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Frequency control improvement of two adjacent microgrids in autonomous mode using back to back Voltage-Sourced Converters

Mojtaba Khederzadeh *, Hamed Maleki, Vahid Asgharian

Faculty of Electrical and Computer Engineering, Shahid Beheshti University A.C., Tehran, Iran

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ABSTRACT

Typically microgrid is composed of Distributed Generators (DGs), storage devices and loads which can be operated in grid-connected or islanding mode. Microgrid brings merits to both suppliers and consumers; hence, there would be a lot of microgrids at the distribution level with different load curves and DG types in near future interchanging their surplus/shortage of supply with each other or the utility grid. Upon inception of a fault in an individual macrogrid, it would be disconnected from the utility grid and operates in an autonomous mode. For the microgrids with all inverter-based DGs, the frequency maybe considerably deviated from the nominal value upon disconnection from the utility-grid; that is impermissible for consumers. In this paper, the interconnection of two adjacent inverter-based microgrids with different frequencies is proposed, using Back to Back Voltage-Sourced Converters (BTB VSCs) with local controllers in order to maintain the frequency in emergencies. By application of the proposed algorithm, two microgrids could play the role of an auxiliary supply/demand for each other without the necessity of implementing a communication link between the two microgrids. Simulation results show that the BTB VSCs with the proposed control strategy can effectively improve the frequency control task of the two microgrids simultaneously.

Introduction

In recent decades, the use of DGs is progressively increasing in both suppliers and consumers sides. Important reasons of the interest in using renewable energy resources could be listed as follows [1–3]:

- Decreasing the greenhouse gas emissions due to the electricity generation.
- Increasing the cost of fossil fuels and their limitations.
- Efficient use of energy resources (Combined Heat and Power Production).
- Rapid increase of energy consumption in developing countries and the limitation of transmission lines capacity.
- Increasing of the sensitive loads in the consumers' side and the use of backup resources.

The increasing penetration of distributed energy resources in the distribution network introduces a new concept called "microgrids", referring to groups of loads and different DG resources which can be operated in macrogrid (utility grid-connected) mode or autonomous (islanding) mode [2]. In normal condition, a microgrid works in grid-connected mode, in which the voltage and frequency of the microgrid are determined by the macrogrid. When the microgrid is disconnected from the grid, it will be operated in the islanding mode in which its control strategy should be changed in order to create a reference for the voltage and frequency [4]. On the other hand, most of the DG resources are connected to the grid by power electronic interfaces. Having these interfaces give technical and operational features to the microgrid which makes it different from the traditional ones. These differences create a new field of researches in control, operation and protection of the microgrids.

Ref. [3] reviews the previous researches in the area of microgrids done by E.U., U.S, Japan and Canada. Different local and central control strategies for power sharing between generating units in microgrids are well presented. In [5] the control management strategy of the microgrid with several generating units and droop characteristics for active power control in islanding mode is presented and a new approach to control the accessible charged energy due to the energy storage devices limitation is proposed. Moreover, the accurate efficiency of the droop-characteristics approach in frequency stability of microgrid with wind turbines is concluded in [6]. Ref. [7] highlights the role of power electronic

* Corresponding author.
E-mail address: khederzadeh@pwut.ac.ir (M. Khederzadeh).

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interfaces in microgrids, especially Voltage Source Inverter (VSI) and introduces the droop-characteristics procedure as an accurate and proven approach for microgrids' control.

A microgrid operates in one of these two modes:

- If the amount of generated power in microgrid is less than the consumer's load, then the main grid will compensate the shortage of power supply.
- If the power generation is more than the consumer's load, then the surplus of the generated power will be injected to the main grid.

Considering the mentioned operating modes, adjacent microgrids can cooperate during the fault condition in order to balance the generation and consumption. Hence, microgrids can help each other and improve their performance during islanding condition by using proper control strategy. Regarding this important point, the direct connection of two adjacent microgrids with central controller to improve their dynamic performance is presented in [8] and significant improvements are achieved in comparison to the individual operation.

In this paper, the interconnection of two adjacent microgrids through BTB VSC with local controllers is proposed. In this system, two microgrids would help each other to restore frequency in the autonomous mode without any communication system between them. The results show that the frequency control of the two connected microgrids is significantly improved during the islanding mode.

Our main contributions underlie on the application of control logics applied to local control of BTB VSCs in order to provide collaborative operation for two individual microgrids without the necessity of informing any of them the supply/demand of the other. The proposed algorithm identifies the necessity for power exchange between the two microgrids locally. Upon existence of such a necessity, it regulates the exchange power between them in such a way to achieve the maximum collaboration with the minimum changes in the microsources' output powers. Therefore, the proposed BTB VSCs can effectively identify the excess/shortage of supply of the microgrids just by measuring the frequency of each microgrid and without the necessity of any communication link. Upon identification of the requirement, it regulates the exchange power between the two microgrids. It is worth mentioning that the proposed system can connect two microgrids with different nominal frequency and voltage levels, the performance remains intact.

Sample microgrid structure and specifications

Microgrids are introduced as radial low voltage distribution networks. Regarding the type of available fuels, different types of controllable resources (Diesel generator, Micro turbine and Fuel cell) can be used in microgrid microsources with the presence of uncontrollable resources (Wind turbine, Photovoltaic and etc). Ref. [9] compares different experimental microgrids and tests microgrids which are introduced in literatures.

In this paper the test microgrid presented in [10] is used with some changes in the generating resources and loads in order to evaluate the proposed method for frequency control. The single line diagram of the test system is illustrated in Fig. 1, indicating that each low-voltage microgrid is connected to the macrogrid via a static switch; and consisting of loads, controllable/uncontrollable resources and also storage devices (flywheel or battery). All energy resources in both microgrids are connected to the network via inverter interfaces. In normal operation mode, two microgrids are connected to the macrogrid, so if a fault happens in the macrogrid, then the two microgrids would be separated from the

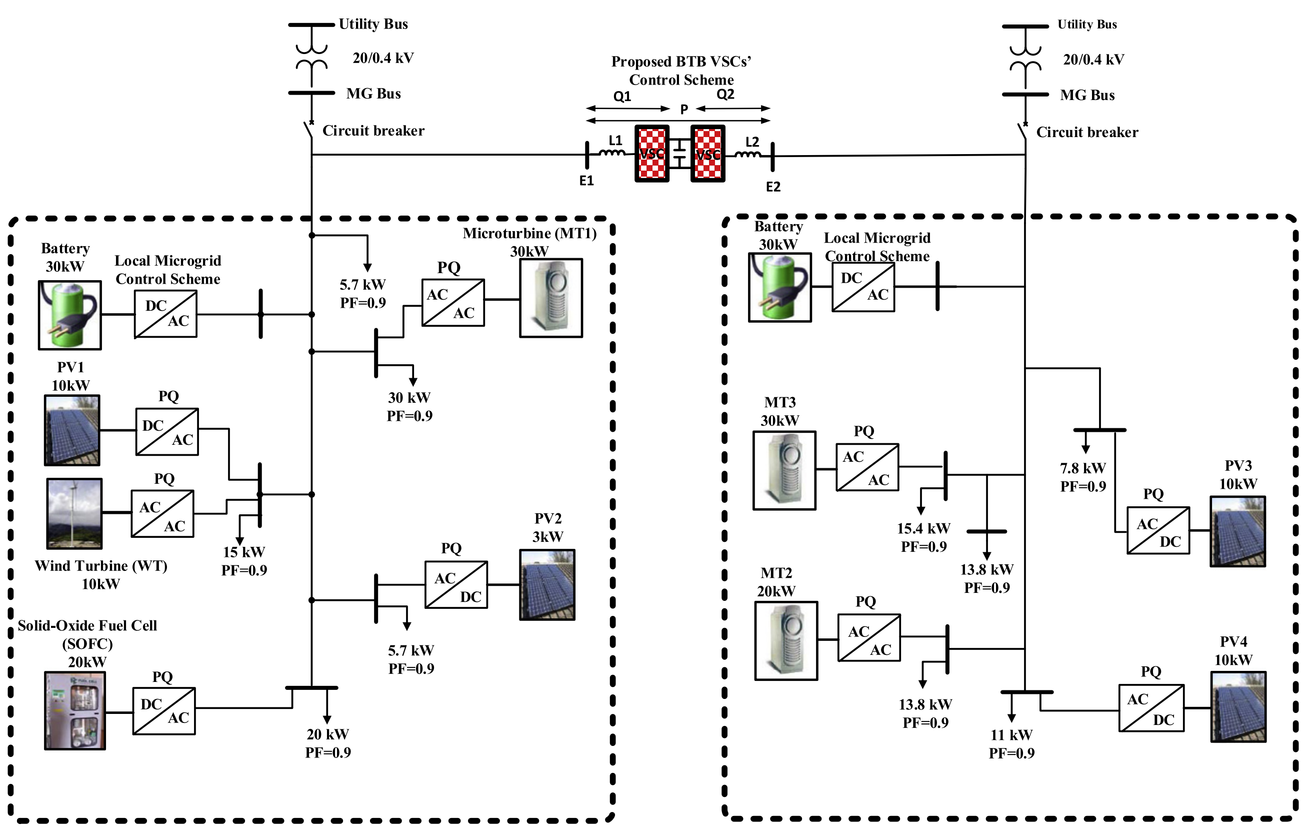

Fig. 1. Microgrids' structures and their connection via BTB VSCs.

macrogrid via the operation of the static switches 1 and 2; hence they continue to operate in the islanding mode.

The main objective of this paper is analyzing the connection of two microgrids via Back-To-Back (BTB) Voltage-Sourced Converters (VSCs) with local control. BTB VSCs with the proposed algorithm not only exchange the specified amount of power during islanding but also force the two microgrids to support each other in the complex function of frequency control.

Modelling of distributed generation resources

In order to evaluate the behavior of the sample microgrid in different operation modes, it is necessary to model its elements in accurate details. In this regard, different models for generating resources and storage devices are presented and discussed in the literature. Controllable and renewable resources as well as storage devices which are used in this paper are briefly introduced as follows:

Controllable resources

These resources whose models are presented in [11] have the ability to control the output power with the responsibility to operate as secondary frequency controllers.

Renewable resources

Two common renewable resources which are usually considered in microgrids are Wind Turbine and Photovoltaic. The output powers of these resources depend on the weather conditions. Photovoltaic model is presented in [12] and different types of wind turbine are available in MATLAB\Simulink prepared models which can be used in microgrid with a little adaptations and modifications [14].

Energy storage devices

Since controllable resources have low inertias and slow dynamic responses, it is necessary to utilize storage devices in the islanding mode to control the frequency of a microgrid. Today different storage devices with various technologies are available which could be used in a microgrid. In this paper, the storage device is considered as a DC voltage resource.

Modelling of energy resources interface inverters

In this paper, slow dynamic model is investigated; hence, ideal inverter model could be used, so the control scheme of the inverter needs special design and attention.

Control scheme for the interface inverter of generating resources

The interface inverter of a microturbine, solid-oxide fuel cell, photovoltaic, and wind turbine uses PQ control scheme in which it is able to inject a specified active and reactive power into the microgrid at the point of common coupling (PCC). Modelling of the control scheme as presented in different Refs. [2,13] could be implemented in both "abc" and "dq" frames.

Control scheme for the interface-inverter of storage devices

The interface-inverter of the storage device plays an important role in the local control of the microgrid in islanding mode. In fact, it sets the reference frequency of the microgrid by means of a droop-characteristics method in the autonomous mode. The mathematical concept of the frequency droop is expressed as [2,13]:

$$\begin{aligned} f_{MG} &= f_0 - k_P \times P \\ V_{MG} &= V_0 \end{aligned} \tag{1}$$

where P is the injected power from the storage device, V_0 and f_0 are nominal voltage and frequency of the microgrid, respectively.

BTB VSCs system's structure

A general diagram of BTB VSCs is illustrated in Fig. 2, where $\mathbf{E}_{\mathbf{k(k=1,2)}} = E_k\angle\delta_{Ek}$ and $\mathbf{V}_{\mathbf{k(k=1,2)}} = V_k\angle\delta_{Vk}$ are the voltage phasors of the microgrid and the BTB VSCs' output buses, respectively. They are also visible in Fig. 1.

The considered BTB VSCs should be able to transfer the specified amount of active and reactive power between E_1 and E_2 buses. To control the transferred power, "d–q" transformation is used. It should be noted that in the following equations, k could be equal to *1* and *2* for obtaining the voltages of both sides of BTB VSCs. By transformation of three phase voltages and currents of both sides of BTB VSC to d–q reference frame, which rotates with an angular velocity synchronized with bus "E_k", the voltages in d–q axes can be expressed. For example for Line 2 we have:

The voltage equations of bus V_2 in d–q axis is obtained as:

$$\begin{aligned} V_{d_2} &= E_{d_2} + R_2 i_{d_2} + L_2\frac{di_{d_2}}{dt} - \omega L i_{q_2} \\ V_{q_2} &= E_{q_2} + R_2 i_{q_2} + L_2\frac{di_{q_2}}{dt} + \omega L i_{d_2} \end{aligned} \tag{2}$$

where we have:

$$\begin{aligned} E_{q2} &= 0 \\ E_{d2} &= E_2 \end{aligned} \tag{3}$$

In (2), the currents of d–q as voltage disturbances and expresses separately as in (4):

$$\begin{aligned} V'_{d_k} &= R_2 i_{d_2} + L_2\frac{di_{d_2}}{dt} \\ V'_{q_2} &= R_k i_{q_2} + L_2\frac{di_{q_2}}{dt} \end{aligned} \tag{4}$$

According to (4), variations in i_q and i_d currents contribute to the voltage variations of the same axis via first order differential equations. Provided a proportional integral controller is implemented, it can produce the references for currents and voltages. Hence:

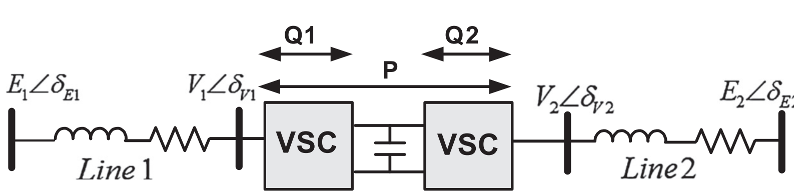

Fig. 2. General diagram of BTB VSCs.

$$V'_{d_2} = \left(K_{dp2} + \frac{K_{di2}}{s}\right)\left(i^*_{d_2} - i_{d_2}\right)$$
$$V'_{q_2} = \left(K_{qp2} + \frac{K_{qi2}}{s}\right)\left(i^*_{q_2} - i_{q_2}\right) \tag{5}$$

By combining (2), (4) and (5) we have:

$$V^*_{d_2} = E_{d_2} + \left(K_{dp2} + \frac{K_{di2}}{s}\right)\left(i^*_{d_2} - i_{d_k}\right) - \omega L i_{q_2}$$
$$V^*_{q_2} = E_{q_2} + \left(K_{qp_2} + \frac{K_{qi_2}}{s}\right)\left(i^*_{q_2} - i_{q_2}\right) + \omega L i_{d_2} \tag{6}$$

To control active and reactive powers with negligence of the inverter losses, active and reactive power produced by the inverter can be yielded by (7):

$$P_2 = \frac{3}{2}\left(v_{d_2} i_{d_2} + v_{q_2} i_{q_2}\right) = \frac{3}{2} v_{d_2} i_{d_2}$$
$$Q_2 = \frac{3}{2}\left(v_{q_2} i_{d_2} - v_{d_2} i_{q_2}\right) = -\frac{3}{2} v_{d_2} i_{q_2} \tag{7}$$

Fig. 3 shows PQ control scheme with its interior and exterior control loops. Interior and exterior control loops provide d–q current and voltage references, respectively.

Fig. 4 shows the schematic control diagram of BTB VSCs which forms the amount of transferred power according to frequencies of the two microgrids. Control algorithm of the system is explained in the next section.

Proposed control algorithm for BTB VSCs

The proposed algorithm to control the microgrids with BTB VSCs is shown in Fig. 5. If an islanding mode occurs, the

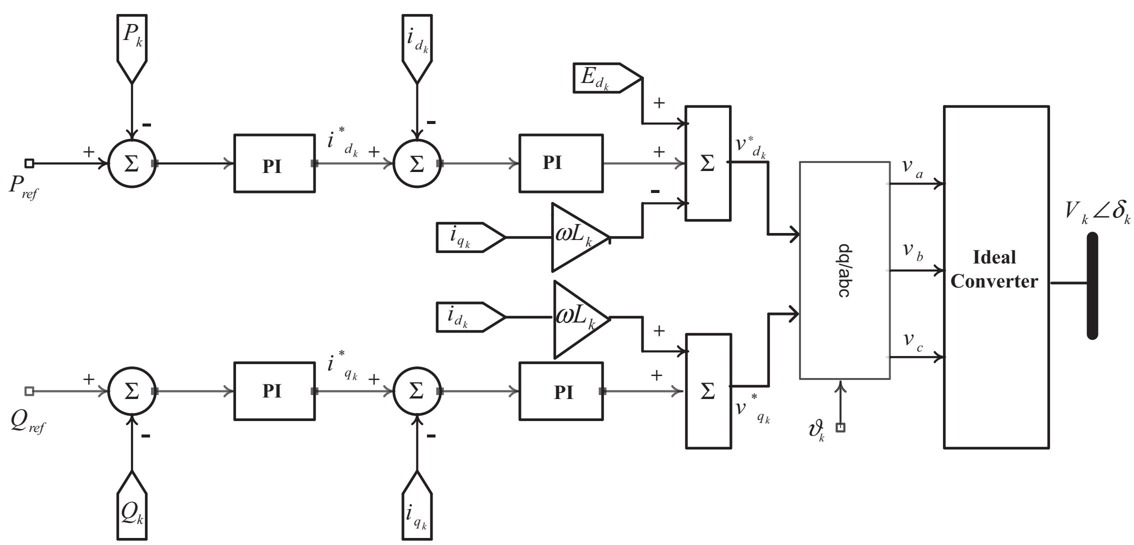

Fig. 3. PQ control scheme structure.

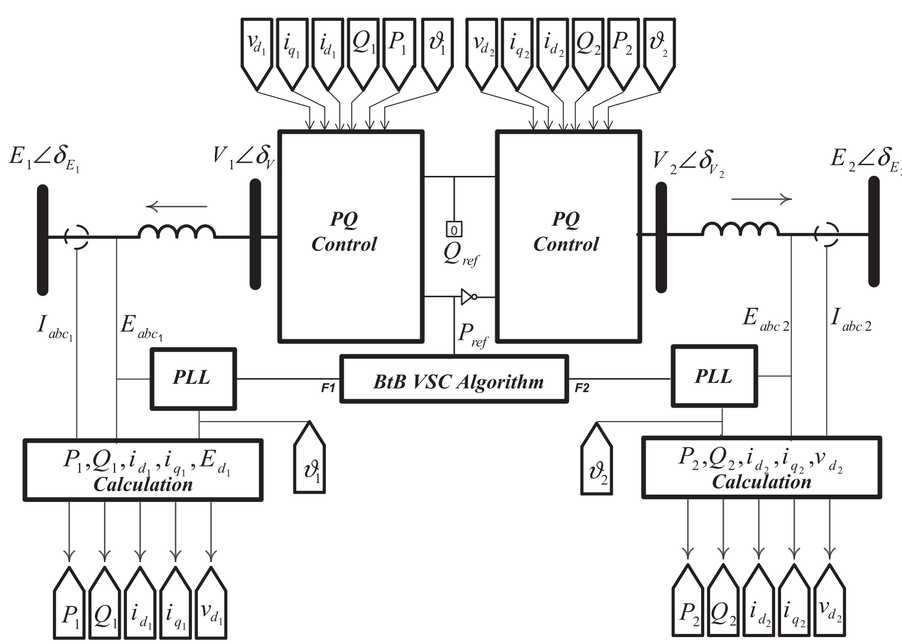

Fig. 4. Proposed control scheme of BTB VSCs.

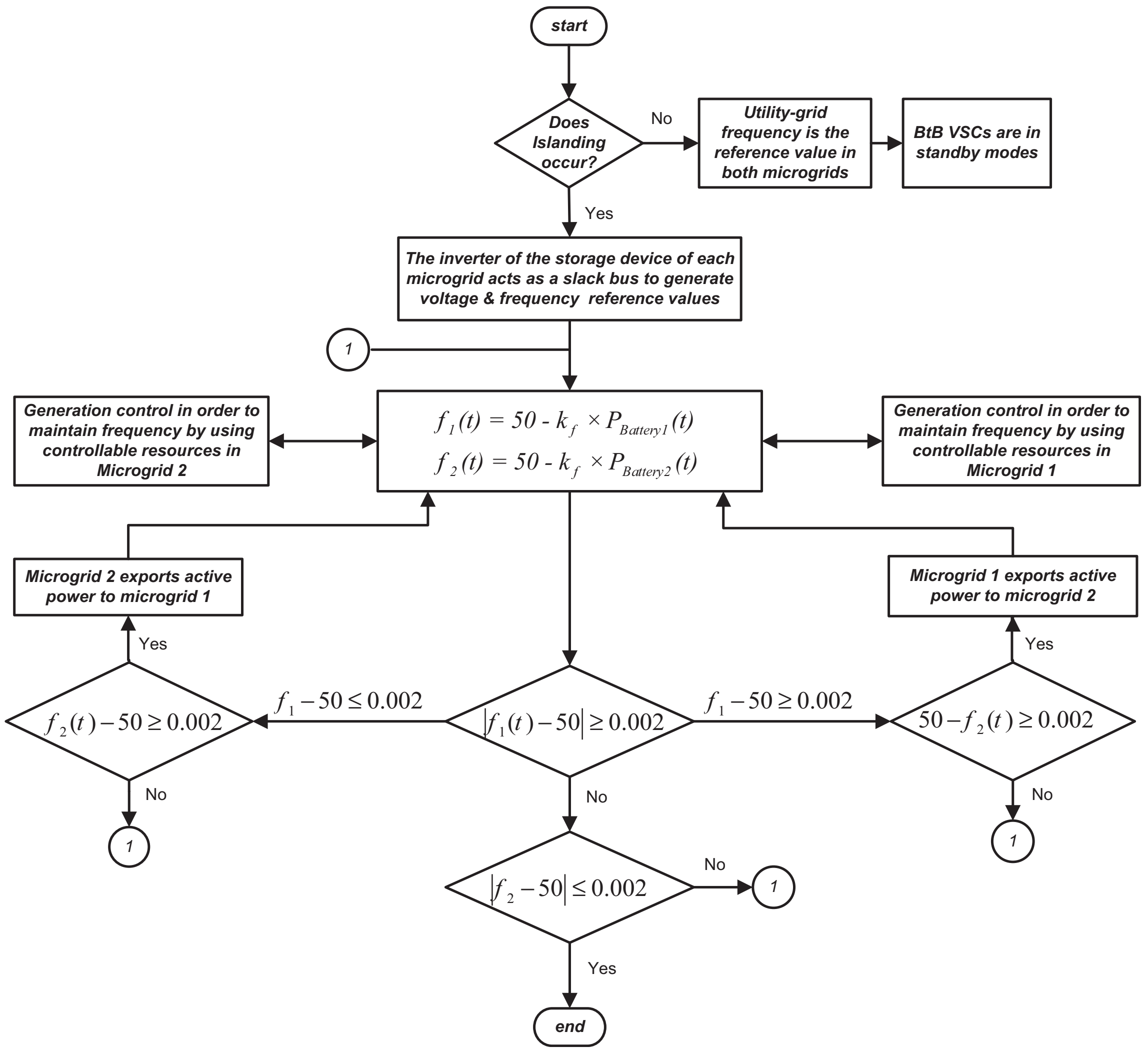

Fig. 5. Frequency control algorithm of two connected microgrids using BTB VSCs.

reference frequency of each microgrid is determined by the control scheme of the interface inverter of their storage devices according to the injected power from the battery in each microgrid. The local controls of the microgrids and the control system of the BTB VSCs are coordinated in kind of hierarchical manner, i.e., if the microgrids could stabilize their frequency by their own resources, no power export/import is necessary from the adjacent microgrid through the BTB VSCs. Whenever the power deficiency or even excess supply could not be managed by the local controls of each microgrid, then intervention of the BTB VSCs is required. Therefore, the control system of the BTB VSCs monitors the frequencies of the two microgrids according to (1) and whenever the absolute amount of frequency deviation is more than a threshold, for example, 0.002 Hz, the BTB VSCs control system is activated. The power exchange between two microgrids is only performed upon the occurrence of one of the following conditions:

- If microgrid 1 has surplus supply which could be realized by $f_1 > 50.002$ and meanwhile microgrid 2 has deficiency of supply, i.e., $f_2 < 49.998$, then microgrid 1 will export power to microgrid 2. The amount of the transferred power is set in such a way that the frequency of any of the microgrids returns to the specified value ($f_1 < 50.002$ or $f_2 > 49.998$).
- If microgrid 2 has surplus supply, i.e., $f_2 > 50.002$ and microgrid 1 has shortage of supply, i.e., $f_1 < 49.998$, then microgrid 2 will export power to microgrid 1. The power transfer is continued until the frequency of any of the microgrids returns to the specified value, i.e., $f_1 < 50.002$ or $f_2 > 49.998$.
- If none of the above conditions exist, then the control system of each microgrid would operate independently via its own controllable resources to maintain the frequency within the specified limits.

Simulation results

In this section the impact of presence or absence of the BTB VSCs in the frequency control is studied in order to evaluate the efficiency of the proposed control scheme. Simulations are performed by considering the following assumptions:

- Both microgrids are completely inverter-based and all of the DG resources exchange power with the microgrid via inverter interfaces.
- Each microgrid is capable to be controlled locally and without any communication links during islanding.
- The output power of the renewable resources is held constant in order to highlight the performance of the BTB VSCs control system. As already specified, each microgrid has its own

independent control system to maintain the frequency during transients, firstly by intervention of the storage device control system through absorption/injection of power and secondly forcing the inverter-based resources to take a new operating point by changing the reference frequency of the microgrid as dedicated by the storage device, so neutralizing the charge/discharge of the storage device and make it ready for the next disturbance [5]. Needless to say that upon disconnection of the micrograds from the utility-grid, the local controls of the DGs could not respond fast enough to maintain frequency, so a control system is designed for the storage device available in each microgrid to respond quickly and restore the frequency. However, as the storage devices have a limited capacity, the adjacent microgrid could be helpful in this regard and assist in restoring the frequency in early times of inception of the disturbance by managing the power transfer through BTB VSCs.

– The slow dynamic is studied and switching functions are neglected.
– Before islanding, the load of first microgrid is set to 60% of its nominal value, so in this case, the microgrid injects power to the main grid. In other word, the first microgrid has excess generation before islanding.
– Each microgrid works on its stable point before islanding.
– Before islanding, the load of the second microgrid is set at 93% of its nominal value; so the second microgrid has generation shortage which is provided by the main grid.

Considering the mentioned assumptions, different scenarios are simulated in MATLAB\Simulink to investigate the proposed algorithm.

First scenario: MGs are independently controlled

Two microgrids are separated and controlled independently. Moreover, each microgrid provides its primary and secondary control using its own resources. In this scenario local control of each microgrid is evaluated.

Second scenario: MGs are connected by BTB VSCs

In this scenario, BTB VSCs system provides local connection of two microgrids. Regarding considered conditions at the islanding instant, BTB VSCs system should exchange power between the two microgrids and provide power shortage of the second microgrid via excess generation of the first microgrid. The simulation results in the presence of BTB VSCs are compared with the results in the absence of BTB VSCs.

Fig. 6 shows the frequency excursions when islanding occurs. The storage device of MG1 absorbs the excess power and establishes the MG's reference frequency at a higher value than the nominal one. Simultaneously in the second MG, the shortfall of frequency will be compensated by the storage device; the reference frequency of the MG will be created in a lower value than 50 Hz. To compensate the MG's frequency to the nominal value according to the proposed algorithm for each individual MG, the controllable resources participate in frequency control according to the frequency excursion caused by the inverter of the battery system. Due to the slow response of controllable resources, this process takes several tens of seconds until controllable resources change their output power. Fig. 7 shows the injected active power by the controllable resources. When the MGs are connected by BTB VSCs, the frequency is monitored at the islanding mode and whenever an extra power in the first MG and a power shortfall in the second one is observed; then, in this condition BTB VSCs' control scheme compensates the power deficiency of the second MG by using the excess power of the first one. Consequently, frequency control of the second MG is satisfactorily performed and the power shortage of the first MG is compensated by its controllable resources.

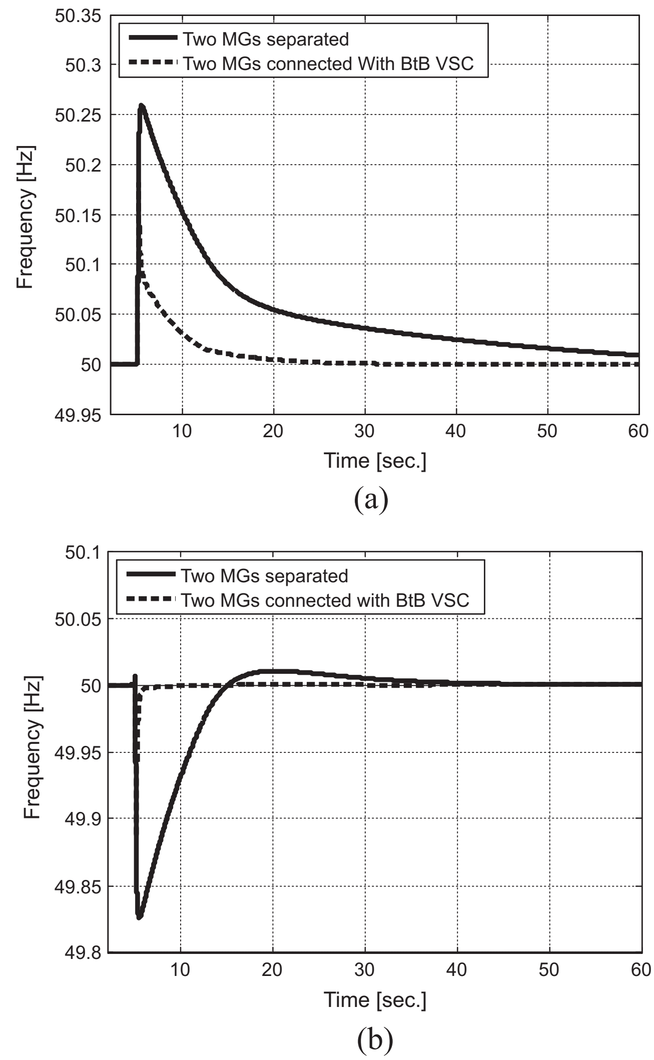

Fig. 6. Frequency of the MGs for individually and BTB controlled systems; (a) Frequency of MG1, (b) Frequency of MG2.

Third scenario: nonlinear stability analysis of the MGs connected by BTB VSCs

In this scenario, single phase to ground faults (SLG), as the most common type of fault in distribution systems is considered for evaluating the performance of the two MGs connected by BTB VSCs. Two SLG faults at $t = 45$ s and $t = 65$ s at two critical points: (1) BTB VSC's busbar at MG2 side; and (2) at the battery interface VSC of MG2 are simulated. Fig. 8 shows the frequency during the simulations. As can be deduced from this figure, the frequency of MG1 is kept intact for such a fault at MG2. As the fault is at the MG2's side, power is extracted from the battery, so the frequency is dropped, but its impact on the output power of the resources and the BTB VSCs are negligible. This is due to the interface inverters with the PQ control systems which limit the active and reactive power; hence the influence of the fault is mitigated implicitly. At $t = 65$ s another SLG fault is occurred at another critical point, so the BTB VSCs' operation is promising and the generated powers and the transmitted power by BTB VSCs are not affected accordingly.

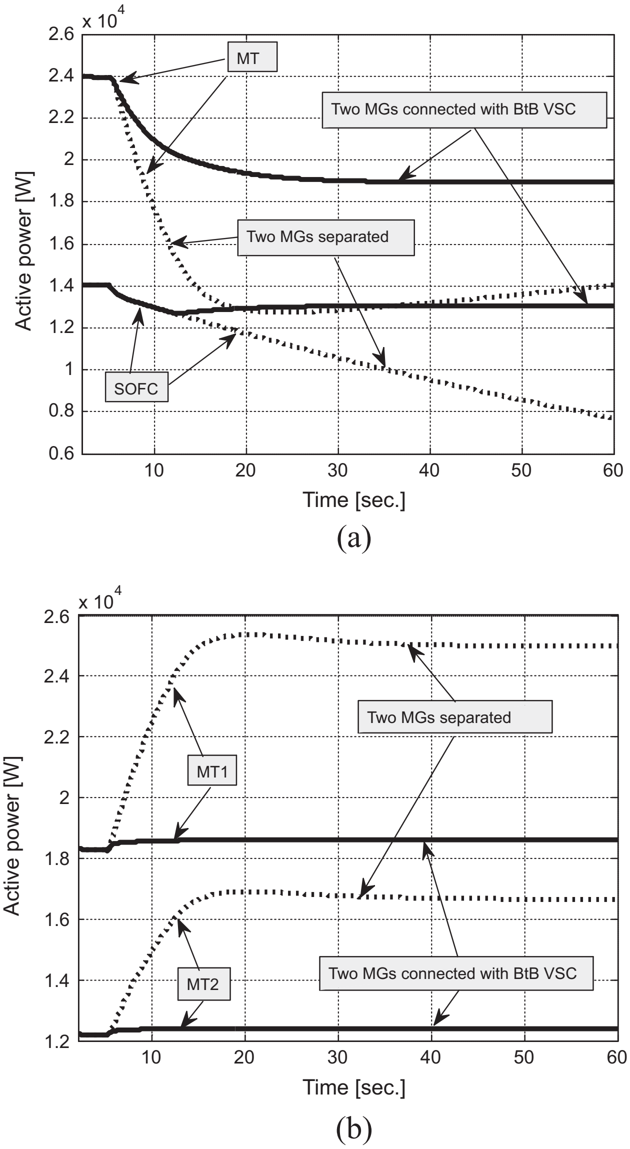

Fig. 7. Active power injected by the controllable resources; (a) in MG1, (b) in MG2.

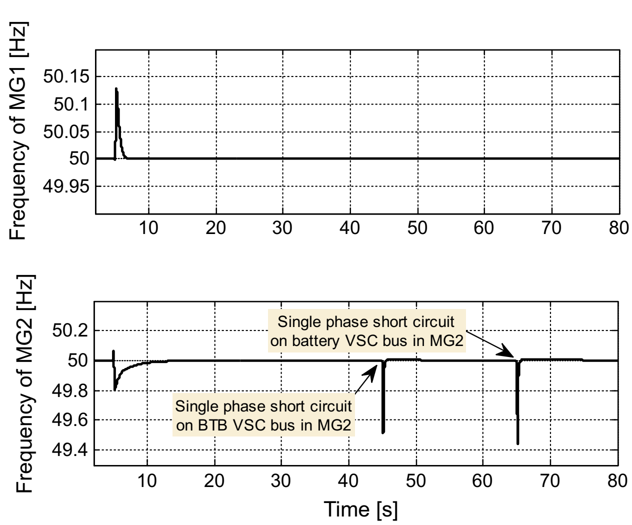

Fig. 8. MGs' frequency during a single phase to ground fault on MG1 (Top: MG1 (healthy) frequency with no clear impact from faulty MG; Bottom: MG2 (Faulty) frequency).

Fig. 9 shows the Power outputs of different microsources during the same faults on MG2, as can be deduced from the figures, MG1 (healthy) power outputs have no clear impact from the fault in MG2; meanwhile power outputs of the faulty MG are slightly affected due to the intervention of the battery to recover the system.

Fourth scenario: BTB VSCs' performance in supply/demand variations

Fig. 10 shows the performance of the BTB VSCs in coping with the intermittent nature of the supply/variations of the load. As Fig. 10(a) shows, at $t = 45$ s MG1's frequency is dropped due to the trip of a wind turbine, as there is no extra generation in MG2, so BTB VSC would avoid any changes on the transferred power. The same applies for Fig. 10(b). At $t = 90$ s a load is increased or decreased, however, as the frequency of MG1 is at its nominal value, so BTB VSC helps it not to be affected from the disturbance, meanwhile, MG2 is responsible to recover the frequency by its own generations.

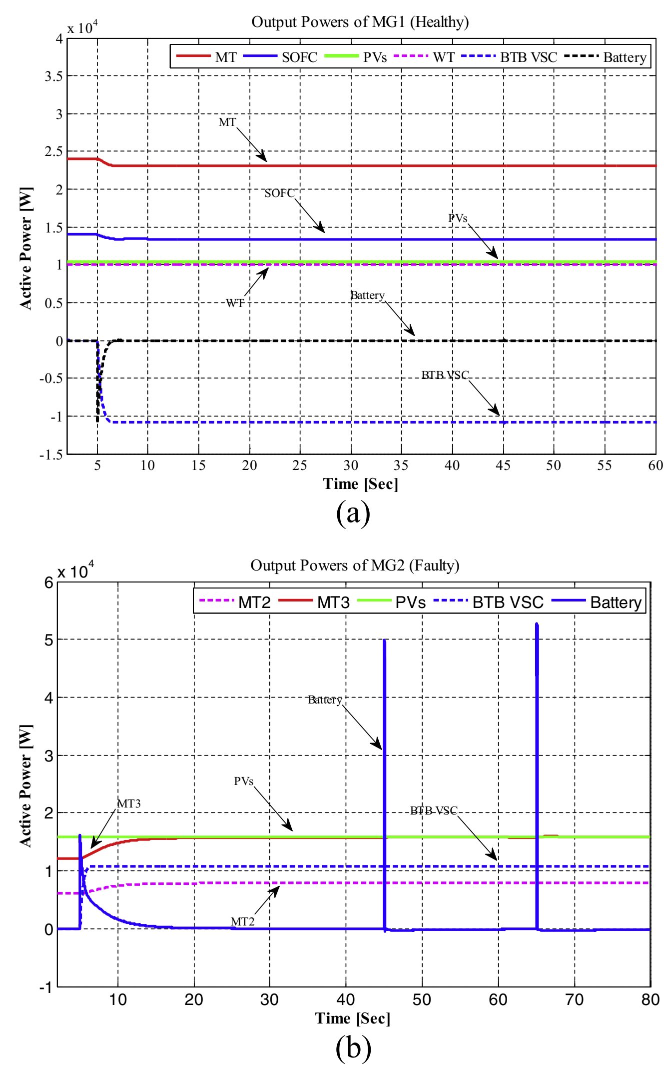

Fig. 9. Power outputs of different microsources during a single phase to ground fault on MG1 ((a): MG1 (healthy) power outputs with no clear impact from the faulty MG; (b): MG2 (Faulty) power outputs with clear intervening of the battery to recover the system).

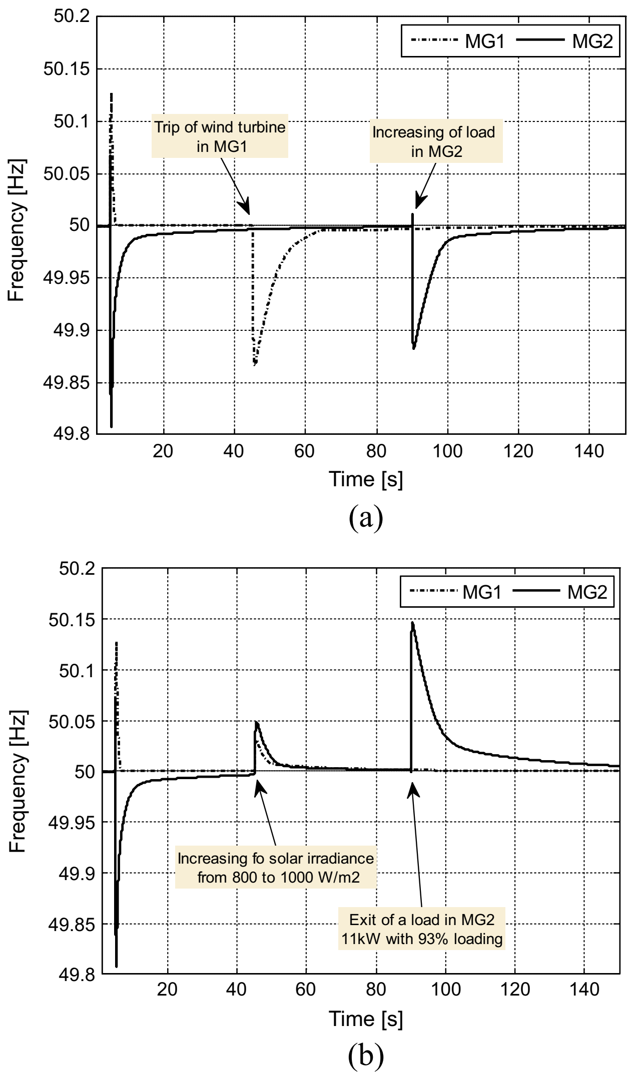

Fig. 10. MG's frequency due to the supply/demand variations; (a) intermittent nature of wind and load increase, (b) solar power variations and load rejection.

Conclusions

Microgrids are the elements of the future power systems in which they will exchange their surplus or shortage of power with the main grid according to their available generation resources and loads. Microgrids cooperation can enhance and simplify the frequency control of the microgrids during a fault in the upstream grid. On the other hand, the microgrid with excess power can transfer power to the microgrid with short supply before islanding. Simulation results show that the two adjacent microgrids cooperate in frequency control using control schemes of BTB VSCs. Moreover, this control scheme requires no communication link and is implemented with the specified available data in the BTB VSCs. Benefits of using this system in conjunction with the inherent advantages of the microgrids can be summarized as: firstly, before islanding the controllable resources are operated in their optimal working points and there is no desire to change them. Secondly, due to the slow response of the controllable resources, their output power cannot be changed immediately, so the frequency excursions bother the sensitive loads. Meanwhile frequency control of the two microgrids is improved by using BTB VSCs during an islanding operation, as well as rapid improvement in frequency would prevent the excessive changes in the amount of storage device's charge/discharge.

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