Active Power Management in a Low-voltage Islanded Microgrid

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Abstract

The growing electricity demand and scarcity of energy sources are the driving force of exploration of the renewable energy sources. However, uncertain energy production of these sources makes difficulties in their control and operation with or without a grid utility connection. This paper proposes a novel power control strategy which employs a voltage band in the DC-link voltage to maintain voltage stability and thereby improve the power quality during temporary disturbances in a network. It is applied to act as an inverter's inertia and obtain maximum benefit from the storage system, based on the features of a DC busbar to avoid a voltage limit violation. It also presents a demand dispatch strategy based on a client's terminal voltage, which avoids the complexity of communication lines, for balancing the network power during power shortages. The developed control algorithm is tested on an IEEE 16 bus test feeder with multiple DG units and from the results it is found that the proposed control methods provide effective control of the voltage and power quality during transient conditions and scarce power generation.

Keywords: DC-link energy, islanded microgrid, balanced power, stable voltage, voltage-band.

1. Introduction

Due to increased concern about energy crisis and environmental issues, the power industry is shifting their power production from conventional power sources to re-

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newable energy sources (RESs). The power industry is incorporating RESs into the
5 grid utility in the form of distributed generations (DGs). The application of DGs
can enhance reliability and stability of the local network, and can reach benefits
to the suppliers by reducing system losses and investment on a new transmission
line due to increased power consumption [1, 2, 3]. Power generation in the form of
DGs for local and grid utility can create issues as many as it may solve. There-
10 fore, a microgrid concept is evolved to coordinate among sources, loads, and energy
storage devices for maintaining a distribution network stability [4, 5]. A microgrid
can be considered as a controlled small-scale power network's system, consisting of
small-scale emerging generators, loads, energy storage elements, and control units,
built within a defined area for maintaining system stability, reliability, and facili-
15 tating improved power quality to the consumer's premises [6]. During autonomous
operation, microgrid elements, such as voltage source converters (VSCs), are princi-
pally responsible for providing voltage and frequency set points within a distribution
network.

In a microgrid, small-scale emerging generators such as wind, solar, fuel cell,
20 and small-scale gas turbine, are installed in proximity to the load side, and use
inverters as interface devices to inject active and reactive power into the network
[7, 8]. Inverters are able to supply controlled voltage and frequency depending on
the control algorithms [9]. The characteristics of inverters are significantly different
from the conventional generators; therefore, specific control algorithms are required
25 for a stable microgrid operation [10, 11, 12, 13].

There are several literatures that propose droop-based control for facilitating high
reliability and avoiding the complexity of communication lines [14, 15, 16, 17]. Droop
control is popular due to its capability to coordinate various power rating units as
well as being flexible and reliable, and is valid for both high-voltage (HV) transmis-
30 sion lines and low-voltage (LV) distribution ones. In an LV distribution network, the
well-known active power/frequency (P/f) droop control requires much more effort
than the active power/voltage (P/V) one because a predominantly resistive network
naturally connects active power to the grid voltage [18, 19, 20, 21, 22, 23]. For this
reason, to control the voltage magnitude and network frequency in an LV microgrid,

35 both P/V and reactive power/frequency (Q/f) droop controls are adopted.

As the application of control algorithms in stead of the straightforward employment of droop control in a microgrid needs to be reviewed due to the increasing penetration of intermittent RESs, considering the renewable energy features mentioned in [23], voltage-based droop (VBD) control is proposed. Such a control approach integrates intermittent RESs rather than dispatchable energy sources by applying
40 delays in the power change points. In it, although the terminal voltage is changed proportionally to variations in the power demand, a terminal voltage deviation is not expected from a consumer perspective. Moreover, the active power control in [23] is postponed up to a certain limit of the terminal voltage considering the features of
45 RESs. However, recently, RESs have been using energy storage elements [24], such as batteries, that can deliver power, as a dispatchable generator, into the network during a power mismanagement. Therefore, the VBD method needs to be modified for application in microgrids.

This paper proposes a control algorithm for minimising changes in consumers
50 terminal voltage while facilitating steady-state power consumption during any small transient event. This strategy enables any unpredictable supply and demand to be balanced within tolerable DC-link voltages (V_{dc}) considering random power/load fluctuations. The proposed control strategy enables balancing unpredictable supply and demand within tolerable DC-link voltage (V_{dc}).

55 To control the power supply and demand in a network, generally, the central energy management system (EMS) [25, 26, 27, 28, 29] needs to access each DG and load point for power measurements through communication lines. The design and modelling of these communication lines can be found in [30, 31]. The communication modules create a complicated network. This is because, if any DG or load point
60 is out of the communication range, the EMS may produce an unexpected signal sufficient to incur an unusual situation. Therefore, using communication lines as a primary control strategy reduces the reliability of a microgrid [32]. However, it is always desirable to use the communication links for an optimal decision process in a tertiary control layer considering the electricity market and fuel cost [33].

65 The influence due to malfunctioning communication on demand response is anal-

ysed, and an optimal resource allocation scheme depending on features of the both power demand and monitoring data transmissions is proposed to minimise the influence in [34]. In [35], an adaptive dynamic model is proposed to regulate voltage based on demand response strategy for reducing voltage fluctuation at customer
70 premises in an LV distribution feeder. To prevent voltage and current limit violation in a distribution network considering fair consumer participation, a proactive centralised control for one hour ahead load and a reactive decentralised control for regulating consumption are presented in [36]. However, in the existing literatures, the concept of primary centralised load control for microgrids without communica-
75 tion is not found.

To improve the reliability of a microgrid, this paper also presents a demand-side management system without communication lines that depend on the terminal voltage of a consumer's premises which assists in providing greater microgrid reliability along with a secondary controller.

80 The major contributions of this paper are summarised as follows.

- (1) A voltage band, which acts as inertia for an inverter's DC-link voltage controller to exploit the stored energy during disturbances and thereby minimise network voltage variations, is proposed. As it improves the quality of the network's voltage, the power quality of a microgrid is enhanced.
- 85 (2) A voltage controller of an inverter, avoiding cascaded PI controller tuning while minimising the cost function of the system, is designed to track the instantaneous reference grid voltage with nullifying steady state error during disturbances. The application of the proposed voltage controller in a natural (abc) frame avoids the complexity of the Clarke and Park transformation.
- 90 (3) A novel and simple demand-side management system based on the terminal voltages of end-users without communication lines is presented. The proposed strategy uses relay-based load curtailment at the connection points of controlled loads in the case of a power deficiency of DG units in a microgrid.

The rest of this paper is structured as follows. In Section 2, an overall control
95 approach for inverters in a microgrid configuration is briefly discussed. Section 3

control algorithms while the source power is changed according to terminal voltage variations using a proportional controller. To attenuate the converted ripple waves, an LC filter is introduced after the VSI, and a capacitor applied at the DC busbar prevents the transient effect with the help of its energy. The dashed line block represents a virtual resistance loop that can be applied to the control loops for decoupling the powers and preventing oscillation, which may appear due to relatively low resistance in line for multiple DG units. A simple microgrid consists of a power source connected to branches of resistive loads with unpredictable levels of participation in a distribution network.

3. Control Methods

The VBD control algorithm enables inverters to control the power flow in a network while considering the characteristics of RESs without the help of the grid utility. The algorithms presented in this paper are extended work of authors' own in [37] and versions of that proposed in [23] modified in two main steps by: (1) using an LQI, instead of linear quadratic regulator (LQR), method for tracking the instantaneous reference grid voltage as it demonstrates better performance for eliminating the steady-state error produced by disturbances in a system; and (2) proposing a voltage band in the DC-link voltage control to optimally exploit the DC busbar's energy. The authors' work is extended by applying the control method in multi-machine microgrid system and proposing a demand-side management without communication lines.

3.1. DC-link voltage control

The relationship between the active power demand and DC-link voltage of an inverter is important for controlling the inverter's power supply in a microgrid. Variations in power demand alter the DC-link voltage (V_{dc}) which can be used as an indicator of the power status in an inverter-connected generator. It is an analogous parameter of the conventional rotating machine, the frequency of which is used as a feedback signal to control the active power.

Therefore, as this grid voltage/DC-link voltage (V_g/V_{dc}) control strategy is applied to control the terminal voltage, the power mismatch information available in

the V_{dc} changes the reference grid's voltage magnitude (V_g^*) to balance the power supply and demand through the P_{dc}/V_g control strategy shown in Figure 1. The V_g/V_{dc} control method is expressed by:

$$V_g^* = V_g^\circ + K_v(V_{dc} - V_{dc}^\circ) \quad (1)$$

where K_v is a positive droop constant, and V_g° and V_{dc}° the set values of the grid and DC-link voltages, respectively. Generally, the value of K_v can be determined from the formula $\frac{\Delta V_g}{\Delta V_{dc}}$, where ΔV_g is the grid voltage deviation and ΔV_{dc} is the DC-link voltage deviation. The droop control in (1) is modified by introducing a voltage-band, b Volt wide, as shown in Figures 2a and 3. This width depends on the characteristics of generation sources, converter topologies, DC busbar, and types of microgrids. For instance, it can be large for getting a wider maximum power point tracking (MPPT) range of solar generators. In this way, a better performance can be achieved for photovoltaic (PV) power. On the other hand, it can be set small to maintain high power quality, such as a hospital, for operating sophisticated equipment used in a microgrid. Moreover, the width of the constant voltage-band can be adjusted in order to meet the specification of a particular microgrid for fully exploiting generation control abilities and avoid frequent voltage changes.

The reference grid voltage of VSIs is set as:

$$V_g^* = \begin{cases} V_g^\circ + K_v\{V_{dc} - (V_{dc}^\circ + b)\} & \text{if } V_{dc} > V_{dc}^\circ + b \\ V_g^\circ + K_v\{V_{dc} - (V_{dc}^\circ - b)\} & \text{if } V_{dc} < V_{dc}^\circ - b \\ V_g^\circ & \text{if } V_{dc}^\circ - b \leq V_{dc} \leq V_{dc}^\circ + b. \end{cases} \quad (2)$$

It can be seen in Eq. (2) that the reference voltage is constant at its previous set value in the voltage band (b) V wide and that, changing the V_{dc} values also changes those of the V_g^* after a certain voltage range which assists in altering the power delivery to the network using the P_{dc}/V_g droop control.

3.2. Active power control

The voltage limit may be violated by employing only the V_g/V_{dc} droop control because the power flow cannot be completely controlled [23]. Therefore, a power

Figure 2: Graphical representations of (a) V_g/V_{dc} droop control and (b) P_{dc}/V_g droop control.

Figure 3: Proposed voltage-band in DC-link voltage control.

control approach based on the relationship between the source power (P_{dc}) and DG terminal voltage (V_g) is developed to supply power during voltage limit violations (Figure 2b). The supply from a DC power source (P_{dc}) can be changed in several ways to control the terminal voltage: decreased by charging the battery, shifting the MPPT points for renewable sources or using a dumping load; and increased by discharging the battery or increasing the power generation for dispatchable sources. In this power control strategy, P_{dc} can be expressed by:

$$P_{dc} = P_{dc}^o + K_p(V_g - V_g^o) \quad (3)$$

where K_p is a negative droop constant, P_{dc} depends on the terminal grid voltage and P_{dc}^o indicates the set value of a generator synthesised according to the optimisation process of a management system.

Figure 4: Combination of V_g/V_{dc} and P_{dc}/V_g droop controls.

3.3. Combined control approach

Applying both controllers (DC-link and power) can be more effective than using only the DC-link voltage controller which can violate the voltage limit in a network and create problems for controlling the power injection. The inter-relationships among the DC voltage, grid voltage and generator power are shown in Figure 4 by bringing two different figures on the same plane of x-y axis for improved clarity. It can be seen that the decreasing V_{dc} after the voltage band is supported by the increasing DG power supply and vice versa. In this approach, the power control strategy (P_{dc}/V_g) is not activated in the balanced condition of a network although it works during a power mismatch between supply and demand. It is clear that the DC-link energy supports energy balance in a network during disturbances without severely affecting the grid voltage and maintaining it within the acceptable bandwidth range much like a mechanical inertia in the flat interval region due to the existence of the DC-link capacitor. This inertia is analogous to the inertia of a large rotating machine that assists in enhancing system stability by minimising dynamic/transient effects. Therefore, this voltage band improves the voltage profile and power quality by reducing voltage variations and exploiting the DC-link energy.

3.4. Reactive power control

The power control of an LV microgrid with multiple generators is not possible by using a simple active power control algorithm as it is regulated by the network's frequency. Therefore, frequency control is an important part of a microgrid's control during a large penetration of DG units to prevent large circulating reactive currents flowing among these units. In a low-impedance line, if Q/V droop control is applied without a special control approach, DG units can derive reactive circulating currents that lead to reactive power flows among them in a microgrid. Therefore, for the integration of multiple generators, a Q/f control algorithm is proposed as:

$$\omega = \omega^\circ + K_q(Q - Q^\circ) \quad (4)$$

where K_q is a positive slope index, Q° the set value of the reactive power and the index “ $\circ$ ” a predefined set value. With the increasing participation of inductive loads in a network, the frequencies of connected DG units will also increase owing to a positive K_q value.

3.5. Voltage controller design

To control the grid voltage, an LQI, which minimises the cost function of the system, is employed to satisfy the fast dynamic response and abolish the steady-state voltage error between the instantaneous grid voltage (v_g) and instantaneous reference grid voltage (v_g^*) during load changes, with its integral term reducing errors between the command and desired signals. It demonstrates excellent performances in terms of changing the LC filter's parameters, noise-affected measured signals and sudden load changes. The primary reason for proposing this method is to easily determine the optimal gains that provide effective tracking with an almost zero steady-state error. The V_g^* is determined using the V_g/V_{dc} droop control strategy, and the design process of the voltage controller is described below.

The modulation index/input of the PWM, which generates duty ratio of the VSI, is calculated by the LQI voltage controller to track the reference grid voltage.

The state-space model for the considered system can be expressed as:

$$\begin{bmatrix} \dot{v}_g \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} v_g \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ 1/L \end{bmatrix} [v_{sw}] + \begin{bmatrix} -1/C \\ 0 \end{bmatrix} [i_g] \quad (5)$$

where i_L and $v_{sw} = \delta V_{dc}$ are the instantaneous inductor current and the mean switching voltage over a PWM period, respectively. Here, δ = duty ratio, whose value varies in between $-1 \leq \delta \leq 1$. In this model, grid current (i_g) variation is treated as a disturbance.

For the grid voltage control, v_g is taken as an output parameter:

$$\begin{bmatrix} v_g \end{bmatrix} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} v_g \\ i_L \end{bmatrix}. \quad (6)$$

The general form of the state space Eqs. (5) and (6) is given below:

$$\dot{x} = Ax + Bu \quad (7)$$

$$y = Cx + Du \quad (8)$$

where

$$x = \begin{bmatrix} v_g \\ i_L \end{bmatrix}; \quad u = [v_{sw}]; \quad A = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix}; \quad B = \begin{bmatrix} 0 \\ 1/L \end{bmatrix}; \quad C = [1 \quad 0]; \quad \text{and} \quad D = [0].$$

The disturbance term, i_g , is not included in Eq. (7) because its effect is negligible in voltage control, and the system can be controlled considering v_g and i_L as state vector.

The input vector of the microgrid system considering the integral action of the controller can be computed using the following formula:

$$u' = -Kx + K_i \int_0^\infty (v_g^* - v_g) dt \quad (9)$$

where K_i is the integral gain used to minimise the error between v_g^* and v_g ; K is the gain obtained using the LQR optimisation method.

The error term requires a definition for solving the integral gain, K_i , value:

$$e = \int_0^\infty (v_g^* - v_g) dt. \quad (10)$$

Differentiating Eq. (10) and substituting the value of $v_g = Cx$; the above equation can be written:

$$\dot{e} = v_g^* - Cx. \quad (11)$$

Rewriting the control law:

$$u' = -Kx + K_i e. \quad (12)$$

Further reducing to

$$u' = -K'x' \quad (13)$$

where $K' = [K \quad -K_i]$; and $x' = [x \quad e]$.

The modified state space equations can be written as:

$$\dot{x} = A'x' + B'u' \quad (14)$$

$$y = C'x' \quad (15)$$

where $A' = [A \quad 0; -C \quad 0]$; $B' = [B; 0]$; and $C' = [C \quad 0]$.

The solution of K' in Eq. (13) should converses the error produced by disturbances to zero, provided there are a stable system and minimisation of the cost function:

$$J' = \int_0^\infty (x'^T Q x' + u'^T R u' + 2x'^T N u') dt. \quad (16)$$

where Q and R are the state and input control weighting cost square symmetric matrices, respectively. The matrices are selected by the designer depending on the relatively importance of parameters for practical control issues. Here, $Q - NR^{-1}N^T \geq 0$, and $R > 0$.

In order to obtain a better performance, Q and R are synthesised in a value that satisfies the controller's requirement. After determining these two values, the matrix S can be determined by solving modified algebraic Riccati-equation:

$$A'^T S + S A' - (S B' + N) R^{-1} (B'^T S + N^T) + Q = 0. \quad (17)$$

The optimal state feedback gain matrix K' can be determined by:

$$K' = R^{-1} (B'^T S + N^T). \quad (18)$$

where S is the solution of the algebraic Riccati-equation and $N = 0$. The solution of K' converse the error to zero provided the stable system and minimisation of the

Figure 5: Simulation diagram for small microgrid system.

4. Case Study using a Small Microgrid System

A power source connected to a resistive network is studied first to understand the performance of the proposed controller and its advantages compared with those of the VBD controller. A lossless line ($R_l = 0 \Omega$) is used to determine the relationship between load power (P_L) and V_{dc} , with only resistive loads connected to the terminal. The DC-link capacitor value is 1.5 mF, the predefined capacitor voltage $V_{dc} = 400$ V, the carrier frequency of PWM 8 kHz, the sampling frequency 10 kHz, the value of K_v equals 0.085, the reference grid voltage for controlling the inverter 50 Hz 220 V (rms) and the filter parameters $L = 2$ mH and $C = 12$ μ F.

4.1. Performance of proposed controller

The proposed controller is employed in the VSI connected to the resistive loads illustrated in Figure 5. The DC-link voltage band is taken as 5% of the DC-link voltage to supply and/or absorb the additional and/or reduced demand in the network [38]. In the proposed control algorithm, terminal voltage variations using the DC busbar's energy are kept to as low as possible to ensure network power quality as consumers do not expect voltage variations when a generated power increases or decreases. Although the V_{dc} provides demand information directly to the network, it is not incorporated directly in the power set-point due to information missing for the autonomous load curtailment that occurs during lower than required power generation. To receive the information for load curtailment on the demand side,

Figure 6: Active power supply in network and responses of electrical quantities.

the DC-link voltage is connected to the grid voltage which is linked to the power set-point.

The purpose of this simulation is to demonstrate how dc-link voltage is related to the power generation unit (P_G). To observe the phenomenon during input power changes, a constant resistive load of 2.0 kW and variable input power supply are taken into account in the load and input sides, respectively. Input power increases and decreases according to the following limits.

$$P_G = \begin{cases} 2.0 \text{ kW} & \text{if } t < 1.0 \text{ s} \\ 2.1 \text{ kW} & \text{if } 1.0 \text{ s} < t < 2.0 \text{ s} \\ 2.2 \text{ kW} & \text{if } 2.0 \text{ s} < t < 3.0 \text{ s} \\ 1.9 \text{ kW} & \text{if } 3.0 \text{ s} < t < 4.0 \text{ s} \end{cases}$$

In this simulation, a power load (P_L) with 50 Hz 220 V (rms) and nominal DC-link voltage (V_{dc}) are considered equal to 2.0 kW and 400 V, respectively. In Figures 6a

235 and 6b, it is observed that the power supply and power demand are similar (2.0 kW) upto 1.0 s, but DC-link voltage reduces. The reasons for declining DC-link voltage are energy conversion losses which are beyond the scope of this paper. The increased power generation (2.1 kW) at $t = 1.0$ s, which is higher than the power consumption (2.0 kW) in the load, is balanced by the DC-link energy during the first 0.5 s interval
 240 and causes the V_{dc} rises to approximate 440 V at $t=1.5$ s. Although the power consumption load is assumed 2.0 kW with 50 Hz 220 V, the power dissipation is not constant due to augmented or reduced voltage supply, which is shown in Figure 6c and related to the DC-link voltage, by the source.

When the power production increases further to 2.2 kW, the DC-link voltage again increases to around 460 V indicating a clear relationship between the power generation and DC-link voltage. At $t=3.0$ s, the generated power decreases to 1.9 kW, i.e., $2.0 \text{ kW} - 1.9 \text{ kW} = 0.1 \text{ kW}$ power is shortage compared to the power consumption at load. This lack of power supply is temporarily met by the DC-link energy stored previously, as shown in Figure 6b. When the V_{dc} reaches the minimum and/or maximum limit, the proposed DC-link controller decreases and/or increases the grid voltage to maintain stability in the network while keeping the V_{dc} within limits. In the interval between 3.4 s and 4.0 s, the power drawn by the load is supposed to be 2.0 kW but, in fact, is less than 2.0 kW. This is because, as the V_{dc} reaches the minimum voltage limit, it causes a decreased grid voltage and, consequently, reduced power is consumed by the loads. The energy stored in the capacitor can be expressed in terms of the capacitor's voltage as:

$$E_{dc} = \frac{1}{2} C_{dc} V_{dc}^2. \quad (19)$$

The energy can be related to the power by:

$$E_{dc} = \int_0^t P_{dc} dt. \quad (20)$$

Substituting Eq. (20) into Eq. (19) and assuming a constant power supply, the mathematical relationship between the V_{dc} and P_{dc} can be derived as:

$$V_{dc} = \sqrt{\frac{2P_{dc}t}{C_{dc}}}. \quad (21)$$

The theoretical DC-link voltage (V_{dc}) for the decreased power can be evaluated using
 245 Eq. (21). It is worth noting that the V_{dc} is directly proportional to the square root
 of the time, that is, the voltage falls in a non-linear manner with time. Therefore,
 small amounts of increased/decreased power in the DC busbar for longer periods
 can lead to violations of the maximum/minimum predefined DC-link voltages.

It is observed in Figure 6d that the instantaneous reference grid voltage is per-
 250 fectly tracked by the grid voltage and controlled by the LQI control method shown
 in Figure 1. It is also observed in Figure 6b that the V_{dc} frequency is 100 Hz because
 of the effect of the capacitor charging and discharging with the full bridge inverter.

This simulation is conducted with the application of the proposed controller
 for an inverter with a voltage controller, by implementing the LQI method and
 255 considering a constant power consumption load and fixed reference grid frequency.
 A high power generation causes an increased DC-link voltage until it reaches a
 certain band limit to absorb the extra power. On the other hand, the V_{dc} starts
 to decrease for low power production at generator side. As it can be concluded
 from Figure 6 that the network power can be predicted by monitoring the DC-link
 260 voltage, the DC-link voltage-based controller proposed in this paper observes the
 network status up to a certain voltage and then the droop-based controller takes the
 necessary action depending on the V_{dc} . It is noticed that the proposed controller
 takes full advantage of the capacitor's energy during an extra and/or insufficient
 power supply with minimum voltage deviations and, thus, improves the stability of
 265 the network.

4.2. Comparative study

In the last simulation of a simple microgrid, the proposed control strategy is
 compared with the VBD control approach shown in Figure 7. Power generation of
 the input source and consumer resistive loads vary according to the following limits.

$$P_G = \begin{cases} 2.0 \text{ kW} & \text{if } t < 1.0 \text{ s} \\ 2.2 \text{ kW} & \text{if } t > 1.0 \text{ s} \end{cases}$$

(a) P_L

(b) V_g

(c) V_{dc}

(d) f

Figure 7: Proposed controller performance with respect to VBD control.

and

$$P_L = \begin{cases} 2.0 \text{ kW} & \text{if } t < 2.0 \text{ s} \\ 2.3 \text{ kW} & \text{if } 2.0 \text{ s} < t < 3.0 \text{ s} \\ 2.0 \text{ kW} & \text{if } t > 3.0 \text{ s} \end{cases}$$

As it is shown that voltage variations are comparatively lower under the proposed controller's algorithm than that of the VBD controller, the power supply to the loads depicted in Figure 7 is justified. Note that the power demands in the network for 2.0 kW do not match exactly because, as the voltage supply in the network increases, a specific load's consumption is more, than its power rating. The power consumption and grid voltage relationship can be established by:

$$P_L = \frac{V_g^2}{R_t} \quad (22)$$

where R_t = total resistance and V_g = terminal grid voltage.

As, for a specific power and voltage rating, the resistance is constant, any change in the grid voltage is proportional to the square root of the power demand. As the voltage deviates from its nominal level of 220 V, the corresponding power consumption in the load also deviates from its rated value; for example, a 2.0 kW consumption load's power rating for a nominal voltage of 220 V provides a 24.2Ω resistance. If the voltage increases to 222.5 V, by applying Equation (22), the power consumption also increases to 2.04 kW for the 2.5 V surplus voltage depicted in Figure 7a between 1 and 2 s. Accordingly, the other power ratings increase/decrease based on the terminal voltage across a load.

In the proposed control strategy, the terminal voltage is used as an information source for balancing the power with minimum voltage deviations from the nominal voltage. Since this strategy uses the capacitor's energy, it provides negligible voltage fluctuations during the turning on/off of the load unless the V_{dc} touches the boundary. The principal advantage of this proposed control strategy is that it prevents a sudden network voltage change during the turning on of a dynamic load such as a motor which is a problem encountered by the VBD controller, as shown in Figure 7b. Generally, turning on a motor takes 3 to 12 times more current than running it and, in such a condition, the VBD controller has a direct effect on the

Figure 8: Simulation schemes for (a) generators and load arrangement, and (b) load participation schedule for controlled and uncontrolled loads.

network voltage whereas the proposed controller resolves this issue. It is concluded that the proposed controller introduces less variation into the terminal voltage with respect to load changes using a voltage band in the DC-link controller, as illustrated in Figures 7b and 7c. Also, the frequency experiences no major change in the connecting/disconnecting load for a constant frequency set-point, as shown in Fig. 7d.

5. Microgrid with Multiple Generators

This section discusses the proposed control strategy used to control multiple DG units and manage the demand dispatch during a power scarcity in a network by implementing a relay operating function at the terminals of the controlled loads.

5.1. Balanced power generation

This simulation considers a realistic microgrid in which two power generators, a dispatchable/gas generator and renewable source, supply power to both critical loads (a hospital and paper industry) and non-critical ones (a lighting load, heating system in a house, boilers and an energy storage system), as shown in Figure 8a. DG-1 is arranged with a dispatchable power supply control strategy, the nominal power set-point of which equals 2.0 kW. Generally, as this set-point is selected by the supervisory control system based on the network's scheduled power, e.g., its load

prediction, it changes over time. The P_{dc} depends greatly on the unit's capacity to obtain its optimum operating point. A renewable energy source, such as solar, and energy storage features, which are assumed to supply 0.8 kW of constant power, are adopted for DG-2 to inject power into the network. As solar power generation varies during a day, its assumed characteristics are varied similar to those of a 24 h day (with a shortened time scale in this simulation), and the DG-2's power production limits given as

$$P_{G2} = \begin{cases} 0.8 \text{ kW} & \text{if } t < 1.0 \text{ s} \\ 1.0 \text{ kW} & \text{if } 1.0 \text{ s} < t < 2.0 \text{ s} \\ 1.2 \text{ kW} & \text{if } 2.0 \text{ s} < t < 3.0 \text{ s} \\ 1.0 \text{ kW} & \text{if } 3.0 \text{ s} < t < 4.0 \text{ s} \\ 0.8 \text{ kW} & \text{if } 4.0 \text{ s} < t < 4.5 \text{ s}. \end{cases}$$

Note that the term “distributed generator (DG)” indicates an inverter and DG power generation its input values.

This simulation uses two types of network loads: (1) uncontrolled; and (2) controlled. In the former, such as a hospital, the constant power supply with uninterrupted delivery required to prevent huge losses. Considering the particular features of an uncontrolled load, its pattern is shown in Figure 8b. In a controlled load, such as lighting in houses, the power supply can be disrupted for a short time during deficit power generation. This situation may happen due to unavailable renewable resources, e.g., less power production under cloudy skies and less wind velocity for solar and wind generators, respectively. The controlled load pattern shown in Figure 8b is adopted from a general residential power consumption rate. The different line resistances ($R_{L1}=0.3 \Omega$, $R_{L2}=0.5 \Omega$ and $R_{L3}=0.2 \Omega$) are chosen for this simulation as they depend on the DGs' installation and load distances. Generally, a generator's capacity is selected to meet the power demand and its variations, an assumption discussed in this section.

The objective of this study is to demonstrate how, by applying the proposed controller, the two sources can meet the power demand of both controlled and uncontrolled loads in a network. The excess and deficit power information can be

(a) P_L

(b) V_g

(c) Q

(d) f

Figure 9: Balanced power generation: participation of controlled and uncontrolled loads in network.

Figure 10: Relay implementation scheme in distribution network.

315 predicted from the terminal voltage depicted in Figure 9b and the starting transient of electrical quantities for the DG units seen within 0.5 s in Figure 9. From time $t=0$ s to $t=1$ s, DGs-1 and -2 deliver powers of 1.8 kW and 0.73 kW which deviate from 2 kW and 0.8 kW, respectively, to balance the 2.5 kW power demand. The corresponding increased grid voltages which indicate the excess power generation are
 320 also observed in Figure 9b. The absence of a reactive load component can clearly be understood from the reactive power and frequency status in Figures 9c and 9d, respectively, that validate the effectiveness of the Q/f droop controller.

In the next 0.5 s interval, DG-2 supplies 0.95 kW and DG-1 1.86 kW of power for the total load of 2.8 kW. It is worth noting that DG-2's power participation is
 325 3 % higher than that of DG-1, i.e., it depends on the source's availability. In this interval, the lower than previous grid voltage value indicates load participation in the network. The increased power supply of 1.1 kW from DG-2 is delivered using the DC-link energy between 1.5 s and 2 s. As the DC-link voltage of DG-2 touches the boundary, the grid voltage reduces and, thus, the DG-2 power supply also decreases
 330 in the (1.8 to 2 s) time slot, as shown in Figure 9a. It is observed that DG-2 provides a stable voltage between $t=2$ and 3 s due to the capacitor's energy. Therefore, it can be concluded that using an energy storage system in the DC busbar can ensure a stable voltage supply to customer premises. In practice, the power generator's

capacity is sufficiently large to prevent any fluctuation in the grid voltage due to
335 the small power demand changes in the network. As the capacitor stores energy on
a temporary basis, instead of using only its own energy, if battery energy is added,
stable voltage in customers premises can be ensured.

In summary, during the availability of renewable sources, the increased power
supplied by DG-2 using the proposed control strategy can be properly used while
340 an energy storage element is responsible for providing stable voltage in the network.
Moreover, it is shown that the proper selection of the generator's capacity can pro-
vide uninterrupted power for both controlled and uncontrolled loads, and ensure
stable voltage profiles at customer terminals.

5.2. Decreasing power generation

345 Traditionally, load curtailments for demand management are performed based on
the global frequency response, which requires communication lines for monitoring
frequency status and controlling loads. This process is unlike the voltage-based
demand side management performed by a relay function at the specific nodes of
the load points. In this study, we propose the idea of a priority list for central
350 coordination of the entire microgrid as a primary load shedding shown in Figure 10.
The priority can be enlisted according to the load distance from the supply points,
types of loads, the status of a customer and economic contributions to the society,
cost for loss of service and other factors. This list will be used to select the load
curtailment voltage profile of customer nodes. For example, if a customer is given
355 the least priority, then the first load curtailment will be imposed while voltage just
crosses 217 V limit for 220 V nominal value. However, for the top priority customer,
the voltage profile of the relay function will be selected at 209 V assuming 5%
variation. In this way, a primary load curtailment can be performed centrally and
the sole dependence on a centralised loop that uses expensive communication lines
360 can be avoided for load demand management.

In the study, the power supply should be available for at least critical/uncontrolled
loads while non-critical/controlled ones are connected to and/or disconnected from
the network based on the power supply available from unpredictable renewable

Figure 11: Reducing power generation: controlled load with relay function.

sources. The terminal voltage is used as a controlling parameter in an LV network and its status indicates any excess and/or lack of power. Based on its status, load curtailment is performed by a relay to sustain stability in the network during deficit power generation.

Since there is less power generation, the only one way to balance the network power is through load control. Therefore, a relay-based grid voltage control is proposed for load curtailment to maintain stability during deficit power generation by renewable sources. For load curtailment, if the voltage goes below a certain value, a relay automatically first disconnects the least priority non-critical load. On the other hand, if it increases and exceeds a certain limit of the V_{dc} , an autonomous control strategy reduces the power generation set-point.

This relay operation is performed for certain load types in a network and its set-points for load curtailment, which are selected from the customer priority list, are marked as 1, 2,n in Figure 10, with these points indicating a sequential relay operation during deficit power generation. Although a smart load application has been shown in a relay operation, to maintain system stability, only normal loads are taken into account for this study.

This simulation is performed assuming that the power demand is satisfied from the stored energy elements, as on a rainy day, and the power decreases in the fol-

Figure 12: Four generators supplying power in 16-node network.

lowing steps.

$$P_{G2} = \begin{cases} 0.8 \text{ kW} & \text{if } t < 1.0 \text{ s} \\ 0.7 \text{ kW} & \text{if } 1.0 \text{ s} < t < 2.0 \text{ s} \\ 0.6 \text{ kW} & \text{if } 2.0 \text{ s} < t < 3.0 \text{ s} \\ 0.5 \text{ kW} & \text{if } 3.0 \text{ s} < t < 4.0 \text{ s} \\ 0.4 \text{ kW} & \text{if } 4.0 \text{ s} < t < 4.5 \text{ s.} \end{cases}$$

In the relay operation scheme shown in Figure 10, the network's lower voltage limit decreases gradually based on the position of the load and customer priority list. In this simulation, the controlled loads are accumulated by a 0.1 kW rating, with each equipped with a relay function, the values of which are separated by 0.1 V after 217 V for the first relay operation. The results for decreasing power are shown in Figure 11 in which it is clear that the decreasing terminal voltage below a defined value of 217 V for the first load at $t=1.65$ s detaches the load from the network to maintain voltage stability. Also, in Figure 11b, it is observed that the first load disconnection improves the voltage profile; but the decreased power generation (from 0.7 kW to 0.6 kW) at $t=2$ s leads to a decreased DG-2 terminal voltage that is then balanced by a load cut-off of 0.1 kW at $t=2.13$ s. This approach boosts the terminal voltage on a temporary basis because of the uncontrolled load participating in the network. Note that the defined relay operational values and DG units terminal values are not the same due to the resistance between the units and lines.

Figure 13: Modified 16-node test feeder.

395 In this simulation, a relay-based load curtailment for an autonomous load-side management is presented. This approach is suitable for primary load control management without depending on communication lines and can enhance the reliability of a microgrid with communication lines.

5.3. Case study

400 The test feeders considered for the application of the proposed control strategy are depicted in Figure 13. The test feeder suitably arranged as an LV microgrid provides higher resistive transmission lines than inductive ones. The purpose of this simulation is to demonstrate the influence of load and generation output changes, and the connections of various loads, i.e., constant current (CCL), non-linear (NLL), 405 constant power (CPL) and dynamic. In this study, four DG units, two dynamic and two static, are connected to provide power to the network and all are equipped with the proposed VBD controller which has a voltage band of 5% of that DC-link voltage.

Figure 14: Four generators supplying power during fault.

To observe a load variation effect **and coordination among the controllers**, changes are made to the two dynamic loads incorporated in this network as shown in Figure 13. Although the load is changed at $t=0.5$ s near DG-4 from 1.5 kW to 2.0 kW which is picked up mainly by DG-4, other generators also contribute to this, as shown in Figure 12a. As all generators participate in the increased power demand, their terminal voltages decrease between $0.5 < t < 1$ s, as shown in Figure 12b. The influence of decreasing power consumption is shown at $t=1$ s by changing the second dynamic load from 1.0 kW to 0.5 kW near DG-1, a power change that is clearer at DG-1 than at the other generators. Any load change in the network is first shared by the nearest DG units although the others also participate.

After load changes in the network, DG power variations, which are a common scenario for renewable sources, are demonstrated at $t=1.5$ s and $t=2$ s in DGs-3 and -1, respectively. It is observed that, at $t=1.5$ s, DG-3 injects more power into the network while the other generators reduce their power production to balance the system. On the other hand, the power production of DG-1, which reduces at $t=2$ s, is compensated by the other generators, as shown in Figure 12a.

Furthermore, the effectiveness of the controller proposed is measured after introducing a fault at point P at $t=0.5$ s, as a result, a circuit breaker disconnects DG-2 from the rest of the network with some local loads. From Figures 14a and 14b, it is observed that DG-2 reduces its power delivery by increasing terminal voltage and other DGs supply more power by decreasing terminal voltage to cover additional

430 power demand in the network, with excellent performance in terms of overshoot, oscillation, damping and settling time.

These simulation results describe the influence of load, power changes on an LV network and response after disconnecting a generator, and prove that the proposed controller provides a more stable microgrid operation with an enhanced voltage
435 profile than the VBD controller. Moreover, it takes full advantage of using the DC-link energy to maintain a stable voltage.

6. Conclusion

In this paper, a voltage band for optimally exploiting the DC-link energy in the V_{dc}/V_g droop control approach of an inverter is proposed. This control method is
440 based on the special characteristics of the capacity of a DC-link storage that can supply power during deficit power production and/or absorb power from surplus power generation. It allows V_{dc} variations up to a certain limit and then this voltage alters the grid voltage to inform the active power controller of the present power status to avoid a voltage limit violation. A comparison of the results obtained
445 from the proposed and VBD controllers demonstrate that those from the former significantly improve the voltage profile during dynamic load changes.

During a power deficit in a network, the only means of balancing the power is a load curtailment strategy. Therefore, terminal voltage-based load curtailment using a relay operation as a primary centralised load control without communication lines
450 is presented. This strategy promotes the reliability of a system during power scarcity by reducing the complexity of its communication lines.

Future work will be focused on an optimal economic dispatch of a microgrid considering the voltage profile of the customers' premises as a tertiary level control for integrating voltage-based control in a hierarchical level.

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