Design and Control of Photovoltaic/Wind/Battery based Microgrid System

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Abstract

This paper deals with the design and control of a micro-grid, including various alternative energy resources (photovoltaic and wind) and battery energy storage system which operates in stand-alone as well as in grid-connected mode. The proposed micro-grid is controlled via various non-isolated converters while an energy management is performed through switching based algorithm. According to the strategy, the wind is used as the primary power source while the Photovoltaic (PV) is added to improve the reliability of system under different weather conditions. The battery module is utilized as an energy storage system during surplus power and/or backup device during demand. The proposed system used real record of weather pattern and load conditions for a small community at Islamabad, Pakistan. This city is gifted with several natural resources that can generate a significant amount of power energy for the region. MATLAB simulation results show the effectiveness of proposed system in terms of grid stability, power sharing, load tracking and power quality.

Index Terms—Micro-grid, Bidirectional Converter, Energy Management, Power Quality and Stability Analysis

I. INTRODUCTION

In Pakistan, about 60% electricity is produced from fossil fuels which are not only very expensive but also emit abundant CO_2 and other pollutants in the atmosphere [1]. Currently, Pakistan is facing the worst energy crisis of its history with demand outstripping supply and frequent power cuts. Only 30% of the population has access to electricity in Pakistan [2]. Most of the power units and transmission lines are old and their efficiencies have weakened significantly. Compensation for energy shortage and reduction in pollution problems would be addressed by using Renewable Energy Sources (RES) for electricity production on a large scale. Although gridintegrated system is commonly practiced in this case all over the world, the instability of grid voltage electricity discourages operation of such system in Pakistan. In this paper, a local micro-grid (MG) based on wind/PV/battery is developed for a small community at Islamabad, Pakistan. Micro-grids offer the potential of substantial environmental benefits and facilitate the public through the integration of RES with high efficiency. MGs have a low impact on the electricity network, despite a potentially significant level of generation by intermittent energy sources. To have the least initial platform and maintenance cost, only DC loads are considered.

Although RES (PV and wind) have many advantages, they are unpredictable, highly intermittent and sensitive to climatic

conditions, which compelled RES to integrate energy sources [3], [4]. A number of studies have been carried out on optimizing and aiming share of RES in MG with or without using conventional generation system[5]–[7]. In [8], the author constructed a solar-hydro based power generation system to 0000000000PV/wind/diesel/battery hybrid system and PV/wind/battery hybrid with the objective of rural electrification in Malaysia. Similarly, for

Islamabad region, the authors presented PV and wind based control and energy management for grid/standalone system with the use of energy storage devices (supercapacitor

and battery) [10], [11]. In [12], the author evaluated a PV/wind/SC/battery for grid-independent applications. In [13], [14], PV/SC/battery based coordinated control system and power management for small scale MG was discussed.

This paper presents design and power control of a PV/Wind/Battery based MG with grid connected and islanded mode. The proposed technique efficiently shares all the available RES and energy storage system according to the real time weather and load conditions. The combination proposed in this paper is recommended as very appropriate selection which assures the power stability and continuity of power, and minimizes the deviation in system's critical parameters and output power.

This paper is organized as follows. First, system description of proposed MG is provided in Section II. Next, Section III explains the control of MG units. Section IV presents the details and working of proposed algorithm. Simulation results are covered in Section V followed by the conclusion in Section VI.

II. Description of Proposed Microgrid

This section explains the architecture of proposed microgrid. The complete structure of MG is shown in figure 1. The proposed MG consists of wind turbine (WT) farm, PV arrays, battery bank, residential load(RL) and national grid(NG). The RES along with energy storage device builds up the DC half of MG while NG and RL build up the AC half of converter. In DC half, the WT is connected with Permanent Magnet Synchronous Generator (PMSG). The PMSG is connected with switch mode based rectifier. At output of rectifier, an optimal torque based boost converter is connected followed by voltage regulator. The second component of DC half is PV array. The PV array is connected with Maximum Power Point Tracking (MPPT) based boost converter followed by voltage regulator. Finally, the battery is connected with buck boost converter. It is used for charging and discharging of battery. In AC half, RL is connected with NG via distribution transformer (11kV/440V) and RES with three phase inverter.

III. Control of Proposed MG Units

A. Wind Trubine Assembly

The WT system is coupled with PMSG. The mechanical power that drives the electrical PMSG, is given by (1). Generally, WT is characterized by Z − γ, where γ is a tipspeed ratio and given by (2).

$$P \frac{1}{2} U A Z V_P{}^3 \qquad (1)$$

$$J_{m} \frac{ZR}{V} \qquad (2)$$

where ρ, A, Z_p and V are air density, area of blades, power efficiency and velocity of air, respectively.

To extract maximum power from available wind speed, an Optimal Torque (OT) based controller is used. The OT algorithm adjusts the PMSG torque according to the maximum power reference torque. It can be achieved once γ reaches γ_{opt}. The optimal torque at a given speed is given as;

$$T_{m\,opt}\; C_{opt} Z_{m2} \qquad (3)$$

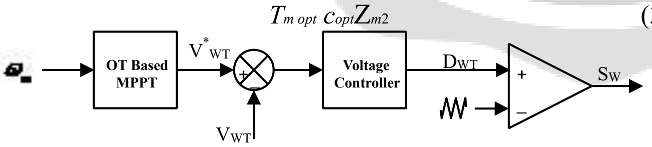


Fig. 2: Control scheme of WT system where c_{opt} is a function of γ_{opt}. The overall control scheme of WT system is shown in figure 2. The OT based MPPT generates voltage references. According to voltages error, voltage controller generates an appropriate duty cycle (D_{WT}).

SWITCH MODE RECTIFIER

B. PV System

A DC–DC boost converter based control system is required to operate the PV at MPP and then regulate the output power of system effectively. In a PV system, the terminal voltage is controlled on the basis of MPPT error signal denoted as “e” in Fig. 3. For the PV system, the PV voltage and current are sensed to find the reference voltage at which MPP occurs. The “e” is the slope of operating point on P-V curve and is calculated using IC algorithm. The slope at MPP is zero. The boost converter is controlled by Proportional Differential Integrator (PID) controllers, which tries to minimize “e”. It is then fed to the voltage controller to control the duty cycle of PV boost converter as shown in Fig. 3.

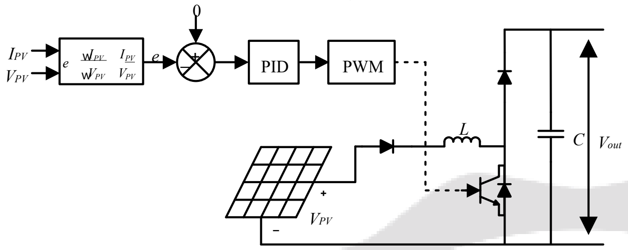
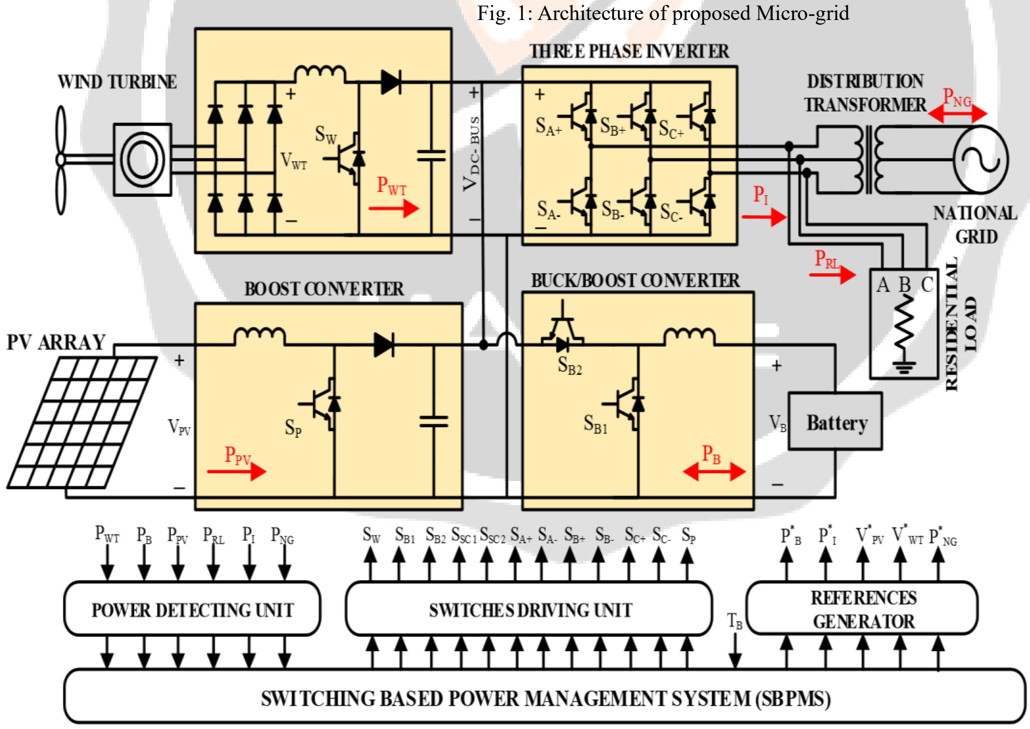


Fig. 3: PV system controller

C. Battery System

The control scheme for battery system is shown in figure 4. The reference power for battery is calculated by taking the difference of RL demand and RES power generation (WT+PV). From reference power, reference

Fig. 1: Architecture of proposed Micro-grid



current is calculated. The PID based controller is used to generate an appropriate duty cycle based on current error. Two comparators are used to check whether the reference power is positive/negative and generate a corresponding signal.

D. Main Inverter System

The entire DC bus is coupled with NG via a three-phase bidirectional converter. Initially, the difference between actual and reference power (real and reactive) is applied to Proportional Integral (PI) controllers. The PI controller generates the dq reference signal and it tries to reduce the error. A dq/abc converter is used to transform the signal into abc axis. Line currents are measured from the output of main converter and compared with reference currents.

Then, it is applied to hysteresis current controller to generate the appropriate switching signal for main converter. The whole control scheme is shown in figure 5.

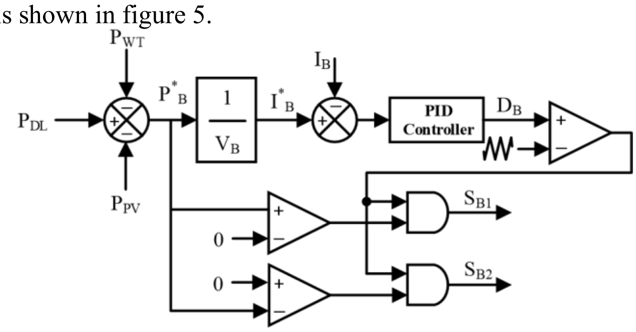


Fig 4: Control scheme of battery system

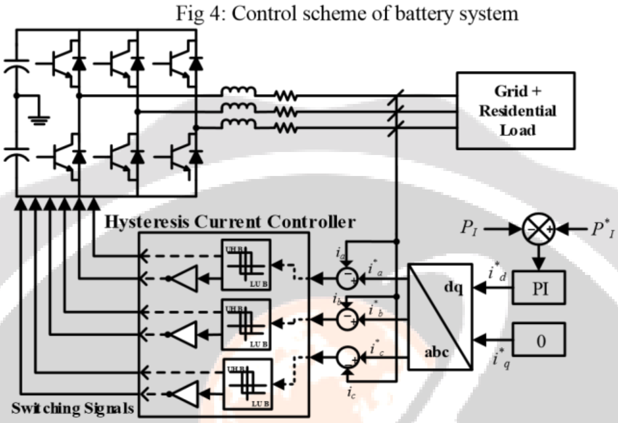


Fig 5: Control system of grid connected converter

IV. SBPMS OF PROPOSED MG

To effectively manage the proposed MG and provide uninterruptable power supply to the load, a Switching Based Power Management System (SBPMS) is designed in this paper. The proposed SBPMS is used to provide power to RL from available REs, energy storage devices and national grid. From figure 1, there are three secondary units on which SBPMS operates, i.e., Power Detecting Unit (PDU), Switches Driving Unit (SDU) and References Generator Unit (RGU). The PDU obtains the instantaneous power of WT (P_{WT}), battery system (P_B), PV system (P_{PV}), RL demand (P_{RL}), three phase inverter (P_I) and NG (P_{NG}). SDU provides an appropriate signal to different converters, i.e., switch mode rectifier (S_W), three phase inverter switches (S_{A+}, S_{A-}, S_{B+}, S_{B-}, S_{C+}, S_{C-}), buck boost converter switches (S_{B1}, S_{B2}) and boost converter of PV system (S_P). Similarly, RGU generates appropriate power references for battery (P^*_B), inverter (P^*_I) and NG (P^*_{NG}). It also generates appropriate voltage references for MPPT (V^*_{PV}) and optimal torque (V^*_{WT}) based boost converter.The power balance equation for proposed MG can be written as;

$$P \; P_{PV} \;\; _{WIND} \; P_{LOAD} \; P \; P_{B} \;\; _{GRID} \qquad (4)$$

Using (8), the excess power generated by REsis written as;

$$P \; P \; P \; P_{EX \; RL \; WT \; PV} \; (P \; P_{B} \;\; _{NG}) \qquad (5)$$

Similarly, the power deficiency created by REs is written as;

$$P \; P \; P \; P \; P \; P_{DF \; RL} \;\; _{WT \; PV \; B} \;\; _{NG} \qquad (6)$$

Based on above power balance equations, the control algorithm is developedto prevent the system from blackouts. The proposed algorithm for SBPMS is shown in figure 6 and described below.

1) Initially PDU captures the required instantaneous powers and State of Charge (SOC (T_B)) of battery.
2) SBPMS checks eq. (1). If RL is satisfied by WT and PV, go to 1; otherwise, go to to next step.
3) Check whether RL is greater than REs power. If yes, go to next step; otherwise, go to step 5.
4) If T_B>20%, deliver the deficient power from battery; otherwise. apply deficient power reference to NG, and then go to 1.
5) If T_B>90%, deliver the excess power to NG; otherwise, send excess power to battery.

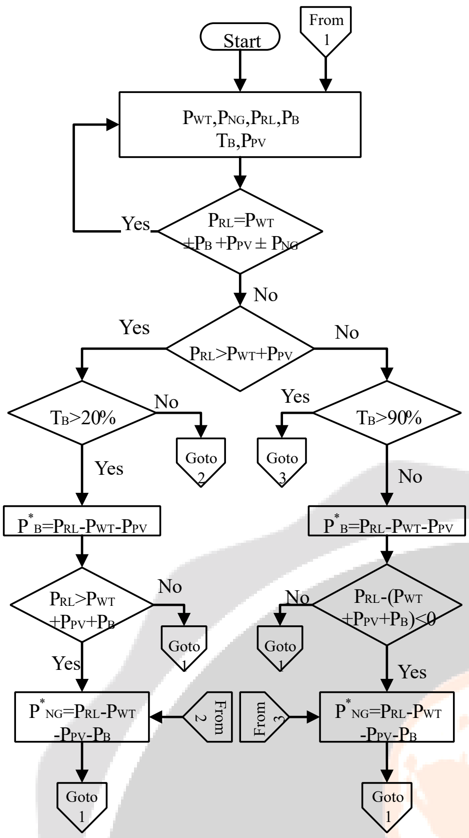


Fig. 6: Proposed algorithm flowchart

V. Simulation Results And Discussion

This is carried out under Simulink environment. Initially, all the MG components are modeled and investigated individually. After that, the sources and converters are combined to build up the whole MG. The MG contains a power converter of different rating, and tested under different environmental and load conditions, which are described below.

A. Rated Powers

The MG sources and power electronic component rating are enlisted in table I.

B. Weather Statistics

As DHA, Islamabad is our case study, the weather data (i.e., irradiance, ambient temperature level and wind speed) are collected from regional station of Pakistan Metrological Department (PMD) Islamabad [15]. These data are taken for a typical week of summer season i.e., 24th June 2016 to 30th June 2016. The temperature, irradiance and wind speed profile for entire week (168 hours) is shown in figure 7.

Table 1: Power electronics components ratings

PV Array	
Module Unit	305 W @ 1kW/m^2, 25 °C
Number of series modules per string	11
Number of parallel strings	30
Power Rating	305 × 11× 30 ≈ 100 kW
Battery	
Capacity	10 kAh
Single module voltage	12 V
No of series connected modules	34
Rated Voltage	12 × 34 ≈ 400V
Wind Turbine	
Rated Speed	800 rpm
Output Voltage at Rated Speed	258 V
Cut-off Wind Speed	12 m/s
Rated Power of each unit	8.5 kW

No of units	12
Total Rated Power	12 × 8.5 ≈ 100 kW
Utility Grid	
Phase Voltage, Frequency	11kV, 50Hz
Rated Power	10MVA
X/R Ratio	5
RL Power Factor	1.0
Main Inverter	
Rated Power	400kW
Rated Voltage	200/540 V
Inductance L-Filter	2.1 μH

C. Dynamic Load

The proposed MG is designed to provide power to seventy five homes. The load is calculated from data provided by Islamabad Electric Supply Company(IESCO) for DHA [16]. The maximum and minimum load demands for an entire week are 123.2 kW and 22.61 kW, respectively. The average load demand is 66.94 kW. The total average load demand for entire week (168 hours) is shown in figure 7 (a).

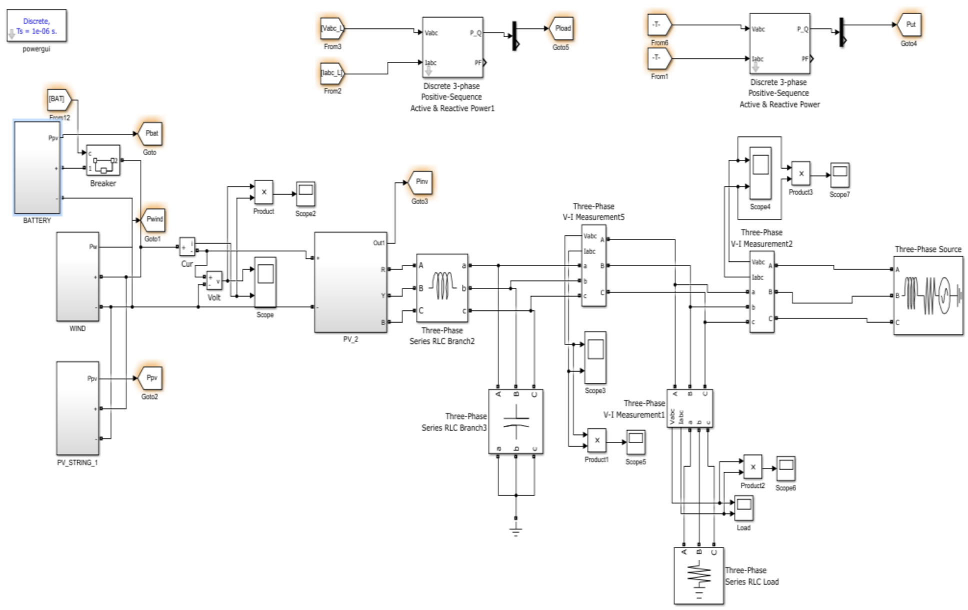
D. Simulation Results

The output powers of different energy sources and SOC of battery for a complete week (168 hours) is shown in figure 8.

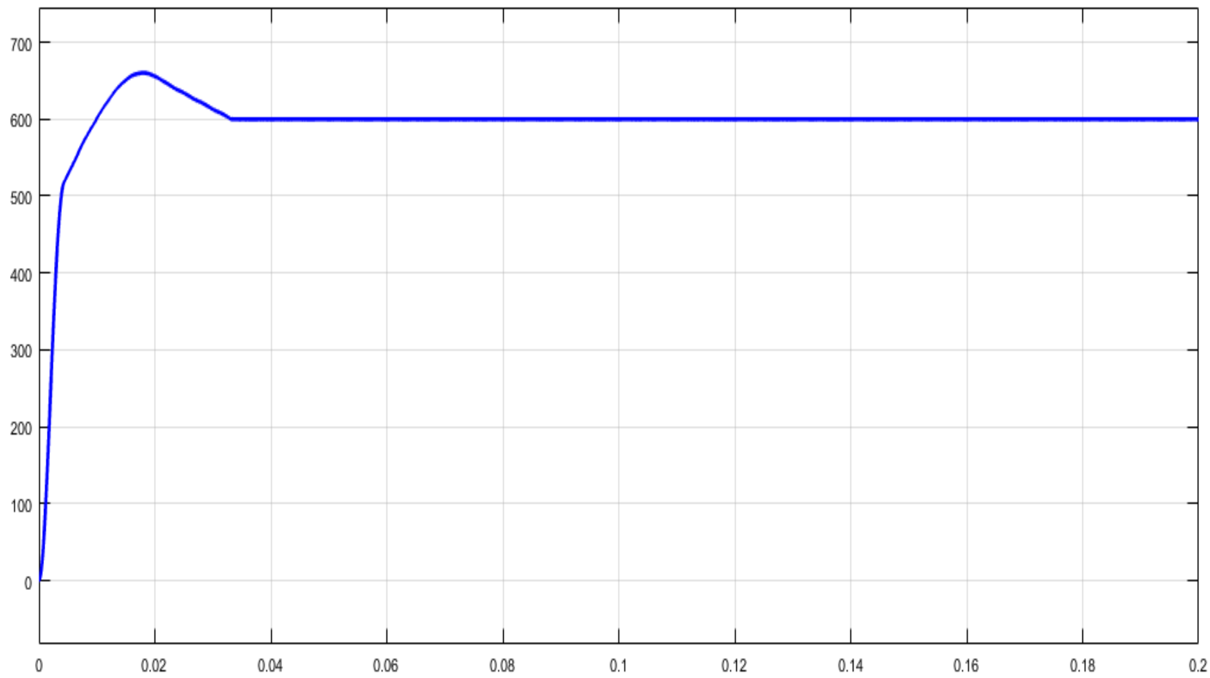
Residential Load: The RL demand for 168 hours is shown is figure 7 (a). The RL demand starts from 25 kW and ends at 37 kW. For every day, there are two peaks which is usually due to office timings and night time. Comparing 7 (a) and 8 (a), it is revealed that the load varies directly with temperature. For example, at t=40 Hrs, the temperature is 40°C and the load demand is 123 kW (which is one of the peak load for entire week). Similarly, for 96-120 Hrs, the temperature is quite low with respect to other days, so the maximum load is only 95 kW (110 Hrs). The average load for entire week is 66 kW.

WT System: The WT output power is shown in figure 8 (b). For majority of time, the output power of WT is below 20 kW. This is due to low capacity factor of Islamabad region (typically 17%) [17]. At t=31-51 Hrs, 61-69 Hrs, 86-95 Hrs and 109-115 Hrs, there are some high spikes of power generated by WT system due to availability of high wind speed. The WT generates maximum of 80 kW at 42.6, 45.6 and 89.2 Hrs, because, wind speed is greater than its cut off speed.

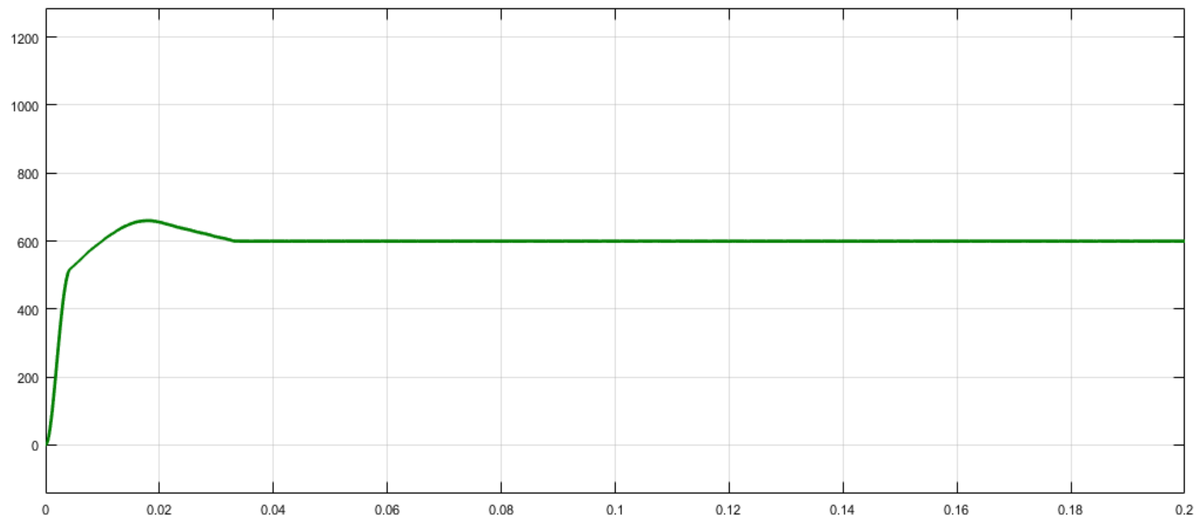
Simulation Diagram of Proposed MicroGrid:



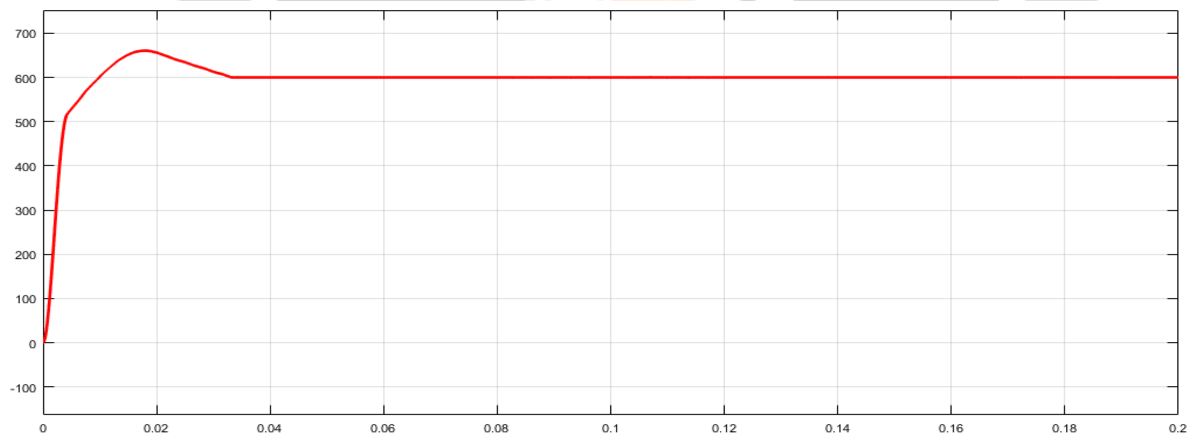
Output Voltage of the Battery:



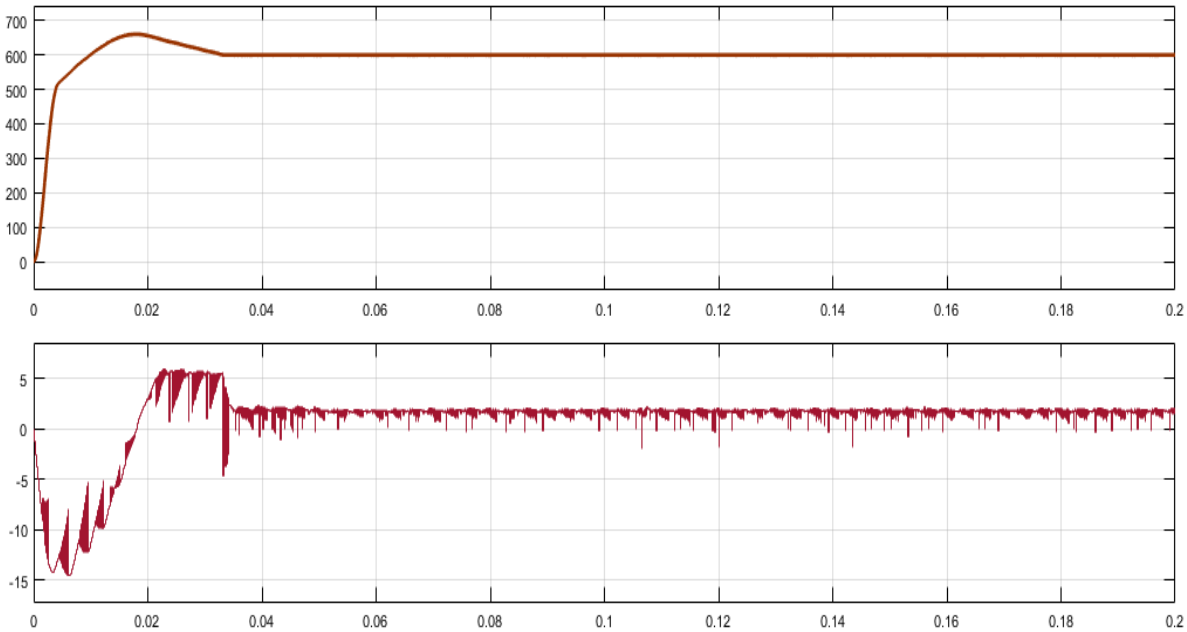
Output Voltage of the wind:



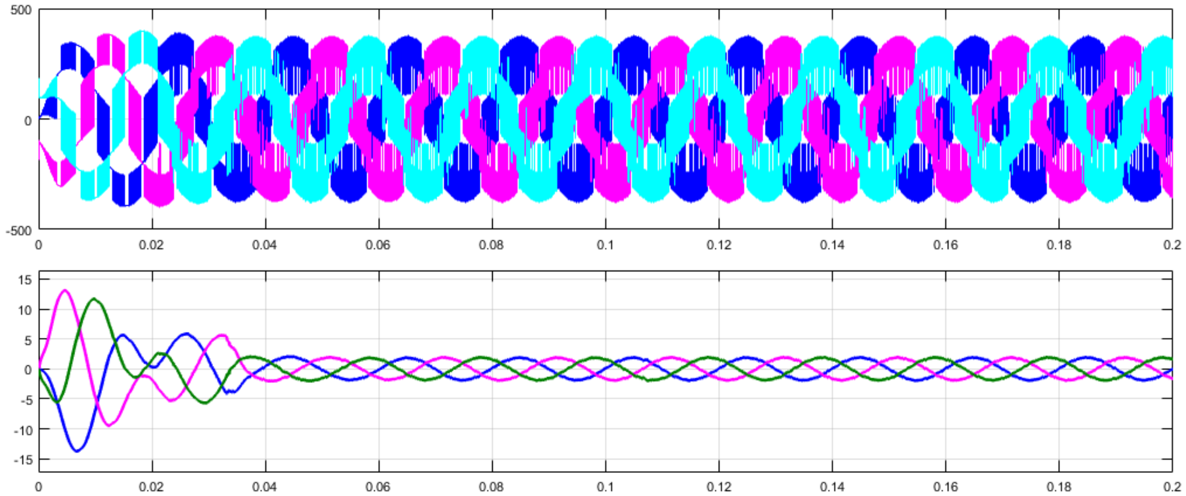
Output Voltage Of the Solar:



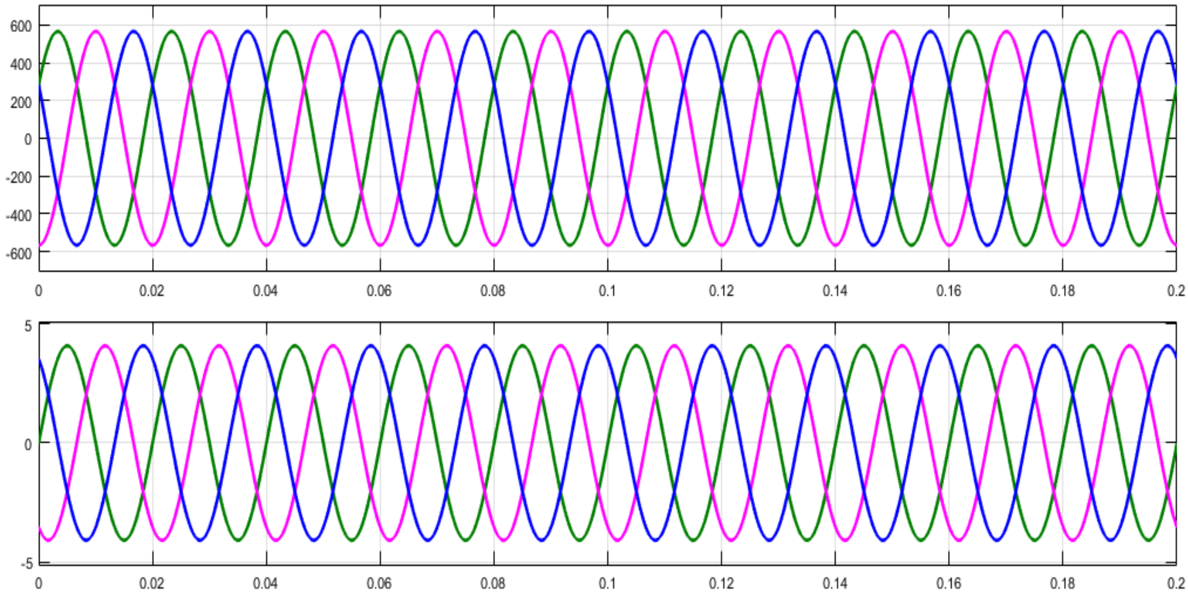
PCC Output Voltage and Current:



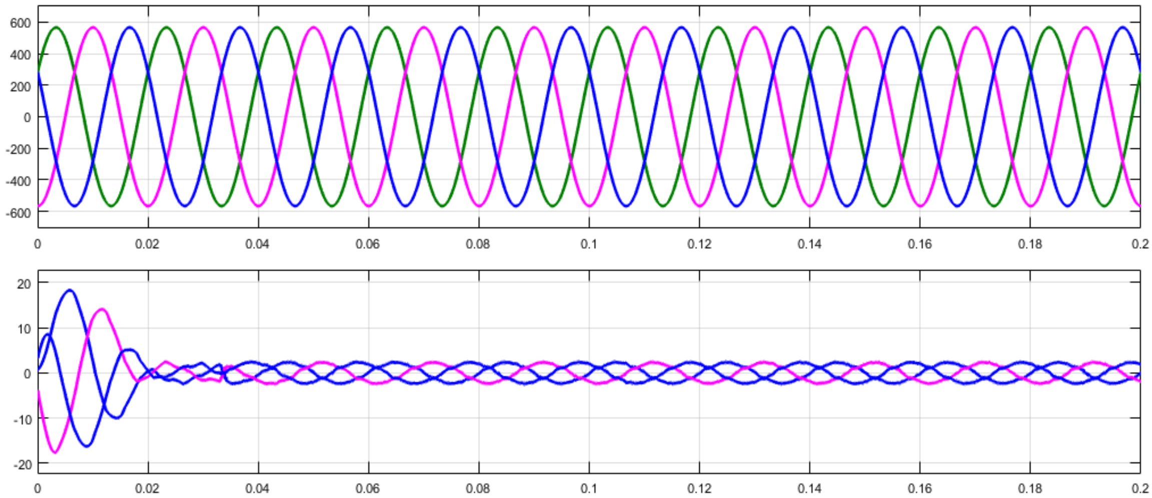
Inverter Output Voltage and Current without Filter:



Load Output Voltage and Current:



Grid Voltage and Current:



PV System: The PV system power generation is shown in figure 8 (c). In Islamabad, sun rises at 5 AM and set at 7:30 PM as shown in figure 7 (b). Due to high level of irradiance at day times, about 120 kW of maximum power is generated at noon. The average power supplied by PV systemfor each day is 40.2 kW, 40 kW, 42 kW, 39.7 kW, 42.2 kW, 41.5 kW and 38.1 kW, respectively. PV supports WT to fulfil the RL demand.

National Grid: The NG output power profile is shown in figure 8 (d). The NG output power depends upon the load distribution and time of the day. From figure 8 (d), usually at peak load hours, the NG is unable to provide power and also take power from MG. While during off peak hours, NG provides maximum of 20 kW power.

Battery System: The battery output power is shown in figure 8 (e). The positive value of power means that the battery is discharging and vice versa. From 0-7.6 Hrs, the WT, PV system and NG do not fulfill the RL demand. Hence, the battery is providing maximum power of 50 kW. In the same way from 7.6-17.2 Hrs, the PV not only generates sufficient power to overcome the RL demand but also produces some excess power which is delivered to NG and battery (charging). The SOC of battery also changes with respect to power delivered/consumed as shown in figure 8 (f). Consider t=100116 Hrs, the PV generates a lot of power, the excess power is sent to battery (maximum 58 kW), the battery SOC changes from 50% to 58.5%.

According to IEEE 1547 standards of interconnecting power system [18], the allowable maximum deviation in load voltage RMS and frequency are ±6% and ±0.8%, respectively. In p.u., the limits are 1.06 p.u. and 0.94 p.u. for load voltage RMS and 1.008 p.u., and 0.992 p.u. for load voltage frequency. It is clearly revealed from the figure 9 that the proposed SBPMS effectively keeps the load voltage RMS and frequency in acceptable limits and prevents systems from blackout.

VI. CONCLUSION

This paper has presented design, control and switching based energy management for a wind/PV/battery micro-grid system. The proposed micro-grid is capable to supply continuous power flow with high reliability. The proposed micro-grid can be used with or without national grid or can be synchronized with different sources to shave the load power during peak hours. The dynamic performance of the proposed model is tested for recorded weather patterns and load conditions. From MATLAB simulation results, it is concluded that the developed micro-grid accomplishes all the conditions needed for the power quality and stability of power system.

ACKNOWLEDGMENT

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