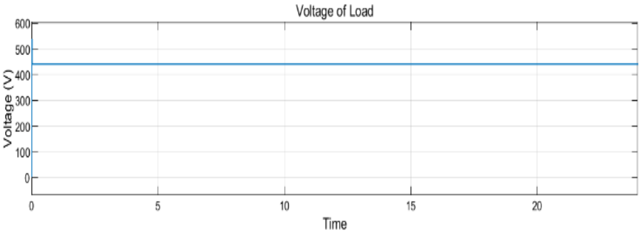

Fig.9. Voltage of load

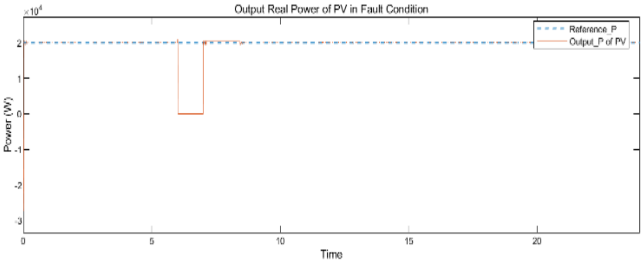

Fig.10. Real power output of PV in switching condition

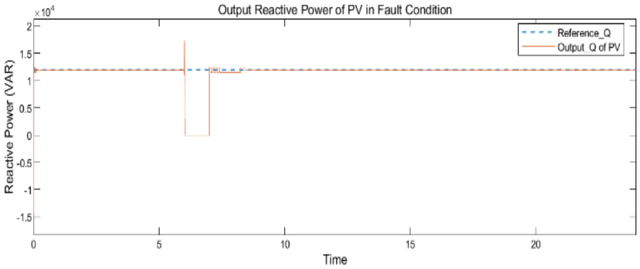

Fig. 11. Reactive power output of PV in switching condition

The second source of hybrid μG is the WT. The WT is turned off at 12 seconds and turned on at 13 hours. The faults and speed of wind cause the WT to turn off. During that time due to the smart switching algorithm in the μG, the backup line utilized that other source should supply the power to load and utility grid is brought online to fulfil the remaining demand of load in case of absence of source. The real and reactive power of WT in switching or fault case is shown in Figs. 12 and 13.

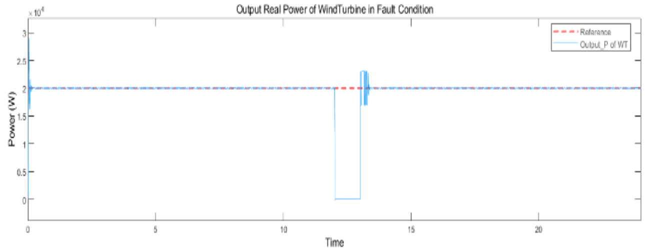

Fig. 12. Real output power of WT in switching condition

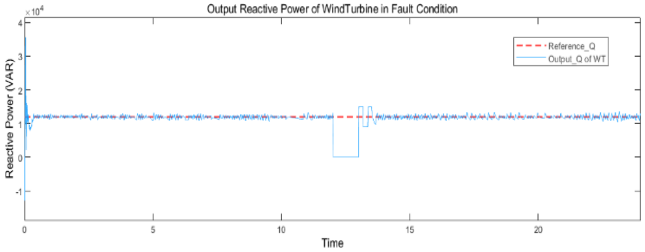

Fig. 13. Reactive output power of WT in the fault condition

The FC is the third source of μG. The FC is turned off at 19 hours and turned on at 20 hours. The source relates to load through smart switching then the smart switching algorithm will switch the sources according to the demand of load and provide the uninterrupted power to load. The power quality parameters (load frequency, RMS load voltage, and RMS load current) are within the standard limits which are shown in the below figures. The real and reactive power of FCs in the condition of fault or switching is shown in Figs. 14 and 15. The smart switching algorithm is working smartly according to the demand of load and availability of sources that if the source is unavailable then through smart switching the other sources are brought online to fulfil the demand of the load. If any of the sources from the primary secondary and tertiary is unavailable, and the demand of load is increased then the utility grid is brought online according to the second mode of power management that system is in deficient mode. The remaining deficient power is used from the grid to satisfy the demand of the load. The real power of load in the switching case is shown in Fig. 16. In the case of smart switching, the demand of load is increased, and the source is unavailable. In that case, the deficient mode of power management of the grid is brought online to satisfy the demand of the load. The reactive power of load in the switching condition is shown in Fig. 17. In the case of switching the load is changing concerning time and the demand of load is increasing every hour and after the peak demand, it comes to its average demand. At every hour when the demand of load changed then concerning load the current of that load is also changed. The RMS current of load in switching conditions is shown in Fig. 18. The power of sources provided to load is through a three-phase voltage controller and the purpose of the controller is to lower the value of error and control the voltage from regulating and keeping the level of voltage at standard level to keep the load safe. The RMS voltage of load in smart switching conditions is shown in Fig. 19. When the demand of load changes then it has some effects on the parameters of power which are current, voltage, and frequency. The frequency controller is utilized to control the frequency in changing the demand of load and keeps the frequency at the standard level. The steady state is reached after 0.096 s and the variations at that time are within 0.1% of the desired frequency, which is within acceptable limits of the applied constraints. The frequency of the system in the switching condition is shown in Fig. 20. When the demand of load changes then it has some effects on the parameters of power which are current, voltage, and frequency. The frequency controller is utilized to control the frequency in changing the demand of load and keeps the frequency at the standard level. Stabilization occurs after 0.09 s. Variations at that time range to 0.1% of the intended frequency, which is within the restrictions' permissible range. The frequency of the system in the switching condition is shown in Fig. 21.

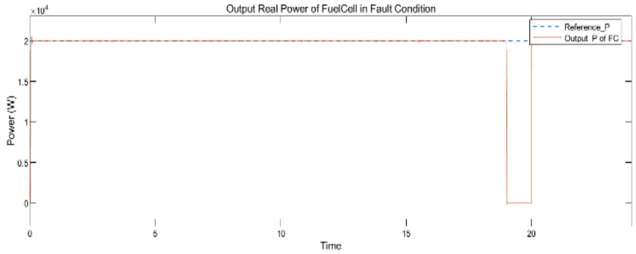

Fig. 14. Real power of FC in the fault condition

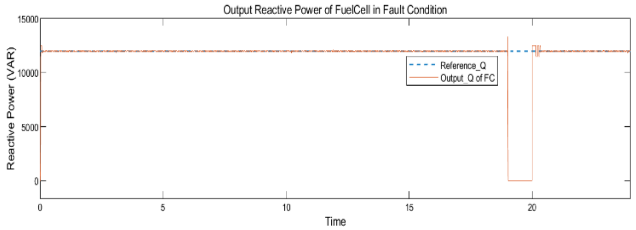

Fig. 15. Reactive power of FC in the fault condition

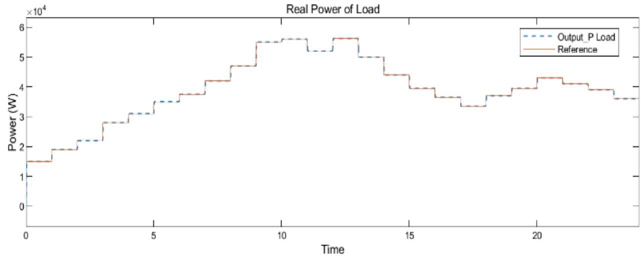

Fig. 16. Real power of load in switching condition

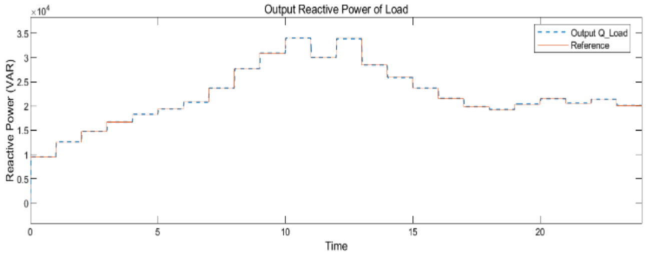

Fig.17. Reactive power of load in switching condition

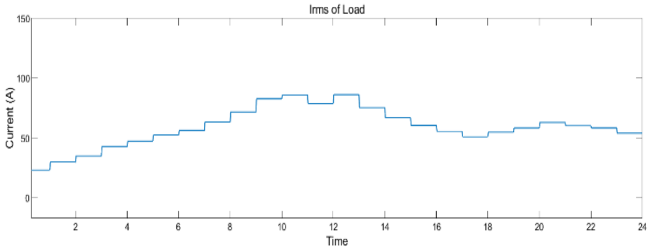

Fig. 18. I_{RMS} of load in switching condition

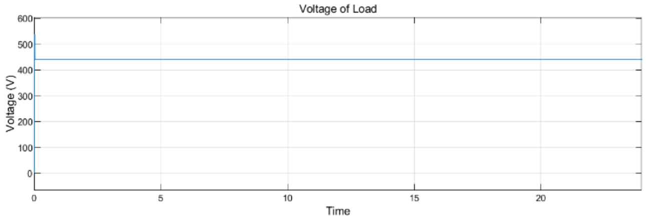

Fig. 19. V_{RMS} of load in switching condition

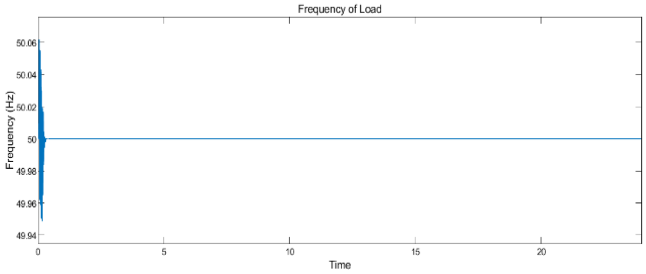

Fig. 20. Frequency of load in switching condition

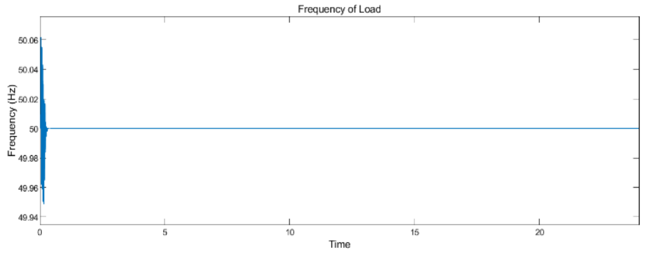

Fig. 21. Frequency of load in switching condition

3.1 Comparison of optimized controllers

The optimized controllers are simulated with PSO as well as GA and then it is compared in form of tabular as well as graphical.

Interestingly, FOPID-GA had the poorest response, with substantial steady-state errors. FOPID-PSO, on the other hand, has shown to be considerably more effective than FOPID-GA in terms of performance. FOPI using both algorithms, on the other hand, has shown better outcomes than FOPID. It is also possible that FOPID-performance GAs has declined to owe to fewer iterations.

The SMC controller that has been tuned for power stabilization has demonstrated excellent results. As soon as the steady-state is established, the fluctuations are within 1% of the target power, which is acceptable given the limitations that have been imposed. Thus, in the suggested system, the SMC is employed to regulate the produced power. Fig. 22 shows a zoomed representation of all the optimized controllers.

As can be seen in the magnified version, SMC's responsiveness is far superior to any other optimized controllers. Fig. 23 compares the SMC to all other optimal controllers.

The results of utilizing the PSO algorithm and SMC are precisely the same as those obtained with the GA algorithm. Gain for the SMC controller has been determined by both methods to be the same. In other words, the steady-state is attained after 0.267s, with fluctuations within 1 percent of the target power, which is within the allowed bounds of the applicable restrictions at that point. Fig. 24 shows a zoomed-in view of all optimized controllers using the PSO method.

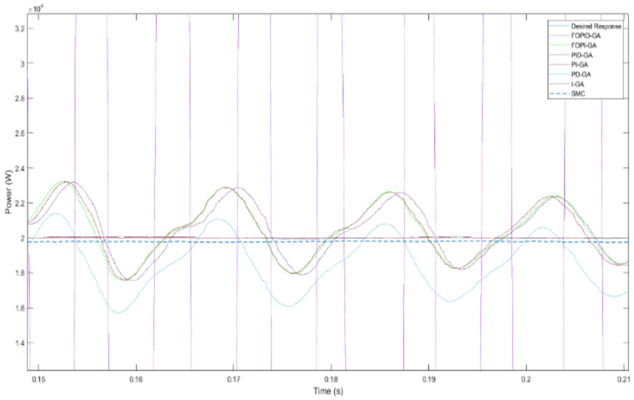

Fig. 22. Zoom image showing the comparison of SMC with all GA optimized controllers

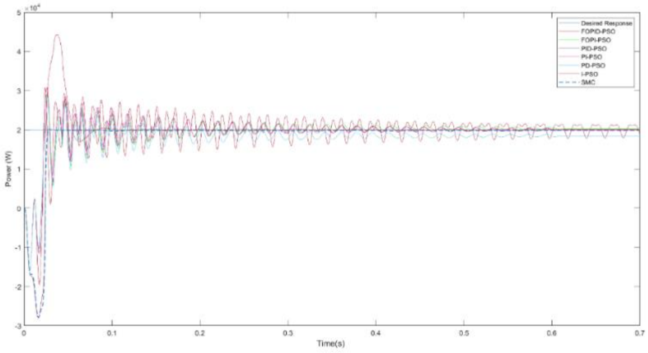

Fig. 23. The SMC is compared to all the optimal controllers using PSO

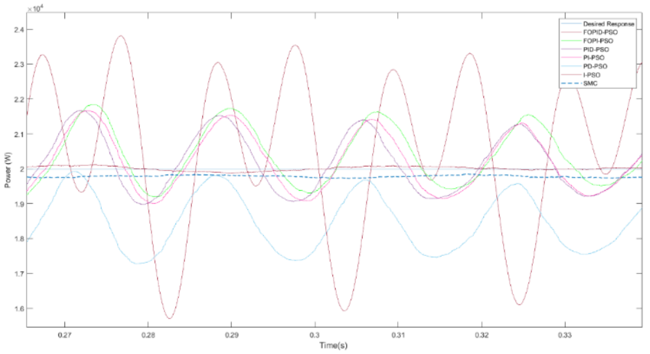

Fig. 24. PSO with SMC and all optimal controllers compared in zoom view

Particle Swarm Optimization and GA algorithms behave substantially identically in the suggested system. PSO has, nevertheless, shown somewhat better outcomes than GA. As a result of the use of SMC with both methods, the power transients are extremely low. The performance of all improved controllers is also analysed numerically. For all controllers employing both methods, Table 1 provides optimized gains values, along with the controllers' respective control settings. In Table 2, the results of all improved controllers regarding PID-PSO increases (positive sign) or decreases (negative sign).

This section describes the results of each source during the normal operation and elaborates on the increasing demand for the load. The fault condition of every source wing is discussed, and the powers of hybrid µG controlled using optimized controllers with PSO and GA algorithms power stability amaryllis are discussed in this section. In less than 0.096 seconds, the actual value of the frequency yielded by using the PID controller is within 0.1% of the desired frequency.

Table 1

Analysis of active and reactive power controllers with GA and PSO algorithms

Controller	Rise Time (s)	Peak Time (s)	Settling Time (s)	Time Constant (-)	K_P	K_I	K_D	λ	µ
I-GA	0.0014	0.0371	0.0747	0.0006	0	3762.6	0	1	1
I-PSO	0.0009	0.0372	0.0752	0.0004	0	3862.6397	0	1	1
PI-GA	0.0020	0.0260	0.4356	0.0009	881	3846.8	0	1	1
PI-PSO	0.0021	0.0263	0.4551	0.0009	880.4	4017.9	0	1	1
PD-GA	0.0027	0.0264	Nan	0.0012	880.2355	0	625.2501	1	1
PD-PSO	0.0027	0.0264	Nan	0.0012	880	0	650	1	1
PID-GA	0.002	0.0262	0.4544	0.0009	900	3801	468	1	1
PID-PSO	0.0019	0.0263	0.4545	0.0008	900	3808	400	1	1
FOPID-GA	0.0089	0.3887	Nan	0.0040	891.8	3933.6	411.3	1.6	1
FOPID-PSO	0.0108	0.0241	Nan	0.0049	940	3994	447	1	0
FOPI-GA	0.0022	0.0261	0.4749	0.001	890.8	3872.1	0	1.1	0
FOPI-PSO	0.0027	0.0268	0.5987	0.0012	880	4100	0	1.3	0
SMC (two loop)	0.0021	0.0166	0.267	0.0009	-	-	-	-	-

Table 2

Performance index of all the optimized controllers

Controller	Rise time (%)	Peak time (%)	Settling time (%)	Time constant (%)	Steady state error
PID-GA	-5.26	0.380	0.02	-12.5	-41.024
PID-PSO	1	1	1	1	-39.3266
PI-GA	-5.26	1.140	4.15	-12.5	54.8799
PI-PSO	-10.52	0	-0.13	-12.5	57.9773
PD-GA	-42.10	-0.380	-	-50	1560.7
PD-PSO	-42.10	-0.380	-	-50	1583.2
I-GA	26.31	-41.06	83.56	25	21.6989
I-PSO	52.63	-41.44	83.45	50	-77.1157
FOPID-GA	-368.42	-1377.9	-	-400	6071.3
FOPID-PSO	-468.42	8.365	-	512.5	1282.5
FOPI-GA	-15.78	0.760	-4.488	-25	-84.3692
FOPI-PSO	-42.10	-1.90	-31.72	-50	-306.99
SMC	-10.52	36.882	41.25	-12.5	186.9294

4. Conclusion and Future Work

This research work focuses on the simulations of a μG framework, its hybridization, and power management of PV, WT, battery, along with FC and the utility grid. Photovoltaic and WT are some of the most promising energy sources for the μG. To ensure uninterrupted power supply to all the loads, power quality and stability analysis has been conducted within the permitted limits of all power quality and stability criteria. The simulations result of the proposed μG and ensure energy management criteria have been explained in detail. Detailed discussion is provided on the implementations and optimizations of all the considered controllers. Furthermore, numerical as well as graphical comparisons for all optimized controller's results are provided. Sliding Mode Controller's outperformed all the others in terms of power quality and stability. With SMC, real power is within 1% of target power that is less than 0.267 seconds.

Future work on hybrid μGs is recommended as follows.

1. Currently, an ideal situation is taken for PV source, real-time case study can also be considered.
2. Another possibility for the future is the inclusion of additional renewable sources and diesel engines.
3. The proposed hybrid power system and proposed controller are designed in MATLAB/Simulink and can be also designed in other software and then compared the results.

Other intelligent algorithms and controllers could be implemented for the performance comparison. Iterations number could be raised for FOPI/FOPID controller to improve its performance.

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