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RESEARCH ARTICLE

Smooth and Uninterrupted Operation of Standalone DC Microgrid Under High and Low Penetration of RESs

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ABSTRACT In this paper, an energy management system (EMS) using intelligent Lyapunov based adaptive fuzzy controller is designed for standalone microgrid having photovoltaic and wind turbines as primary sources, while battery storage system and diesel generator are available as secondary sources. Moreover, any remnant power available in the system is guided by the controller towards the dump load. The centralized controller based on intelligent adaptive fuzzy system helps to optimize the power flow in the system during high and low penetration of renewable energy resources under variable load conditions. Additionally, voltage regulation is carried out using nonlinear Lyapunov controller which kept the output voltages in desired range. The proposed control system helps in increasing the efficiency and reliability of standalone microgrid. Furthermore, the proposed system is validated by comparing the simulation and hardware results with the PID and sliding mode controller, which are consider as benchmark controller techniques for standalone microgrid. The outcome of the system validates the superiority of proposed techniques and achieved global asymptotic stability under variable load conditions.

INDEX TERMS Microgrid, adaptive fuzzy based Lyapunov controller, DC-DC converter, energy management, voltage regulations.

I. INTRODUCTION

Electricity demand is increasing with every passing day due to expansion in populated areas. However, connecting far away remote places such as villages situated in hilly regions with the national grid system, is becoming more and more difficult as compared to the urban territories. Electrification by grid extension is not feasible in most of the cases due to huge capital and running cost [1]. Conventionally, standalone diesel generators are extensively used in these remote areas. However, these fossil fuel energy sources have the huge cost of maintenance as well as operation expense, leading to very costly production of electricity and have adverse effect on environment. Due to this scholars divert their attention towards solar and wind which are the most promising renewable energy resources due to its abundant availability and eco-friendly behavior [2], [3]. Fortunately, most of the remote areas are located among the rich solar potential and have high wind flow which are sufficient to generate solar or wind power [4], [5]. Utilization of these RES is a challenging task for the researchers due to their nonlinear behavior [6]. The hybrid RES system with backup secondary sources provides uninterruptable energy and increases the reliability of standalone microgrid. Maximum power point tracking (MPPT), selection of converter topologies, voltage regulation and energy management are the most considerable concerns of RESs due to its nonlinear nature. In literature, many control approaches were designed to address these issue but still a more efficient control system is required for the smooth operation of standalone microgrid [7]. A standalone

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microgrid with perturb and observe method is proposed in [8] for MPPT of RES. In this study, Photovoltaic (PV) and Wind are used as the primary source and diesel generator (DG) has been used as an auxiliary source for backup during inclement weather circumstances. PV systems are reliable and emission less renewable sources with fewer maintenance requirements to operate [9]. Linear control strategy for DC microgrid is proposed in [10] to address the voltage regulation and power flow under different operating conditions. Linear control strategies cannot perform well with the DC converter operation due to nonlinear nature of these converters. In [11] and [12], droop controller is presented to address the voltage regulation and power flow issues of microgrid. One of the major drawback of droop controller is that it does not provide precise voltage regulation under varying load conditions with multiple energy sources. Hybrid model predictive controller is proposed in [13] and Lyapunov based hybrid model predictive control technique is proposed in [14] for voltage regulation and energy management. The key sources considered in this study were PV, Wind turbine, fuel cell, DG and an EV charging station unit. The computational complexity of MIQCQP is the major drawback of the designed model. Integral backstepping and adaptive backstepping techniques are proposed in [15] and [16] for voltage regulation and energy management under different load conditions. A barrier function based adaptive sliding mode control technique is proposed in [17] for voltage regulation of microgrid under islanded mode. These studies increase the battery stress under variable load and generation condition, which reduce battery life [18], [19]. Fractional-order proportional integral derivative controller with the combination of the fuzzy logic controller is proposed in [20] for hybrid energy sources based on DC microgrids. Voltage regulation in highly penetrated microgrids is a serious concern during peak hours [21]. Therefore, dump load with electronics load controller gives a sufficient way to consume the excess power of RESs [22], [23]. All the techniques discussed above focus mainly on stability of standalone microgrid. These techniques have limitations in precise voltage regulation and energy management under varying conditions with high and low penetration of RESs. However, Addressing the persistent challenges of energy management and voltage regulation under variable load profile are still serious concerns, which requires improvement.

In this work, intelligent Lyapunov based adaptive fuzzy controller is designed to regulate the voltage fluctuations and enhance the EMS for extreme penetration of RESs and variable load conditions. Proposed control system is simulated in MATLAB simulink and hardware results are generated using dSPACE controller. Both simulation and hardware results shows the superiority of our proposed controller over previously discussed controllers in literature. The main contributions of proposed controller are:

- Ensure the optimal converter operation and operates the renewable energy sources to yield maximum power.
- Provide better voltage regulation and energy management under high and low penetration of RESs with variable load. Controller trigger the activation of dump load and diesel generator in case of excess and shortage of power respectively.
- Constantly monitoring the state of charge (SOC) of battery storage system and control the charging and discharging of battery storage system based on battery health, availability of renewable power, load demand and DC bus voltage.

II. ARCHITECTURE OF PROPOSED SYSTEM

The proposed system is shown in Figure 1, where PV and wind act as primary sources for providing continuous power while storage system and diesel generator is considered as auxiliary source for emergency conditions [24]. The dump load is connected with system to consume the excess RESs power during off peak hours.

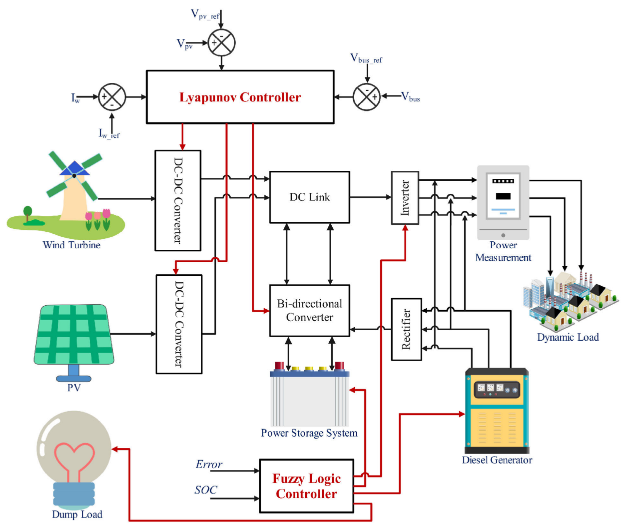

FIGURE 1. Block diagram of proposed standalone microgrid.

III. MATHEMATICAL MODELING OF PROPOSED SYSTEM

Primary sources of microgrid consist of Solar Energy Conversion System (SECS) and Wind Energy Conversion System (WECS). Whereas, secondary sources are consist of battery and diesel generator.

A. SOLAR ENERGY CONVERSION SYSTEM

SECS employ PV, non-inverting buck-boost converter and MPPT controller. Due to the intermittence of PV, they should be operated at MPPT and the regression plane method is adopted in this paper to obtain MPPT of SECS. Regression plane method relies on historical data and mathematical modeling to approximate the MPPT. Pictorial representation for this regression plan is shown in Figure 2. V_{pvref} is calculated through the following equation where I is the irradiance and T is the temperature of the PV panels [17].

$$V_{pvref} = 322 - 0.00964 \times -1.34 \times T \tag{1}$$

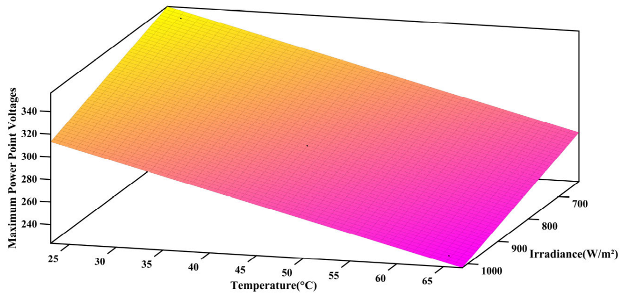

FIGURE 2. Pictorial representation for this regression plan.

The non-inverting buck-boost converter is connected to the output of PV panels and operates in continuous conduction mode to track the MPP, as shown in Figure 3. It consists of two switches (Q_1, Q_2), and two diodes (D_1, D_2). The non-inverting buck-boost converter have two mode of operations: mode-I, when the both switches Q_1 and Q_2 are ON then D_1 act as reverse bias and DC bus will be disconnected. Mode-II, when the switches Q_1 and Q_2 both are OFF then D_1 act as forward bias and load is connected to L_1 through D_2. In Figure 3, V_{pv} and i_{pv} denote the PV output voltage and current respectively, V_{dc} is DC bus voltage, and μ_1 is control signal that ensure the converter operation. The average state

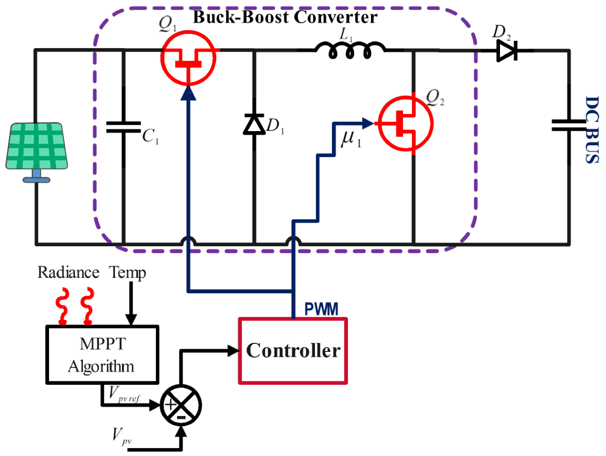

FIGURE 3. Internal circuitry of SECS.

model for the non-inverting buck-boost converter is derived as follows:

$$\frac{dV_{pv}}{dt} = \frac{I_{pv} - I_L\mu_1}{C_1} \tag{2}$$

$$\frac{dI_L}{dt} = \left(\frac{V_{pv} + V_{dc}}{L_1}\right)[scale = 0.98]\mu_1 - \frac{V_{dc}}{L_1} \tag{3}$$

$$\frac{dV_{dc}}{dt} = \frac{I_L - I_{pvref}}{C_{dc}} - \frac{I_L}{C_{dc}} \tag{4}$$

B. WIND ENERGY CONVERSION SYSTEM

WECS has consisted of Permanent Magnet Synchronous Generator (PMSG) that is associated with wind turbine. Furthermore, generated power injected in to a three-phase rectifier and its output is connected to DC boost converter. The unidirectional boost converter with continuous conducting mode for WECS is shown in Figure 4.

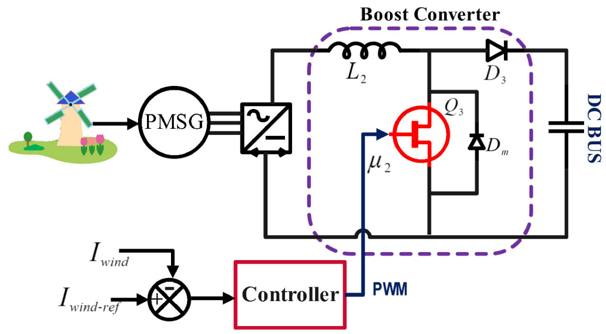

FIGURE 4. Internal circuitry of WECS.

To extract the MPPT power from wind system, we use wind current as a reference instead of voltages (indirect method). The voltage reference is not considered due to the non-minimal phase of boost converter (direct method). Wind Power P_w generated by PMSG is expressed in the equations (5),(6), and (7).

$$P_w = \frac{1}{2}\pi\rho v^3 r^2 C_p \quad (\lambda, \alpha) \tag{5}$$

$$\lambda = \frac{\omega_{wind} R}{v} \tag{6}$$

$$P_w = \frac{1}{2\lambda}\pi\rho\omega_{wind}^5 r^5 C_p \tag{7}$$

In the above equations ρ is the air density, r is turbine radius, C_p is the power coefficient of the turbine, α is the pitch angle of the blade, v is the wind speed and ω_{wind} represents the angular velocity of the rotor. Optimal Torque Control is applied for achieving MPPT which calculates the reference rotor speed using wind speed and the turbine power-speed curve. The turbine has a maximum power coefficient ($C_{p\max}$), rotor optimum tip speed ratio (λ_{op}) and optimum wind power $P_{w_{op}}$ is expressed as:

$$P_{w_{op}} = \frac{\pi\rho\omega^3 r^5 C_{p\max}}{2\lambda^3} = \omega^3 K_{p_{op}} \tag{8}$$

The reference torque and current can be determined by putting the value $P_{w_{op}} = \omega T_{w_{op}}$ in equation (8) as

$$T_{w_{op}} = \omega^2 K_{p_{op}} \tag{9}$$

$$I_{wref} = \frac{\omega}{V_{dc}} T_{w_{op}} \tag{10}$$

Boost converter for WECS consists of a switch (Q_3), and diodes (D_3, D_m). If V_w is WECS input voltage, R_w is input resistance, V_{dc} is DC bus voltage, I_w is wind current and μ_2 is control signal of WECS system, then the average state model of the unidirectional boost converter can be derived as:

$$\frac{dI_w}{dt} = \frac{V_w + I_w R_w}{L_2} + \frac{V_{dc}}{L_2}(1 - \mu_2) \tag{11}$$

$$\frac{dV_{dc}}{dt} = \frac{(1 - \mu_2)[scale = 0.98]I_w - I_{w_{ref}}}{C_{dc}} \tag{12}$$

C. BATTERY STORAGE SYSTEM

Battery storage unit is connected to DC bus through a bidirectional buck-boost converter as shown in Figure 5. The

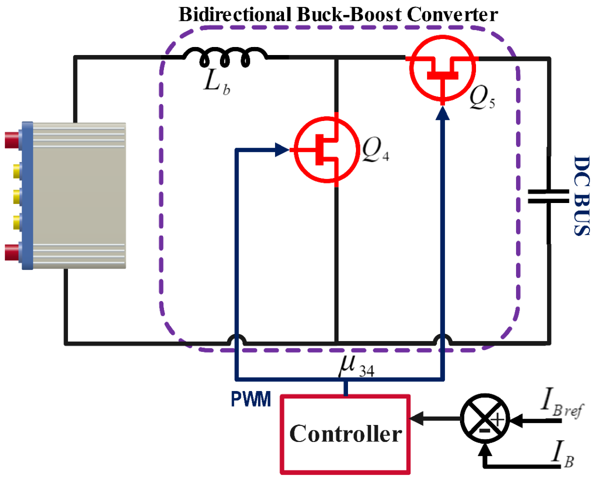

FIGURE 5. Internal circuitry of battery storage system.

circuitry of the buck-boost converter is consisted of two IGBT switches Q_4 and Q_5, high frequency inductor L_b and filter capacitor C_{dc}. Mathematical expression for the operation of the bidirectional buck-boost converter can be represented as:

$$K = \begin{cases} 1, & if\ i_{bref} > 0 \\ 0, & if\ i_{bref} < 0 \end{cases} \tag{13}$$

In equation(13), i_{bref} is the battery reference current, that is generated according to the SOC of the battery and load demand through the proposed energy management system. Battery reference current is essential for efficient energy management and ensuring that the battery operates within safe and optimal conditions. When the battery is discharging, converter will operate in the boost mode ($i_{bref} > 0$). In this mode, the switch Q_4 will turn ON for $\mu_3 Ts$ time period and switch Q_5 will be ON for $(1 - \mu_3)Ts$ time period. The boost mode of the converter is expressed mathematically as:

$$\frac{di_b}{dt} = \frac{V_b - i_b R_b}{L_b} - \frac{V_{dc}}{L_b}(1 - \mu_3) \tag{14}$$

$$\frac{dV_{dc}}{dt} = \frac{i_b \mu_3 - i'_b}{C_{dc}} \tag{15}$$

In above equations i_b and V_b are the battery current and voltage respectively, whereas Rb is the internal resistance of the battery. i'_b represents the current of the converter and V_{dc} is the DC bus voltage. On the other hand, when battery is in charging state, the converter operates in the buck mode ($i_{bref} < 0$). In this mode, the switch Q5 turns ON for $\mu_4 Ts$ time period and switch Q_4 will ON for $(1-\mu_4)Ts$ time period. Buck mode is expressed mathematically as:

$$\frac{di_b}{dt} = \frac{V_b - i_b R_b}{L_b} - \frac{V_{dc}}{L_b}\mu_4 \tag{16}$$

$$\frac{dV_{dc}}{dt} = \frac{i_b}{C_{dc}}\mu_4 - \frac{i'_b}{C_{dc}} \tag{17}$$

A centralized control signal can be obtained through virtual control that simplifies the control system as represented in the equation (18).

$$\mu_{34} = [(1 - \mu_3) K + \mu_4 (1 - K)] \tag{18}$$

μ_{34} represent the virtual control law for the battery storage system and using the above equations, the average state model of the bidirectional buck-boost converter can be simplified as:

$$\frac{di_b}{dt} = \frac{V_b - i_b R_b}{L_b} - \frac{V_{dc}}{L_b}\mu_{34} \tag{19}$$

$$\frac{dV_{dc}}{dt} = \frac{i_b}{C_{dc}}\mu_{34} - \frac{i'_b}{C_{dc}} \tag{20}$$

D. DIESEL GENERATOR

Diesel generator is connected as the dispatchable source to provide continues power during emergency conditions. The generation of diesel generator (P_{DG}) is based on generator capacity (PC), efficiency (η_{DG}) and fuel consumption rate (ρ_{fuel}). The mathematical expression of diesel power generation can express as:

$$P_{DG} = P_C \times \eta_{DG} \times \rho_{fuel} \tag{21}$$

The modeling and sizing of the diesel generator for the proposed system is out of scope of this study. The proposed energy management system will only turn ON and OFF the generator under extreme conditions.

E. GLOBAL MODELING

The global model of proposed standalone microgrid is derived below using the above described equations:

$$\frac{dx_1}{dt} = \frac{I_{pv}}{C_1} - \frac{x_3}{C_1}\mu_1 \tag{22}$$

$$\frac{dx_2}{dt} = \frac{V_{in} - R_w x_1}{L_2} - \frac{x_5}{L_2}(1 - \mu_2) \tag{23}$$

$$\frac{dx_3}{dt} = x_1\mu_1 + \frac{x_5}{L_1}(1 - \mu_1) \tag{24}$$

$$\frac{dx_4}{dt} = \frac{V_b - R_b x_4}{L_b} - \frac{x_5}{L_b}\mu_{34} \tag{25}$$

$$\frac{dx_5}{dt} = \frac{x_2}{C_{dc}}(1 - \mu_2) + \frac{x_3}{C_{dc}}(1 - \mu_1) + \frac{x_4}{C_{dc}}\mu_{34} - \frac{I_o}{C_{dc}} \tag{26}$$

In the above equations, the current value of L_1, L_2, and L_b are expressed by x_1, x_2, and x_4 respectively. x_3 and x_5 is represented by the voltage value of the capacitor C_1, and C_{dc} respectively.

IV. CONTROLLER DESIGNING

In this work, intelligent Lyapunov based adaptive fuzzy control system is design where Lyapunov is responsible for MPPT and voltage regulation by controlling the converter operation. The output of Lyapunov controller is fed to adaptive fuzzy based centralized controller that control the power flow of the proposed system. Fusion approach is used to synchronize the control signal of both controllers.

Lyapunov controller adopts knowledge of mathematical model whereas, adaptive fuzzy handle the system with nonlinear dynamics. The proposed control system offer following benefits:

- Effectively address the nonlinear behavior of system under variable load conditions.
- Provide stability and robustness under uncertainties and disturbances in the system.
- Improve the overall control performance of system as compare to existing controllers in literature.
- Provides intelligent incorporation that help to handle the control objectives and operating conditions.
- Provide flexibility that assist to adapt different system dynamic and control objectives.

A. LYAPUNOV CONTROLLER

Lyapunov controller ensured the MPPT of renewable sources and voltage regulation of DC bus under varying load and environmental conditions. The following errors are tracked to make sure the stability of the system:

$$\begin{cases} e_1 = x_1 - V_{pvref} \\ e_2 = x_2 - I_{wref} \\ e_3 = x_4 - I_{bref} \\ e_4 = x_5 - V_{dcref} \end{cases} \tag{27}$$

Taking the time derivative of the error signals gives the change in error over a small interval of time. It will helps Lyapunov controller to perform more efficiently. The time derivative of equation (27) is taken as:

$$\dot{e}_1 = \frac{I_{pv}}{C_1} - \frac{x_3}{C_1}\mu_1 - \dot{V}_{pvref} + \vartheta_1 \tag{28}$$

$$\dot{e}_2 = \frac{V_{in} - R_w x_1}{L_2} - \frac{x_5}{L_2}(1-\mu_2) - \dot{I}_w + \vartheta_2 \tag{29}$$

$$\dot{e}_3 = \frac{V_b - R_b x_4}{L_b} - \frac{x_5}{L_b}\mu_{34} - \dot{I}_{bref} + \vartheta_3 \tag{30}$$

$$\dot{e}_4 = \frac{x_2}{C_{dc}}(1-\mu_2) + \frac{x_3}{C_{dc}}(1-\mu_1) + \frac{x_4\mu_{34} - I_o}{C_{dc}} - \dot{V}_{dcref} + \vartheta_4 \tag{31}$$

In the above equations ϑ_1, ϑ_2, ϑ_3 and ϑ_4 are the untilled bounds and uncertain dynamics and the deftness of the controller tends to remove these parameters adaptively. The derived control laws using the equations (28), (29), (30) and (31) are:

$$\mu_1 = \frac{C_1}{x_3}\left(-\dot{e}_1 + \frac{I_{pv}}{C_1} - \dot{V}_{pvref}\right) \tag{32}$$

$$\mu_2 = 1 - \left(\frac{V_{in} - R_w x_2}{L_2} - \dot{I}_{wref}\right)\frac{L_2}{x_5} - \frac{L_2}{x_5}\dot{e}_2 \tag{33}$$

$$\mu_{34} = \left(\frac{V_b - R_b x_4}{L_b} - \dot{I}_{bref} - \dot{e}_3\right)\frac{L_b}{x_5} \tag{34}$$

The Lyapunov convergence functions for $\dot{e}_1$, $\dot{e}_2$, $\dot{e}_3$ and $\dot{e}_4$, for the error convergence towards zero are expressed as:

$$\begin{cases} \dot{e}_1 = -K_1 e_1 \\ \dot{e}_2 = -K_2 e_2 \\ \dot{e}_3 = -K_3 e_3 \\ \dot{e}_4 = -K_4 e_4 \end{cases} \tag{35}$$

where K_1, K_2, K_3 and K_4 are representing the adaptive gain. Now put the value of equation (35) in the control laws.

$$\mu_1 = \frac{C_1}{x_3}\left(-K_1 e_1 + \frac{I_{pv}}{C_1} - \dot{V}_{pvref}\right) \tag{36}$$

$$\mu_2 = 1 - \left(\frac{V_{in} - R_w x_2}{L_2} - \dot{I}_{wref}\right)\frac{L_2}{x_5} + \frac{L_2}{x_5}(K_2 e_2) \tag{37}$$

$$\mu_{34} = \left(\frac{V_b - R_b x_4}{L_b} - \dot{I}_{bref} + K_3 e_3\right)\frac{L_b}{x_5} \tag{38}$$

1) STABILITY ANALYSIS

In proposed controller, the control laws are defined as μ_1, μ_2, and μ_{34}. The stability of entire system can be ensured by using a positive definite Lyapunov candidate function as:

$$V = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2\right) \tag{39}$$

By taking the derivation of equation (39), the equation become:

$$\dot{V} = \left(e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3\right) \tag{40}$$

As given in equation (35) we have Lyapunov convergence functions for the derivatives of all the errors. By putting these values in the equation (40) and equation become as:

$$\dot{V} = -\left(K_1 e_1^2 + K_2 e_2^2 + K_3 e_3^2\right) \tag{41}$$

Equation (41) ensure the closed loop control system is asymptotically stable by considering the Lyapunov stability criterion. The values of the adaptive gains are chosen according to the following equation [17]:

$$K_i(x_i) = \frac{|x_i|}{\varepsilon_i - |x_i|} \tag{42}$$

In the above equation (42), $K_i(x_i)$ is the adaptive gain for the $i-th$ component of the system, and it is a function of the state variable xi. Whereas is the threshold associated with the $i-th$ component introduces non-linearity into the gain. This non-linear behavior is often used to prevent division by zero and to introduce saturation in the control system.

B. FUZZY BASED ENERGY MANAGEMENT

The Energy Management System (EMS) is designed to utilize inputs derived from the available RESs, load demand, and SOC of the battery. Energy management system accomplished the Kirchhoff's current law that ensure the zero value of power sum at DC bus. The flow chart of the energy management strategy is shown in Figure 6. The energy management strategy is designed according to three different conditions. In the first condition, the load demand is equal to

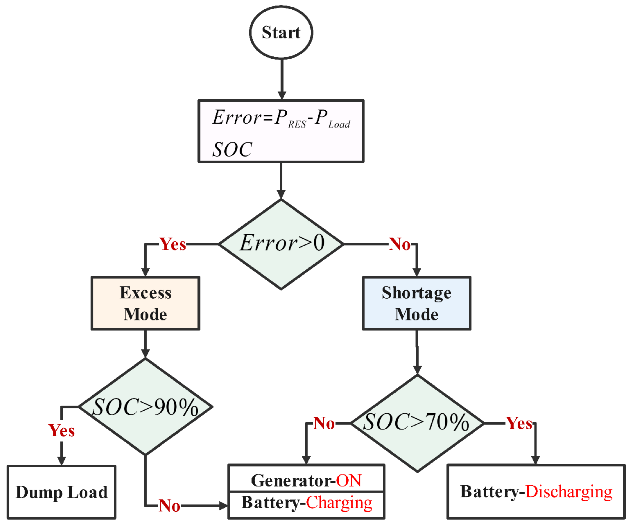

FIGURE 6. Flowchart of energy management strategy.

renewable power then power is supplied directly towards the load. In the second condition, when the grid have more power than load demand, then remnant power will use to charge the battery. If the battery is fully charged, the dump load is ON to consume the remnant power. The third condition activate if the load demand is greater than renewable power then the battery will provide the power to fulfil the load demand. When the state of charge of the battery is low then DG will provide the backup power to the load and charge the battery bank simultaneously.

The definite and acceptable output is produced by the Fuzzy Logic System in response to distorted, incomplete, inaccurate and ambiguous Fuzzy type input. Fuzzy logic is a process of reasoning like the human nervous system [25], [26]. The formalization of fuzzy logic simulates the mode of deciding as in humans, which pertains to entire possibilities intermediate between the numerical values 0 and 1. Fuzzification is the process that converts the crisp numbers to fuzzy sets and defuzzification converts the fuzzy sets to crispy numbers. The system is trained by "IF-Then" rules. Membership functions are the graphical representation of fuzzy sets and have all information with a degree of truth, shown in Figure 7.

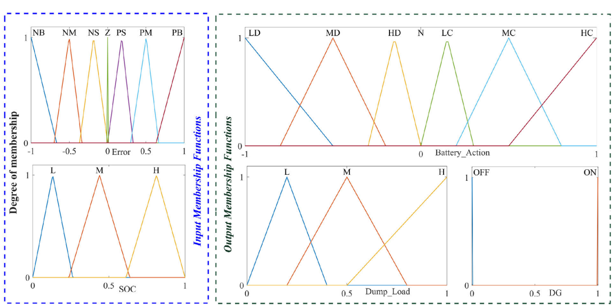

FIGURE 7. Input and output membership functions.

The proposed controller is designed for a better and optimized energy management system as compared to the previous technique. Remnant power (error) and SOC of battery are the input of fuzzy controller, whereas load, battery action (charging/discharging), dump load and DG are the output. The output membership functions relation with fuzzy input is shown in Figure 8.

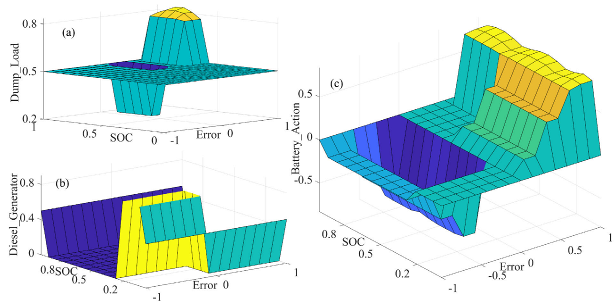

FIGURE 8. Surfaces characterizes of Fuzzy controller (a) Inputs vs dump load (b) Inputs vs Diesel Generator (c) Inputs vs Battery charging/discharging.

The fuzzy rules are designed according to energy management strategy. The value of power difference for controller can be positive or negative based on surplus or deficit respectively. Centroid defuzzification method is used to convert the aggregated fuzzy outputs into crisp control signals that strikes a good balance between accuracy and simplicity. It helps to converting the fuzzy control output into a specific control value and allow the controller to make decisions for energy management.

V. RESULTS AND DISCUSSION

A standalone microgrid system is simulated through MATLAB/Simulink programming environment with proposed controller techniques for testing and validating the performance of the proposed system. Two controller Lyapunov and Fuzzy controllers are proposed in this paper for bus voltage regulation, MPPT of RESs and energy management. Energy sources and simulation model parameters are mentioned in Table 1 and Table 2.

TABLE 1. Parameters of energy sources.

PV Model		Wind Turbine Model	
Modules per string	10	Wind speed	5 m/s
Parallel linked strings	10	Rotor diameter	5.5 m
Cell per module	60	ρ_{air}	1.225 kg/m^3
P_{max}	2.1 kW	C_{p-max}, λ_{opt}	0.43, 7.5
V_{oc}	363 V	**PMSG**	
I_{sc}	7.84	Rated power	4.5 kW
Lead Acid Battery		Moment of inertia	0.011 $kg.m^2$
Capacity	33.9 Ah	Viscos damping	0.0019 N.ms
V_b	540 V	Flux linkage	0.192 Wb
$I_{max charging}$	17.5 A	Number of poles	4
$I_{max discharging}$	30 A	R_s	0.036Ω
Diesel Generator		L_d	0.334 mH
Rated Power	10 kW	L_q	0.217 mH

A. SIMULINK MODEL

The proposed system is tested under two different scenarios. Scenario-I is normal mode condition: when no need to

TABLE 2. Parameters for simulation model.

Converters	
C_{dc}, C_1, C_2	16μF, 16μF, 68μF
L_1, L_2, L_3	20mH, 20mH, 3.3mH
f_{switching}	100kHz
Control System	
e_1, e_2, e_3	1000, 1000, 3000

activate the dump load and diesel generator. Scenario-II relates to high and low penetration of energy sources: when dump load and diesel generator are required to balance the power. Load power curve from 2kW to 14kW for 20sec is shown in Figure 9. In the proposed system the first

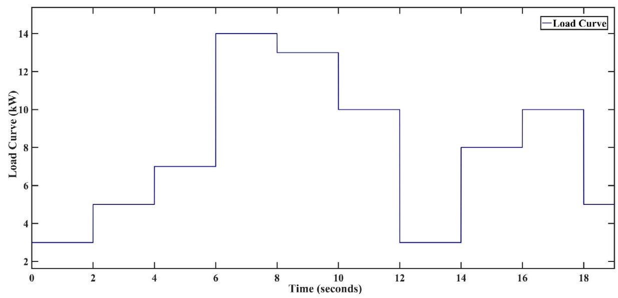

FIGURE 9. Load power curve.

target is to track the MPPT of RESs which is achieved through the Lyapunov controller. The MPPT of PV and the wind is successfully achieved reference MPPT values, shown in Figure 10. Furthermore, battery reference current

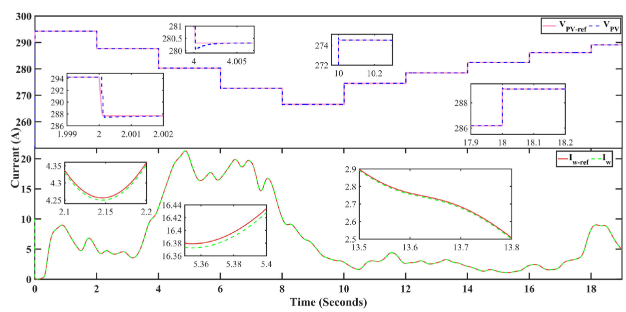

FIGURE 10. PV voltage and wind current tracking.

is tracked by incorporate error feedback through proposed controller. Battery operations are based on constant current and constant voltage (CC-CV) that prevents the battery from overheating and over voltage. The proposed control system adjusts the control signals to minimize the error toward zero and maintain the optimize operation of BSS. The tracking of battery reference current is shown in Figure 11.

Scenario-I: The output powers of RES are based on irradiance, temperature and wind speed. When the temperature, irradiance and wind speed are low and attached to high load then the battery will provide the power to meet the required demand. When the speed of wind, temperature and irradiance are high and attached to low load, RES power is sufficient for the load and surplus power is consumed to charge the battery. The output power of PV, wind and battery under variable load

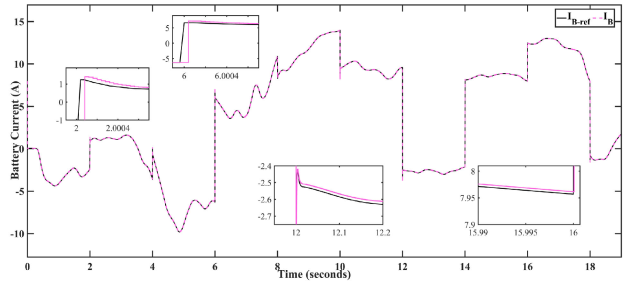

FIGURE 11. Battery current tracking.

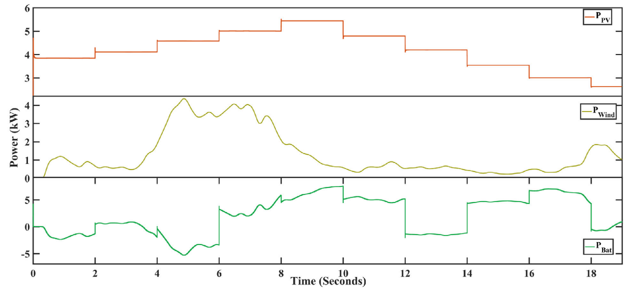

FIGURE 12. Power curves.

curve are illustrated in Figure 12. By referring to the above Figures, at the time t=0-2sec when load power is 3kW, the generated PV power is 3.84kW and wind power is varying between 0 to 2.36kW. During this period remnant energy is utilized to charge the battery. At the time t=2-4sec the load power is 5kW, the PV provide 4.1kW and wind vary from 0.9kW to 3.3kW power respectively. In this interval system have little discrimination at some points between load and demand, which is fulfilled through the battery. At the time t=4-6sec when load demand is 7kW, the generated renewable power is varying 7.6kW to 13.3kW. During this period battery is again in charging mode and consume the surplus amount of energy. At the time t=6-12sec, the load demand is varying from 10kW to 14kw the maximum renewable power available is 11.5kW. During this period generated power is less than the load demand and BSS provide backup to fulfil the power deficient. At the time t=12-14sec and 14-16sec the battery is in charging and discharging mode to balance the power flow. The battery provides a backup system to ensure voltage regulation and power balance under variable load conditions. BSS is not beneficial for power balancing and voltage regulation under two circumstances: 1) when the SOC of the BSS is low and power demand is high during low penetration of renewable resources 2) when the SOC is 100% and the power demand is less than the generated renewable energy. To deal with these circumstances, the proposed controller turn ON the diesel generator in the first scenario and turn ON the dump load for the second scenario.

Scenario-II: The performance of proposed controller during high and low penetration of renewable resources is tested under different SOC of BSS and shown in Figure 13. In case-I, the load demand is higher than generated renewable power and BSS cannot provide surplus power due to low

SOC of batter. In this case diesel generator is ON to fulfil the load demand. During case-II, when load demand is less than renewable energy and SOC of battery is low. In this case surplus power is provided to BSS to charge the battery. When battery is fully charged but renewable power is still greater than load demand. Dump load is ON in this scenario to balance the power flow and maintain the voltage during high penetration. During case-III, the load demand is higher than renewable power and SOC of battery is not low. Now BSS provides the backup to fulfil the load demand. In case-IV, when the generated renewable power and load demand are equal then BSS remains at idle. Finally, Figure 13 shows the efficient control of power flow under difference scenarios.

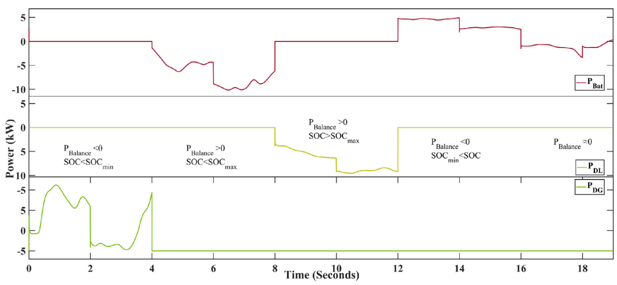

FIGURE 13. EMS under different Battery-SOC.

Voltage regulation of DC bus under variable load conditions is shown in Figure 14. The result shows the asymptotical stable tracking of reference voltage.

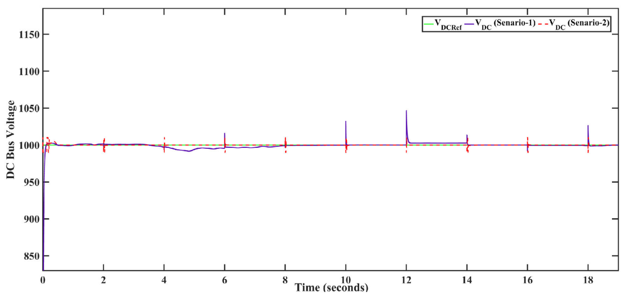

FIGURE 14. DC bus voltage.

The validity of the proposed control system is tested by comparing with PID and sliding mode control techniques [27]. The comparison analysis of proposed system with above techniques are shown in Figure 15 and Table 3. Zoom windows show, PID controller takes large time to reduce steady state error and settling time, while sliding mode controller has chattering issues due to large sliding values under variable load conditions. Results are clearly showing the superiority of proposed techniques to provide better voltage tracking, stability and energy management under variable load condition.

B. HARDWARE TESTING RESULTS

Laboratory prototype of 4KW for the proposed controller was executed to test its performance in a realistic and time-critical environment. dSPACE controller is used to integrate

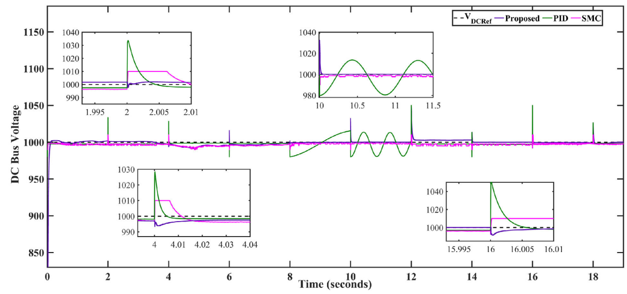

FIGURE 15. Comparison with PID and SMC.

TABLE 3. Comparison table.

Performance	Proposed	PID	SMC
Steady State Error	0.2	0.32	0.5
Rising Time	0.05	0.5	0.035
Settling Time	0.05	0.6	0.051
Overshoot	2.1	15	4.7

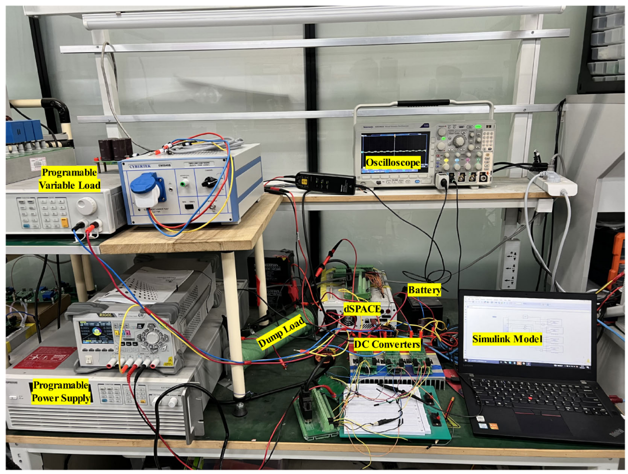

FIGURE 16. Hardware test bench for proposed controller.

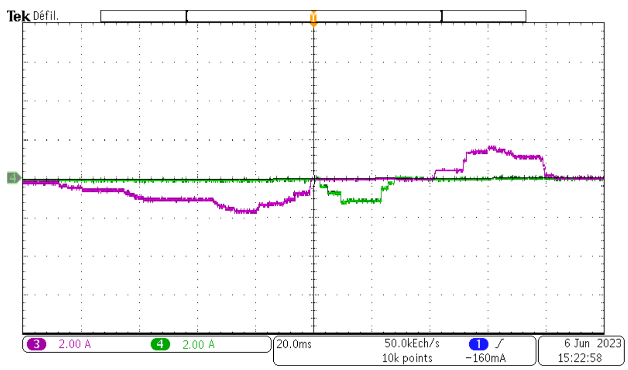

FIGURE 17. Experimental results of battery and dump load current.

the proposed control technique with the hardware setup. Two programmable power supplies are used in the hardware to imitate the PV panel and wind power source. BSS is included in the hardware using a battery of 50 Ah. Dump load is added in the hardware using different resistances. DC-DC converters in the system were designed with IGBTs and controlled using dSPACE controller through Simulink model.

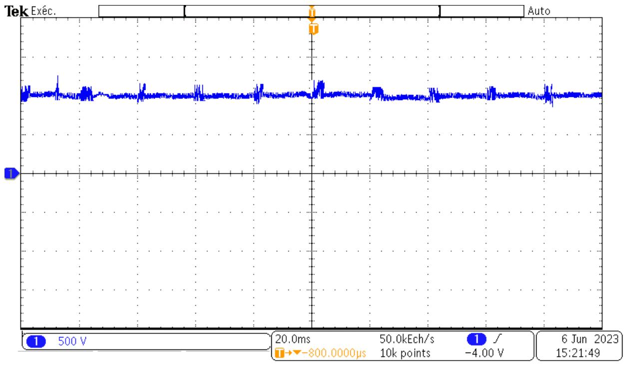

FIGURE 18. Experimental output voltage of proposed technique.

The switching frequency for all IGBTs was set to 10 kHZ. A dead time of 0.5μs was set for bidirectional converters. The output load profile is generated using programmable electronics load. The output results are observed using oscilloscope and power analyzer. The hardware setup of proposed controller is shown in Figure 16. Battery and dump load current curves are shown in Figure 18 (channel-3 for battery and channel-4 for dump load current). Figure 18 shows the output of the DC voltage regulations curve. Distortion at different points is due to the fluctuation in the load curve. Proposed controller minimized those fluctuations and provide a constant DC output voltage and current. The hardware results of the purposed system shows the effectiveness of the proposed controller in real time scenario. Our proposed system shows better performance in both simulation and hardware setups.

VI. CONCLUSION

Intelligent Lyapunov based adaptive fuzzy controller is implemented to ensure the converter operation, MPPT of RESs, energy management and DC bus voltage regulation for standalone microgrid. PV and wind turbine are used as primary sources, battery and DG is used as secondary sources. Regression plane and optimal torque control methods are applied to track maximum power from PV and Wind system respectively. Controller ensure the charging process by implementing CC-CV that prevents the battery from overheating and over voltage. Surplus power during low load demand and 100% SOC, is utilized through dump load which ensures stable power flow and voltage. The proposed standalone microgrid system is verified using MATLAB/Simulink and real-time hardware setup in the lab. Results show that the proposed control system provides an asymptotical stable system with better MPPT, energy management and DC bus voltage regulation. Overall, the simulation and hardware results have proven that the centralized controller meets all the control objectives successfully and outperforms the existing systems.

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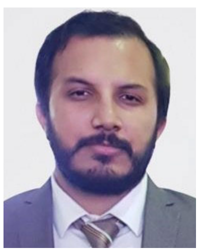

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