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Voltage and frequency control of solar – battery – diesel based islanded microgrid

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Islanded microgrids with low-inertia distributed energy resources (DERs) are prone to frequency fluctuations. With the increasing integration of DERs in microgrids, the complexity of control and stability has also increased. Moreover, the integration of DERs into microgrids may result in a power imbalance between energy supply and demand during sudden changes in load or energy generation. This can cause frequency variations in the microgrid, which could have disastrous consequences such as equipment damage or even blackouts. This paper proposes a control strategy to ensure the efficient operation of an islanded hybrid microgrid consisting of a PV generator, battery energy storage system (BESS), and emergency diesel generator. According to Energy Exchange Model proposed in this paper, the hybrid system presented operates independently without being connected to the electrical grid, where the PV system and BESS act as the main energy sources, while the emergency diesel generator provides active power backup with voltage and frequency regulation. The novel in this paper is also that DER aids in frequency regulation during active power transients by delivering and absorbing active power in accordance with the inverter's suggested P droop control strategy. In this way inverter droop control decreases system frequency nadir emulating so called "synthetic inertia". To design both the islanded hybrid system and the proposed control strategy, the MATLAB/Simulink environment is utilized. Based on the results, it can be concluded that the analyzed microgrid system is capable of maintaining stability and operating efficiently in a range of operating conditions.

Keywords: diesel generator, energy storage system, frequency control, islanded microgrid, PV, voltage control

1 Introduction

One of the most promising solutions for the distribution of electrical energy to remote areas is the installation of autonomous hybrid energy systems. These energy systems are able to provide a reliable supply of electricity to meet the demand through the combination of different energy sources, such as photovoltaic (PV), wind energy, biomass or small-scale hydro systems. Those renewable energy sources play vital role in isolated electrical grids and microgrids as alternative to fossil fuel based generators used for electricity supply in islanded mode [1]. They have significant potential to expand access to electricity, particularly in rural and remote areas that lack access to traditional grid infrastructure. They can also improve energy security and resilience by providing a localized source of power generation and reducing reliance on centralized power grids that are vulnerable to disruptions. Moreover, the current Green Deal policy emphasizes the idea of a transition to more decentralized, sustainable energy systems where individuals and small-scale producers play a significant role. Those systems are based on the hybrid system that operates in isolated mode. This shift towards decentralized, sustainable energy systems not only reduces the carbon footprint but also empowers local communities to actively participate in the green energy revolution.

Just as interconnected electrical systems, hybrid energy systems in isolated mode have to meet reliability and adequacy standards related to the system frequency and voltage. The IEC 62898 and IEC 62257 standard series require that all controllable units in the system should be actively involved in preserving both system voltage and frequency within the allowed limits [2-4]. This is particularly challenging, as there is no external support from the larger electrical grid to help balance supply and demand. Moreover, due to the variable electricity production from intermittent renewable energy sources and low inertia of the hybrid system, frequency fluctuation may occur, that will cause further deviation from the nominal operating conditions [5]. If the frequency of the system deviates too far from the standard value, it can cause instability, damage to equipment, and even blackouts. Therefore, effective frequency and voltage controls are crucial for the safe and reliable operation of isolated hybrid systems such as microgrids. With the increasing adoption of microgrids, especially in small and medium-sized applications, there will be a growing need for advanced control techniques to ensure optimal system performance [6]. The control operation and control techniques of microgrids will need to evolve to meet these future requirements.

To handle the challenge of frequency regulation in isolated hybrid systems, several strategies can be applied. One common approach is to use energy storage

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systems to smooth out fluctuations in the output of renewable energy sources, ensuring that the frequency of the system remains within a safe and stable range. Other approaches may include using advanced control algorithms and deploying demand response strategies. Various control strategies for the operation of hybrid energy systems has been extensively discussed in the literature [7]. In [8], battery energy storage systems (BESSs) control technique to reduce frequency fluctuations and improve the dynamic response of islanded microgrids. For better frequency responses during transients, a piecewise linear-elliptic (PLE) droop characteristic is suggested and used in BESS to ensure faster power balance between generation and consumption. In order to provide the best possible frequency response as well as stability, the use of voltage setpoint control and an adaptive active power droop controller in isolated microgrids is provided in [9]. In order to maintain the system's frequency within acceptable bounds and improve its primary frequency response, the control scheme employs an optimal and model predictive control approach that continuously modifies the voltage setpoints of DERs and the active power droop gains. The control strategy analyzed in [10] has been designed such that the biogas-based system of each individual microgrid increases or reduces its generation to meet system requirements whenever there is a disturbance in the system brought on by an increase or decrease in load or input from renewable energy sources. In [11], a disturbance observer based control (DOBC) strategy to regulate the frequency and voltage of a hybrid microgrid powered by diesel generators (DG) and solar PV in the event of an islanding has been analyzed. The frequency control of islanded microgrids by voltage control approach was examined in [12]. The suggested strategy is based on Decentralized Voltage Frequency Controller (VFC) and inertia control of virtual synchronous generator used to improve frequency in microgrid. However, the performance of these controllers is fully based on the load characteristics of the microgrid. A method for regulating voltage for a microgrid operating in stand-alone mode that comprises of a BESS and a PV generator with maximum power point tracking (MPPT) algorithm is analyzed in [13]. Nonetheless, the voltage control method described in the paper does not take into account the interdependence of active and reactive power, nor its impact on system frequency.

The main objective of the paper is to provide possible solutions for the proper functioning of the small scale microgrid, from the aspect of the voltage and frequency control based on energy control strategies. Effective frequency and voltage regulation are paramount for the reliable operation of microgrids, as they ensure stable and resilient energy distribution, making these control strategies a critical aspect of sustainable energy solutions. According to Energy Exchange Model proposed in this paper, the hybrid system presented operates as a single grid in islanded mode, where the PV system and BESS act as the main energy sources, while the emergency diesel generator provides active power backup with voltage and frequency regulation. This research is innovative in that it presents DER's assistance in frequency regulation during active power transients by supplying and absorbing active power in line with the recommended P droop control method of the inverter. By reducing the system frequency nadir in this manner, inverter droop control simulates the phenomenon known as "synthetic inertia."

In this study, MATLAB/Simulink software was used to propose and assess the effectiveness of employing multiple mechanisms and control strategies concurrently, such as P droop control, MPPT control of the PV system to achieve the highest output power, and Battery power regulation. MPPT control is achieved with fuzzy logic control (FLC) based MPPT algorithm.

The paper is organized into six sections. Section 2 details the islanded microgrid structure and the modeling of specific components, such as the PV system, BESS, and diesel generator. Section 3 covers system operation and control strategies, including the P droop control scheme and MPPT algorithm. Section 4 describes the proposed Energy exchange model. Finally, section 5 presents the simulation findings and discussion, while section 6 provides the summary and conclusion.

2 System configuration

Figure 1 depicts the main configuration of the islanded microgrid under analysis, which includes an AC load, a diesel generator, a PV system, and a BESS. To meet the load demand, the PV system is linked to the AC bus via an inverter and a boost DC/DC converter, which provide the necessary active power. However, if there is a substantial difference in inertia between the PV system and diesel generator, it could lead to a mismatch between the generation of active power and consumption during transients. Consequently, frequency variations occur that could lead to grave aftereffects like total losses in electricity supply of consumers.

To address frequency deviations and mitigate the intermittency of PV systems, the BESS is employed to balance energy generation and consumption. This is achieved by supplying or absorbing active power as needed. The diesel generator's governor controls the frequency of the AC bus in the microgrid in both steady-state mode and during transients. Inverter of DER operates in PQ mode by following system voltage and frequency. The novel in this paper is that DER aids in frequency regulation during active power transients by delivering and absorbing active power in accordance with the inverter's suggested P droop control strategy.

In this way inverter droop control decreases system frequency nadir emulating the so-called “synthetic inertia”. According to the Energy Exchange Model proposed in this paper diesel generator produces active power only when there is lack of active power from DER. Since the reference value of reactive power is set to constant value (zero value), the inverter is not involved in regulating the voltage of the AC grid. In this way a diesel generator must be connected to the AC grid even if it is not producing active but only reactive power for the purpose of AC bus voltage regulation and for purpose of regulation system frequency.

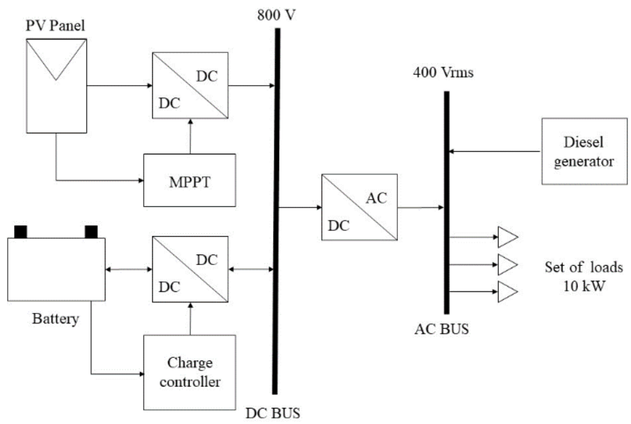

Fig. 1. Microgrid configuration

2.1 Diesel generator

When renewable energy production is limited or there is a significant demand for electricity, diesel generators are frequently employed as backup power sources in microgrid systems to maintain an uninterrupted power supply. They can either serve as the main source of electricity in the absence of renewable energy sources or as a complement to the power provided by the PV system and BESS to fulfil the load requirement. This enables microgrid systems to operate more reliably and efficiently, providing stable power supply to customers even in adverse conditions. However, it is important to ensure that the diesel generator operates efficiently and at optimal levels to minimize fuel consumption and reduce emissions. Diesel generators are a popular choice as dispatchable distributed energy resources in microgrids, due to their ability to act as grid-forming sources and support the frequency of the microgrid [14]. Swing equation reflects the dynamics of the frequency of diesel generators. The relationship between the microgrid’s frequency to the and power imbalance is given as [15]:

$$M_{GEN}\frac{d\omega}{dt} + D_{GEN}\Delta\omega = P_m - P_{GEN}.$$

In the above equation, P_m is the mechanical input power into the generator, P_{GEN} is the electrical output power, for the rotor speed, M_{GEN} is the inertia coefficient, and D_{GEN} is the diesel generator's damping coefficient. The governors in synchronous generators are used to perform the following primary frequency control [15]:

$$K_P(f - f_o) = -(P_{GEN} - P_{GENo}),$$

where f_o and P_{GENo} are the nominal frequency and power of the generator, respectively, and K_P is the droop parameter.

As a result, the governors in synchronous generators provide primary frequency control, which aims to limit frequency deviations caused by loads, distributed energy resources, or other system disturbances. Consequently, this control mechanism seeks to restore power balance within the system.

The standard model of the diesel generator used in the research is composed of the speed regulator, excitation system and synchronous generator as shown in Fig. 2. The reactive power produced by the diesel generator is controlled by the excitation system while the speed control is obtained by governor mechanism. Figure 3 represents the diesel engine governor that describes dynamic behavior of small diesel generator sets very well and is widely used [15].

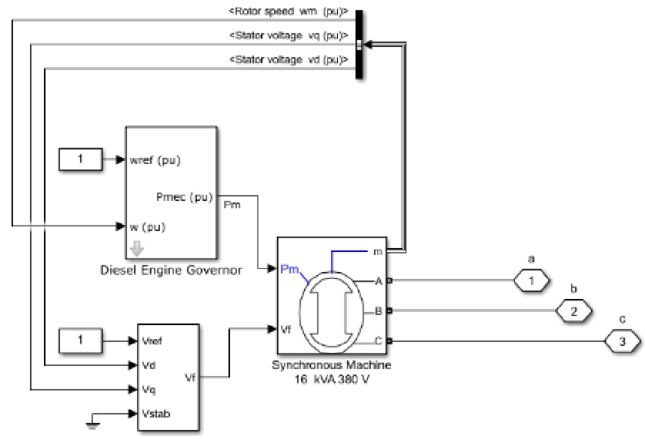

Fig. 2. Diesel generator

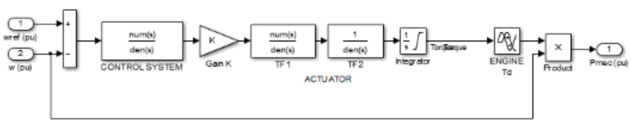

Fig. 3. Diesel engine governor

Variations of the frequency affected by the load changes are followed by the diesel engine, where diesel generator and its governor mechanism provide the balance between the produced active power and load demand. When there is lack of active power production, system frequency decreases and vice versa, when there is surplus of active power production system frequency increases. By comparison of reference frequency (50 Hz) and measured frequency, diesel engine governor controls mechanical power of the diesel engine and consequently active power of diesel generator in order to control system frequency. Since actuator od diesel engine includes integrator, after active power disturbance, active power of diesel generator is adjusted until frequency steady state error is set to zero. In this way diesel engine control system covers primary and secondary frequency control used in classical electrical power systems. Range of voltage change is controlled by the voltage regulator through the generator excitation maintaining reactive power voltage balance. In transient state and during the power imbalances, the frequency and the voltage will not be at its nominal value.

2.2 PV system

The PV system consists of the PV panel, a DC/DC boost converter, and an MPPT algorithm. A light-generated current source, p-n diodes, and a cell shunt resistor are linked in parallel to represent the PV cell. Moreover, series cell resistance is taken into account. Detailed model of the PV cell is given in [16].

To extract maximum power from the PV system, an FLC based algorithm is used. In the previous work [16], it was shown that FLC MPPT algorithm improves dynamic characteristics of the PV system and has more superior performance in terms of adaptation to solar irradiance variations in comparison to P&O algorithm.

2.3 BESS system

The bidirectional DC/DC buck-boost converter, a battery, and a charge controller are the main components of the BESS model used in the study. BESSs function as a source in discharging mode and as a load in charging mode. Additionally, they are used in regulating voltage on the DC bus. A bidirectional DC/DC converter is utilized to connect the battery to the DC bus, regulate the battery's charging and discharging, and enable the transfer of energy in both directions. The standard cascade control technique with PI voltage and PI current controller is used by the BESS bidirectional converter to maintain power balance in the microgrid.

This paper utilizes a lead-acid battery model based on the on-time constant model depicted in Fig. 4. To accurately represent the dynamic behavior of the battery during charging or discharging, the model incorporates an RC network that is connected in series with the internal resistance R_0. This network simulates the electrical behavior of the battery and allows for a more accurate prediction of its response to varying conditions. The model consists of a voltage source V_{OC}, a resistance R_0 measured in ohms, and R_{cs} and C_{cs}, which together describe the battery's transient response. Below, v_{cs} is the voltage across C_{cs}, i_{cs} is the current that flows in C_{cs}. Equations (1) and (2) in continuous time mathematically represent the electrical characteristics of the on-time constant model used in this paper for the lead-acid battery:

$$\dot{v}_{cs} = -\frac{V_{OC} - v_{bt}}{R_{cs}C_{cs}} + \frac{R_{cs} + R_0}{R_{cs}C_{cs}} i_{bt}, \tag{1}$$

$$v_{bt} = V_{OC} - v_{cs} - R_0 i_{bt}, \tag{2}$$

where i_{bt} and v_{bt} are the battery current and voltage, respectively.

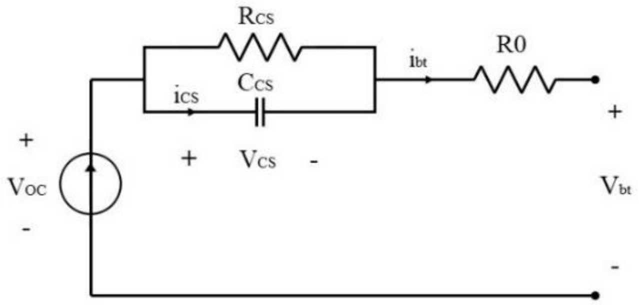

Fig. 4. Model of the battery

The state of charge (SOC) of the battery is determined through the integration of current, assuming i_{bt} as the current of the battery, the battery's initial charge is denoted by $Q(t_0)$ at time t_0, while α represents the charge/discharge efficiency [17].

$$SOC(t) = \frac{Q(t_0) + \int_{t_0}^{t} \alpha i_{bt} dt}{Rated \quad capacity} \times 100$$

2.4 Inverter droop control

Control of the active power injected by the inverter during frequency transients is implemented by an inverter droop control block, which implements droop characteristics shown in Fig. 5. It is used to imitate the behavior of the synchronous generator with P droop controls [15] and inertial response during frequency transients. PQ inverter implements this droop as a frequency dependent function. Unlike synchronous generator, PQ inverter measures the frequency of the grid using a phase locked loop (PLL) and operates at that frequency. It does not set the frequency. The nominal and measured frequencies are compared in order to adjust the inverter’s active power during system frequency transients.

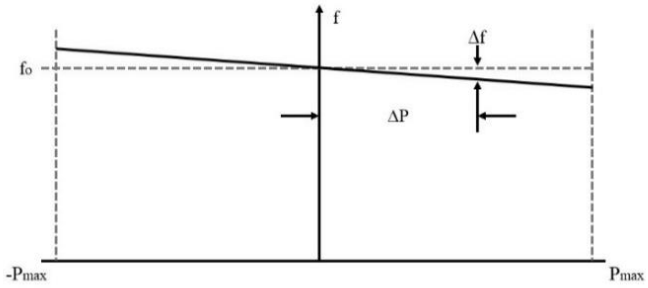

Fig. 5. Droop characteristics

Equation (3) describes this droop characteristics:

$$P(f) = P_0 - (f - f_n)k_f \quad (3)$$

The droop constant, k_f, specifies how much the active power P will change owing to a change in frequency f. P_0 is the power of the inverter at nominal frequency f_n.

System frequency difference at the right-hand side of equation (6) in the steady state equals to zero due to integrator in the actuator of diesel engine governor system. It means that inverter droop control is only active during system frequency transients but not at steady state. In this way inverter droop control decreases system frequency nadir emulating so called “synthetic inertia”.

Block Energy Exchange Model, shown in Fig. 6 changes the active power reference, Pinit1_pu, of DC to AC converter (inverter) according to Energy Exchange model explained in section 4.

Block Qinit1_pu, shown in Fig. 6, sets reactive power injected by the inverter into AC system/network. In this example, active power injected by the inverter is set to zero.

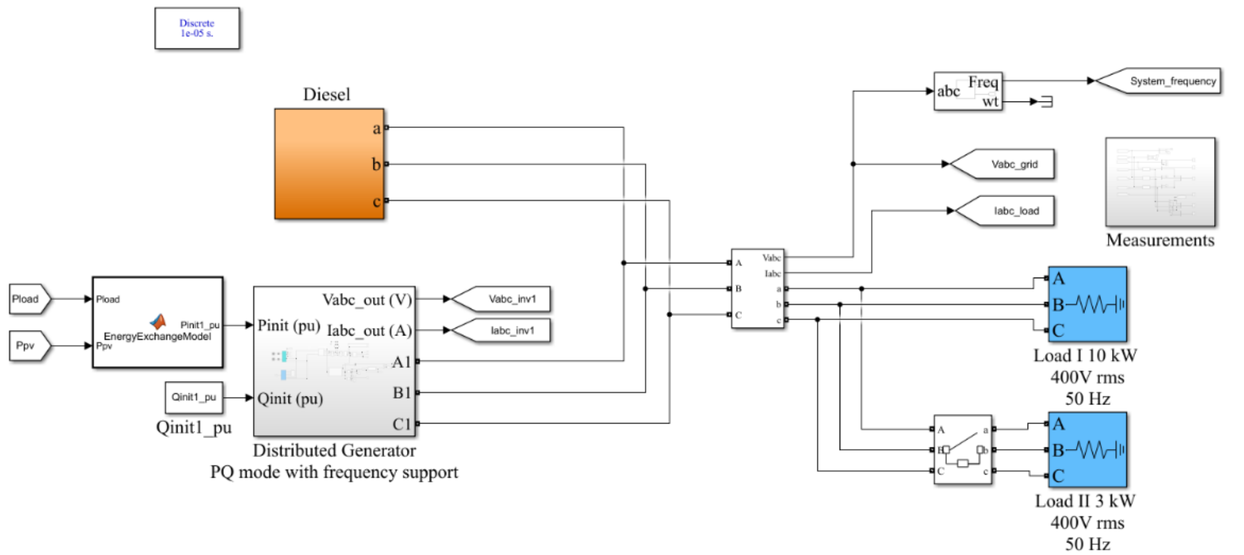

Fig. 6. Hybrid microgrid modeled in Simulink

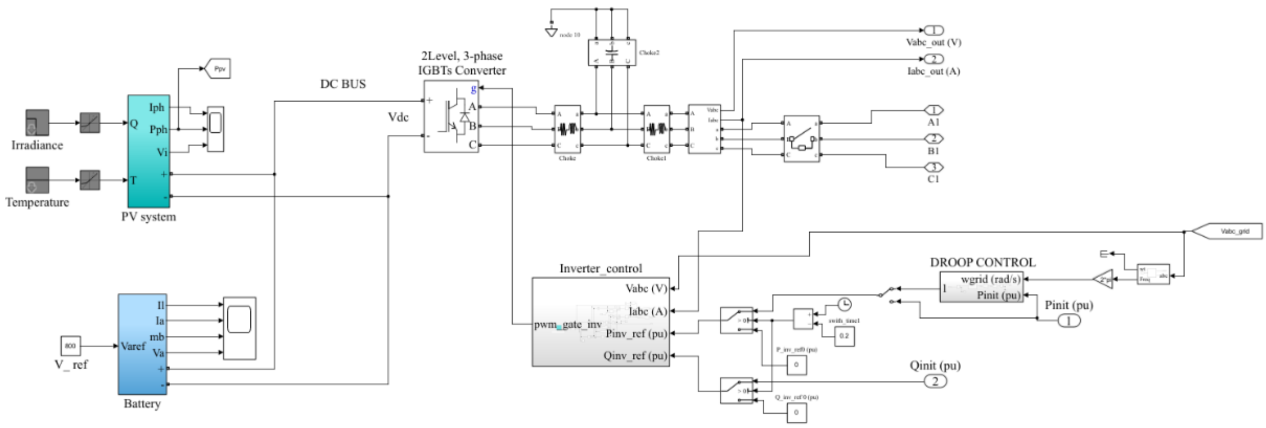

Fig. 7. Distributed generator modeled in Simulink

3 System operation and control

The control objectives for an isolated microgrid are to regulate system frequency, control voltage at the DC bus, maintain load voltage, and optimize the power output of the PV system. To model a hybrid islanded microgrid, Simulink was used, and the resulting model is depicted in graphical form in Figs. 6 and 7. The microgrid's DC bus is connected to both the PV system and BESS, while the AC bus is linked to a diesel generator and other loads. To enable power flow between the DC and AC buses, a DC/AC converter is utilized.

Two case cases are looked at in this study. The first case examines a situation in which solar radiation is abundant and all of the loads are provided by the DC side of the system. The PV system and BESS are used to do this, with the diesel generator still connected to the AC bus to control the system's voltage and frequency. When there is sufficient solar energy available, the PV system powers the loads predominantly in this configuration. BESS backs up the power supply if there is insufficient solar energy. In order to control the DC bus voltage as a result, the bidirectional DC/DC buck-boost converter will work in boost mode while the battery is in draining mode. If the PV systems produce more energy than is required to fulfill demand, the extra energy will be stored in the BESS, which will put the battery in the charging mode. As a result, the DC/DC buck-boost converter will run in buck mode to control the battery's charging current.

The second case analyzes the scenario in which solar irradiation and SOC of the battery are low, which requires the use of the diesel generator as the main source which is responsible for voltage and frequency control.

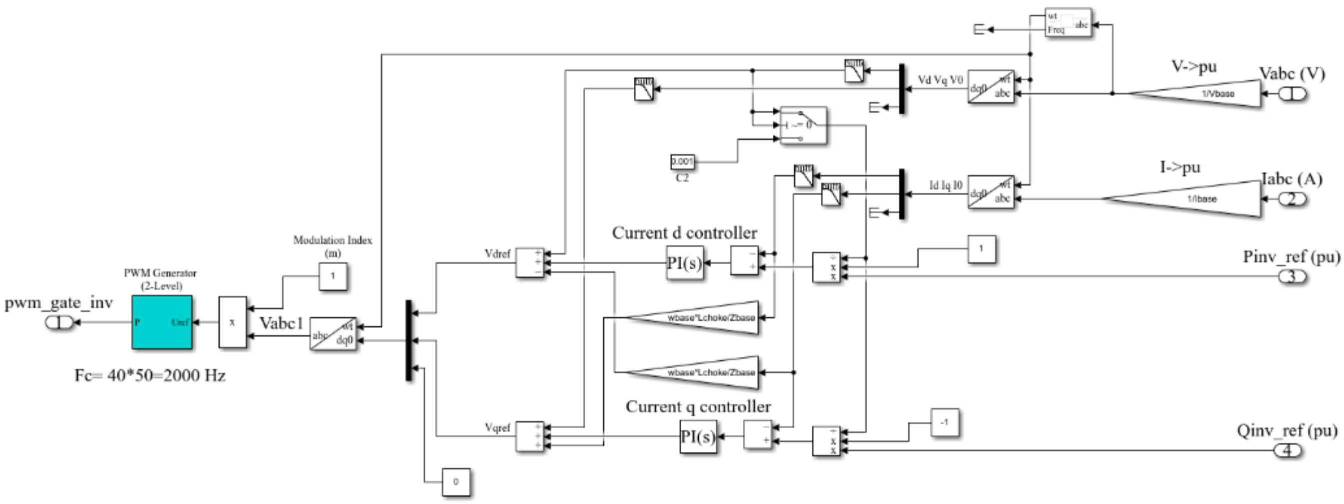

Fig. 8. Inverter control modeled in Simulink

To get the most power out of the PV systems in both cases, the PV system runs in MPPT mode and uses the FLC MPPT algorithm. The regulation of load-induced power imbalances, source changes and frequency, droop control and governor of diesel engine are used to keep the frequency and voltage at the AC bus within allowable bounds. The suggested control scheme's schematic form is shown in Fig. 8. The PQ control scheme, based on the two PI controllers regulates the power unbalance. As shown in Fig. 8, AC voltage and current are measured and converted to per unit values. Then, they are converted to dq0 frame using the Park's transformation [18]. On the other hand, active and reactive reference power values, taken as the power required by the load, *ie*, 10 kW, are converted to per unit values as well. They are used to generate the reference values for the current controllers, I_{dref} and I_{qref}. These reference values are then compared with the filtered values of I_d and I_q and fed to the PI controllers, d controller and q controller, respectively.

The expressions for the outputs of the d and q controllers, are given by Eqns. (4) and (5) respectively.

$$V_d' = K_{Pd}\left(\frac{P_{inv}}{V_d} - I_d\right) + K_{Id}\int_0^t \left(\frac{P_{inv}}{V_d} - I_d\right) dt, \qquad (4)$$

$$V_q' = K_{Pq}\left(\frac{-Q_{inv}}{V_d} - I_q\right) + K_{Iq}\int_0^t \left(\frac{-Q_{inv}}{V_d} - I_q\right) dt\,. \qquad (5)$$

Here, the proportional and integral gains of the d controller are denoted by K_{Pd} and K_{Id}, respectively, whereas the proportional and integral gains of the q controller are denoted by K_{Pq} and K_{Iq}, respectively. P_{inv} is the active power of the inverter in per unit, while Q_{inv} is its reactive power in per unit.

Overall outputs of the control scheme, d component of the voltage V_{dref} and q component of the voltage V_{qref} are expressed by Eqns. (6) and (7), respectively. These components together with 0 component are combined and are subject to the inverse Park's transformation in order to obtain a real value of the three-phase voltage reference signal for the inverter PWM.

$$V_{dref} = V_d + V_d^{'} - Z_{choke} I_q \tag{6}$$

$$V_{qref} = V_q + V_q^{'} + Z_{choke} I_d \tag{7}$$

The frequency of the microgrid is regulated using the frequency support droop control scheme shown in Fig. 9. In order to calculate the frequency deviation in the microgrid, the nominal angular frequency is compared to the actual angular frequency of the system. This change is then converted in per unit, divided with droop constant, k_p, and filtered to obtain the change in power, ΔP. The output of this control scheme is obtained from the addition of the power Pinit required by the load, *ie*, 10 kW, and the change in power, ΔP. Newly obtained value of the P is then fed to the PQ control scheme of the inverter, and overall control of the microgrid is achieved.

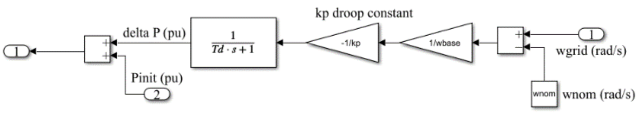

Fig. 9. Frequency support droop control modeled in Simulink

As stated earlier, the inverter control scheme is in coordination with the battery control scheme shown in Fig. 10. To balance the microgrid's supply and demand, the battery is integrated into the PV system architecture.

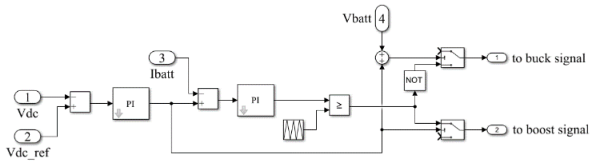

Fig. 10. BESS control modeled in Simulink

Figure 10 illustrates the input signals for the first PI voltage controller, which are the reference voltage of 800 V (V_{dcref}) and the instantaneous voltage of the DC bus (V_{dc}). The controller's output serves as the reference input for the second PI current controller, as described by

$$I_{ref} = K_{P1}\left(V_{dcref} - V_{dc}\right) + K_{I1}\int_0^t \left(V_{dcref} - V_{dc}\right)dt, \tag{8}$$

where, K_{P1} and K_{I1} are the proportional and integral gains of the first PI controller, respectively.

Both the measured battery output current and the reference current are sent to the system's second PI controller for comparison. The first PI controller generates a reference current to manage the battery's charging or discharging if the DC bus voltage deviates from the reference voltage. The battery will start to charge and store extra energy if the DC bus voltage is higher than the reference voltage, which will cause the DC bus voltage to drop to the reference value. The battery will drain to provide more power to the system when the DC bus voltage is lower than the reference voltage.

4 Energy exchange model

The PV power and load demand dictate how the system operates. The energy exchange model is based on the following guiding principles:

- Power of the PV system is mainly used to supply loads.
- The BESS discharges when the PV system is insufficient.
- The BESS is recharged with power surplus (when production exceeds loads).
- Diesel generator produces active power when the PV system and BESS are insufficient.

Comparing the PV system's power output with the load, four different modes can be obtained.

Mode 1: The PV system's power output is less than the load:

$$P_{PV}(t) < P_{Load}(t)$$

The PV power is insufficient for the load, so the BESS and diesel generators should be adopted to meet load demand. The diesel generator is sized to cover the entire consumption in the event of any outages.

Let $P_{vac}(t)$ be the vacancy between PV power and the load:

$$P_{vac}(t) = P_{Load}(t) - P_{PV}(t)$$

Mode 1.1: If the vacancy is less than the battery's maximum discharging power, $P_{dischmax}(t)$,$P_{vac}(t) \leq P(t)_{dischmax}$ battery output for discharging during period t is then equal to vacancy $P_{vac}(t)$, and the diesel generator will not be started. In this case, the discharging condition should be satisfied. The SOC of the battery should not fall below the minimum SOC:

$$SOC(t) \geq SOC_{min},$$

while reference power for inverter is calculated as

$$P_{init}(t) = P_{Load}(t).$$

Mode 1.2: If the vacancy is greater than the battery's maximum discharging power, $P_{vac}(t) > P(t)_{dischmax}$, then, the battery runs at its fastest rate of discharge. The amount of power vacancy determines the diesel generator's power output, which must be started in this case.

The reference power for inverter is calculated as:

$$P_{init}(t) = P_{PV}(t) + P(t)_{dischmax}$$

Mode 2: The PV system's power output is greater than the load:

$$P_{PV}(t) > P_{Load}(t)$$

The excess power is absorbed by the battery if the charging condition is satisfied:

$$P_{init}(t) = P_{Load}(t).$$

The SOC of the battery should not exceed the maximum SOC, which is represented by the charging condition:

$$SOC(t) \leq SOC_{max}.$$

The excess power should be abandoned by PV system working out of MPPT if the battery is unable to meet this charging condition. There is no need to turn on the diesel generators in this case.

Mode 3: The PV system's power output is equal to the load:

$$P_{PV}(t) = P_{Load}(t).$$

The load is supplied just by the PV system working in the MPPT mode. BESS and diesel generator are in standby mode in this case while active power reference of calculated as follows:

$$P_{init}(t) = P_{PV}(t).$$

These modes of energy exchange model are represented through the results in the next section. The inverter has a main role in control of energy exchange as well as in regulation of voltage and the frequency of the system.

5 Results and discussion

The isolated microgrid 10/0.4 kV is used as a test system to verify proposed control strategies. The proposed microgrid model in MATLAB/Simulink is illustrated in Fig. 6 and Fig. 7. On the DC side, it consists of the PV system and BESS, and on the AC side, the diesel generator and a 10 kW 3-phase load.

Table 1. Parameters of the PV panel [16]

Parameter	Symbol	Value
Maximum power	P_{MPP}	14.75 kW
Voltage at maximum power	V_{MPP}	249 V
Current at maximum power	I_{MPP}	59.24 A
Open circuit voltage	V_{OC}	310.83 V
Short circuit current	I_{SC}	64.24 A

Table 1 lists the typical set of settings for the PV system in operation [16]. These are acquired under the standard test conditions, which are 25 °C and 1000 W/m^2 of solar radiation. The maximum power that can be generated from the PV system is 14.75 kW. Key battery parameters are based on the BESS ability to compensate for the lack of the power when the level of produced energy from the PV system is low. The rated capacity of the battery is 30 Ah, while its nominal voltage is 400 V. The SOC of the battery is 100% at the initial point.

Table 2. Parameters of the diesel generator

Parameter	Value
Nominal power	16 kVA
Nominal voltage	400 Vrms
Nominal rotor speed	1500 rpm
Nominal frequency	50 Hz

Table 2 provides the primary characteristics of the utilized diesel generator. Nominal power and the voltage of the diesel generator are 16 kVA and 400 V, respect-tively.

The first 0.2 seconds of the simulation are devoted to the synchronous machine of the diesel generator to obtain its steady state. Then, the switch connecting AC bus and DC/AC converter is closed, so that the load can be supplied from DC bus, as well. Therefore, the analysis of the system is performed from this point.

5.1 The first scenario – PV and BESS

The first case has been analyzed for two different values of solar irradiance, 500 W/m^2 and 250 W/m^2. The temperature has been kept constant at 298 K (25 °C). Solar irradiation is 500 W/m^2 for the first 5 seconds before dropping to 250 W/m^2. This case includes Mode 1.1 from the energy exchange model. In Fig. 11, the power output of the PV system is presented for this scenario. The battery is fully charged at the beginning. The PV panel takes 0.1 seconds to reach its maximum power point, during which time the battery compensates for the lack of PV power, resulting in a 0.02% drop in SOC. In the first 5 seconds, the PV system generates only 7.29 kW, which is insufficient to meet the load demand. Consequently, the SOC of the battery starts to decrease, and the BESS acts as a backup power source. Subsequently, the power generated by the PV system decreases to 3.53 kW, and the battery discharges more, causing the decline in its SOC to intensify.

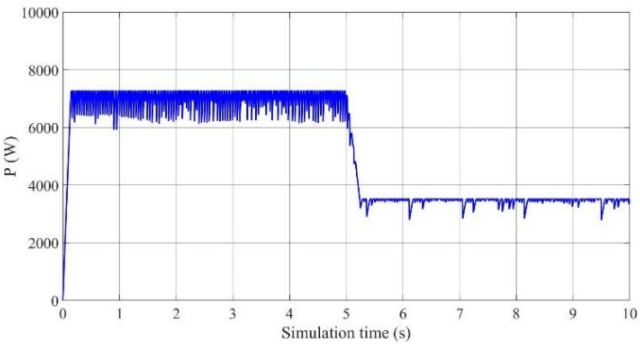

Fig. 11. The PV output power

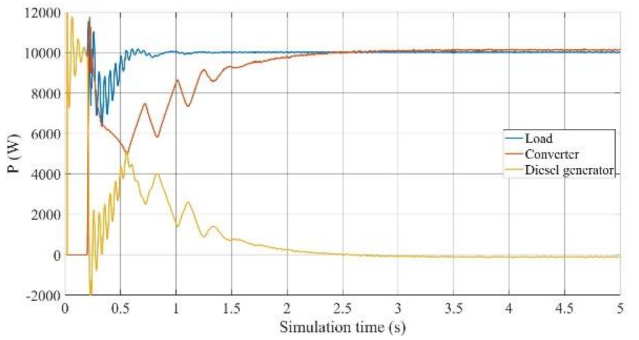

Fig. 12. Active power of the diesel generator, converter and the load in the first case

Figure 12 illustrates the output data of the converter, load, and diesel generator, where the diesel generator is not generating any active power. The results show that the PV system and BESS are capable of supplying the load.

The switch linking the AC bus and DC/AC converter closes at 0.2 seconds into the simulation, and the system enters steady state at 3 seconds, as shown in Fig. 12. The change in solar irradiation has no impact on the power of the load since BESS fills the necessary power deficit. It is maintained at 10 kW.

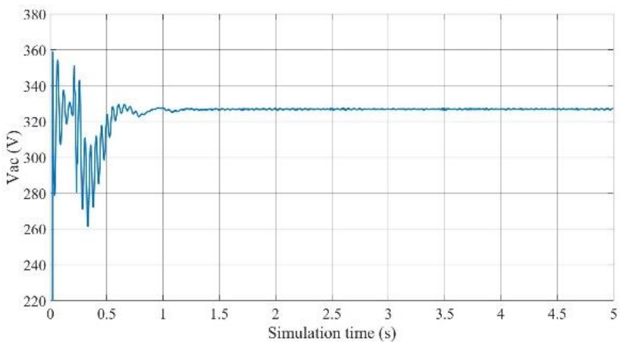

Fig. 13. AC bus voltage in the first case

The magnitude of the AC bus voltage in this case is depicted on the graph in Fig. 13. Significant deviations can be seen when the diesel generator is inserted to the system at the beginning. It requires 0.2 seconds to reach the steady state voltage. At 0.2 seconds, due to the inverter and inclusion of other components, the voltage is disturbed and afterwards regulated and kept constant at 326.7 V after the system reaches a steady state.

The frequency control of the system begins at 0.2 seconds, but during the transition period caused by the switch, the frequency is disrupted as shown in Fig. 14. The proposed control strategy regulates it back to 50 Hz and maintains it at that value throughout the simulation.

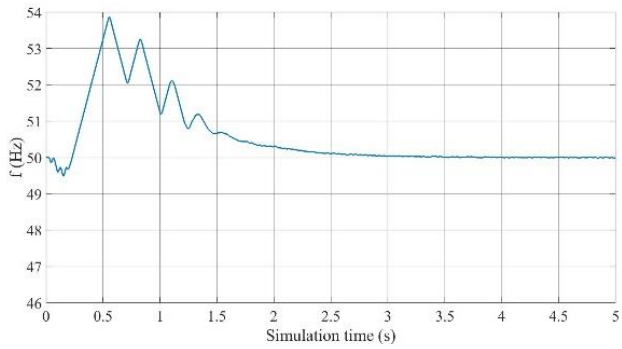

Fig. 14. Frequency of the microgrid in the first case

5.2 The second scenario – PV, BESS and diesel generator

In the second scenario, the system is evaluated when the solar irradiance is 250 W/m^2 and the battery is completely discharged. This situation necessitates the operation of the diesel generator to maintain the voltage and frequency regulation on the AC bus, as described in Mode 1.2 of the energy exchange model. In this case, step load response is presented as well. In the first 5 seconds, load demand is 10 kW. Afterwards, an additional load of 3 kW is connected to the microgrid, and again disconnected at 15 seconds.

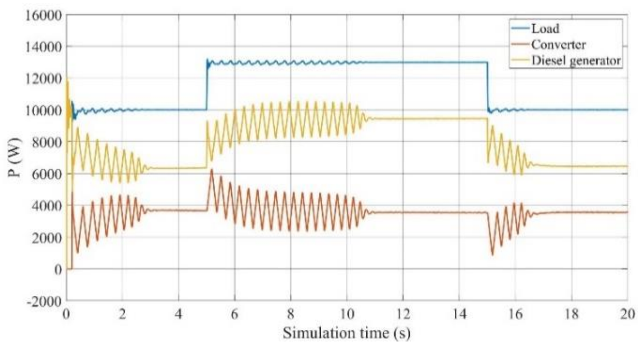

Fig. 15. Active power of the diesel generator, converter and the load in the second case

The ability of the microgrid to handle changes in the load demand efficiently is an important aspect of its performance. This is demonstrated in the stability of the load power output as seen in Fig. 15. However, it is worth noting that the system may require more time to reach a steady state when additional load is connected compared to the time required when only a 10 kW load is present. This is due to the additional power demand placed on the system, which may take some time for the diesel generator and other components to adjust to and stabilize. It is important to take this into account when designing and operating a microgrid, especially in scenarios where the load demand may vary significantly over time.

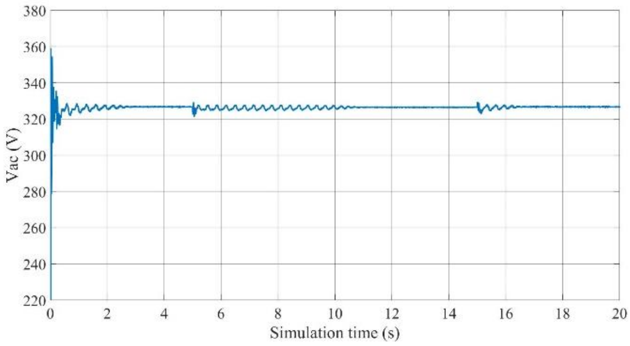

Fig. 16. AC bus voltage for the second case

Figure 16 illustrates the voltage of the AC bus provided by the microgrid. After the closure of the switch, at 0.2 seconds, there are no significant deviations in AC bus voltage, voltage deviations are kept within allowed limits. During transition times, its value remains unchanged.

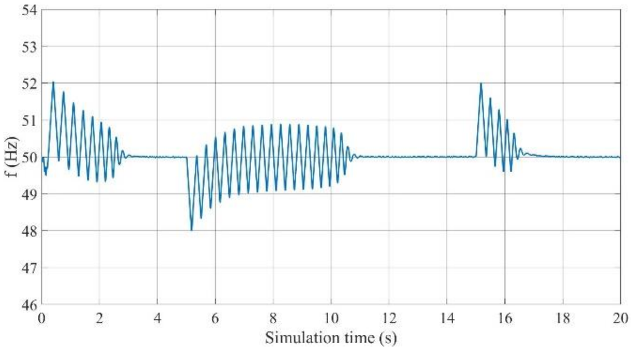

Fig. 17. Frequency of the microgrid in the second case

Figure 17 depicts the microgrid's frequency response for the second scenario. Smooth frequency response is achieved by the application of droop control. It has been controlled and maintained at 50 Hz throughout the simulation.

5.3 Effect of frequency support

To evaluate the effectiveness and efficiency of the proposed frequency support method, various scenarios were established. The first 15 seconds of the simulation involved solely the diesel generator as the source of power for the load, with the generator responsible for regulating the voltage and frequency. At the 15-second mark, the switch that connects the AC bus and DC/AC converter was closed, enabling the load to be supplied from both the DC bus and AC bus, thus activating the frequency support. The load was changed every 5 seconds during this time interval, with a load of 5 kW for the first 5 seconds, an additional load of 3 kW being turned on at 5 seconds, then turned off at 10 seconds. At 20 seconds, the additional load of 3 kW was turned on again, and at 25 seconds, it was turned off. Figure 18 illustrates the active power of the load, diesel generator, and converter for this particular scenario.

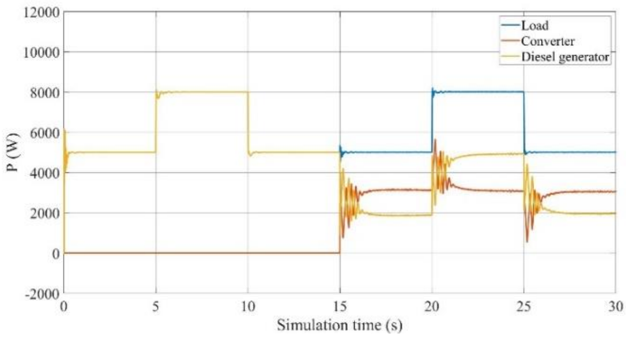

Fig. 18. Active power of the diesel generator, converter and load for the frequency support analysis

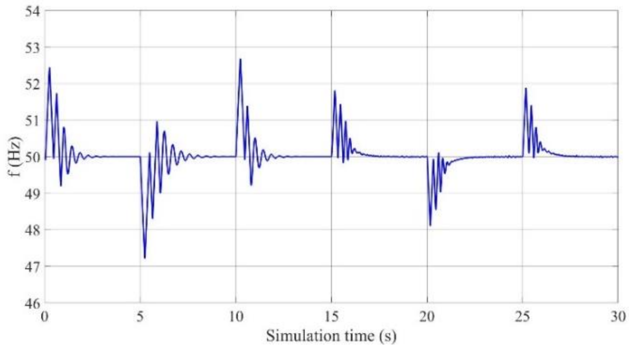

Fig. 19. Frequency of the microgrid for the frequency support analysis

In this scenario, Figure 19 illustrates the frequency response of the microgrid. The simulation maintains a frequency of 50 Hz throughout. It is worth noting that the maximum frequency deviation during the simulation is smaller when frequency support is enabled, as opposed to the situation where the frequency is solely regulated by the diesel generator.

The results presented demonstrate that the proposed microgrid system can operate effectively and maintain stability under varying operating conditions. The supply of the load demand is not compromised by changes in environmental conditions, as the BESS and diesel generator are capable of compensating for any potential power deficit. Additionally, there are no fluctuations in voltage or frequency, as the microgrid is controlled to remain at its nominal values.

6 Conclusion

The aim of this research was to examine the regulation of voltage and frequency in a hybrid microgrid system comprising a PV generator, BESS, and diesel generator. For this purpose, a test system was employed, and an FLC-based MPPT algorithm was utilized to operate the PV generator in MPP mode. The proposed strategy has been confirmed and verified through simulations, and the results obtained are similar to the results found in the literature. Through the application of two distinct scenarios, the efficacy of the suggested approach was confirmed: one where the DC side of the system primarily supplied the load and the other where the load was provided from both the AC and DC sides.

Both case studies utilized frequency droop control to support regulation of the microgrid's frequency during transients, and the results indicated that the load voltage and frequency were consistently maintained, despite variations in power input. By implementing the proposed approach, the PV system, BESS, and diesel generator could operate simultaneously, which contributed to the stability of the microgrid's voltage and frequency. This concurrent operation is vital for the proper functioning of a microgrid, as it offers various benefits. Firstly, it allows for optimal utilization of all available resources, which can lead to reduced operating costs. Secondly, it can improve the microgrid's overall reliability and stability by providing backup power when necessary.

The future research direction of this study involves developing and evaluating control algorithms that utilize different computational intelligence techniques. This will enable a more comprehensive analysis of the microgrid's performance under varying operating conditions, leading to the development of more robust and efficient control strategies.

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