Frequency Control in Networked Microgrids with Voltage-Sensitive Loads

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***Abstract*—This paper presents a frequency control scheme for a networked microgrid system through the coordination of the conventional frequency controller and a novel dual-mode voltage-based frequency controller. The proposed voltage-based frequency controller has two operating modes: a frequency restoration mode to restore the frequency immediately upon the frequency deviation from the nominal value being beyond a certain limit, and a voltage restoration mode to restore the voltage after the frequency is recovered to a satisfactory range. The controller aims to reserve enough voltage margin in case of consecutive disturbances, as well as to mitigate any negative impact on loads. A proper switching logic is designed to enable the mode switching. On the other hand, microgrids in a networked microgrid system can help each other during transients when emergencies happen. By combining the advantages of both networked microgrids and the characteristic of voltage-sensitive loads, the system frequency response is improved dramatically. The effectiveness of the proposed controller and superiority of the networked microgrid system over single microgrids in terms of system response under disturbances have been tested and validated through various simulations in PowerFactory.**

***Index Terms*—Frequency control; voltage-sensitive loads; switching control; networked microgrids**

I. INTRODUCTION

The concept of the microgrid (MG) has been proposed due to its ability to integrate a greater penetration level of distributed generators (DGs) and renewable energy sources (RES) driven by technical and environmental concerns [1]. With the development of DGs and RES, future distribution systems will acquire different characteristics compared with traditional ones, and significant and challenging problems will inevitably arise. One of these problems is the frequency control issue brought by the intermittent nature of RES and the low system inertia caused by inverter-based DGs, which is especially severe in isolated MGs without support from main grids.

To solve this problem, droop control is widely adopted for its advantages of cost-effectiveness and relieving of communication burden. Note that operation without or with few communication links is desirable in MGs for ease of system expansion, as the number of DGs as well as loads are expected to grow in future [3]. However the disadvantages of conventional droop control also limit its application, among which are the existence of steady state error, ignorance of load dynamics and line impedances, poor transient performance, and potential negative effects on system stability [2], [3]. To overcome these drawbacks, various improved droop control strategies are proposed. Angle droop control is proposed in [4] to overcome the steady state error; however, system instability may happen if local synchronization cannot be achieved. A general droop control method is introduced in [5] to address the line impedance dependency and transient response issue, but the R/X ratio needs to be known in advance.

In addition to droop control, another frequency control technique with few or no communication links, utilizing the characteristic of voltage-sensitive loads to stabilize the system frequency received attention recently [6], [7]. The basic idea is to dynamically change the load demand by regulating the load operating voltage, in order to eliminate the power imbalance. Frequency control strategies employing the characteristic of voltage-sensitive loads offer various appealing advantages, including:

- Instantaneous response which is especially useful for MGs with high penetration of RES-based DGs.
- Ability to cooperate with the existing frequency controllers properly.
- Increase of system damping.
- Little or even no communication is needed.

In view of these advantages, a novel frequency control strategy through voltage regulation is proposed in [6]. By adding a proposed voltage-based frequency controller (VFC) to change the terminal voltage set point of the excitation system of synchronous generators (SGs), the system voltages decrease immediately upon sensing a frequency drop, and the system frequency can be quickly restored. The control strategy can be easily implemented but it has several shortcomings. Firstly, the grid voltage cannot be brought back after each power imbalance disturbance. Supposing that an active power deficiency happens and thereupon the VFC will lower the terminal voltages of SGs. But if another active power deficiency happens later on, the VFC will not have enough voltage margin to restore the frequency since the generator terminal voltage has to be restricted in a certain range in order to avoid voltage collapse. Secondly, the operating voltages of loads also deviate from their nominal values without intended restoration after disturbances. Therefore, the actual consumption of loads will greatly deviate from the value at nominal load voltage, which may be undesirable and even harmful to loads.

Inspired by the idea in [8], and in the interest of better harnessing the benefits brought by the characteristic of voltage-sensitive loads, this paper proposes a dual-mode VFC to solve the above-mentioned problems. The proposed VFC has two operating modes, a frequency restoration mode (FRM) and a voltage restoration mode (VRM). The working principle of the proposed VFC in the FRM is the same as the VFC in [6]. Furthermore, the VRM of the proposed dual-mode VFC can restore the terminal voltages of SGs after the frequency is restored to a satisfactory region. Enough voltage margin can be reserved in case of later disturbances, while the operating voltages of loads can also be recovered significantly from the large deviation caused by the FRM of VFC, and normal demand of loads can therefore be satisfied.

On the other hand, the networked MG system, defined as a local power system that consists of interconnected MGs, has been proposed as an integral part of future power systems [9]. It is shown that due to prominent characteristics of networked MGs such as coordinated energy management, interactive support, and power exchange, the networked MGs can further improve the system reliability, quality, and security [9]. However, most of the existing literature has focused on the energy management strategies and few research works have been done to explore the promising benefit on frequency control brought by the networked MGs, i.e. the mutual assistance between interconnected MGs during transients when emergencies happen. Therefore, this paper proposes to combine the advantages offered by the networked MGs and the characteristic of voltage-sensitive loads in order to improve the system frequency response under disturbances without the support from the main grid.

In summary, the proposed frequency control scheme in a networked MG system can be described as follows. In each MG, the proposed dual-mode VFC works in coordination with traditional primary and secondary frequency control. Under normal conditions, the proposed dual-mode VFC works in the VRM to maintain the terminal voltage of SGs, and each MG in the system should be in steady state and certain tie-line powers between areas should be maintained. If a large disturbance happens and triggers the FRM of the proposed dual-mode VFC, the VFC in the FRM of each MG will quickly restore the system frequency. Furthermore, MGs will help each other with power exchange in the FRM. After the frequency is restored to a satisfactory region, the VRM of the VFC will be activated to restore the system voltage. And the AGC of selected SGs will eventually take the full power mismatch, and restore tie-line power between MGs to their scheduled values in this voltage restoration process.

The main contributions of this paper are as follows:

- Considering the limited allowable range of the grid voltage, a dual-mode VFC is proposed to better utilize the characteristic of voltage-sensitive loads. A switching logic is designed to achieve proper mode switching, so as to enable the proposed dual-mode VFC to reserve enough voltage margin to withstand consecutive disturbances automatically.
- The proposed dual-mode VFC can also mitigate the negative impact on loads caused by the intended regulation of system voltage after disturbances.
- A networked MG system is used in this paper to enable a better frequency response, and the superiority of the networked MG system over a single MG is tested in this paper.

The rest of the paper is organised as follows. Section II introduces the networked MG system model used in this paper, as well as the characteristic of voltage-sensitive loads. Section III gives a brief review of conventional frequency and voltage control in power systems. Section IV presents a detailed explanation of the proposed dual-mode VFC and its mode switching logic. The results acquired by various simulations in PowerFactory are shown in Section V to demonstrate the effectiveness of the proposed controller and superiority of the networked MG system over single MGs in terms of system response under disturbances. Conclusions are drawn in Section VI.

II. SYSTEM MODEL

This paper considers a networked MG system that consists of N ($N \geqslant 2$) MGs. These MGs are interconnected by tie-lines in order to help each other when the system is subjected to disturbances, and each of these MGs consists of inverter-based DGs, voltage-sensitive loads and at least one SG.

The main purpose of this paper is to design a fast dual-mode VFC for SGs in each MG that works together with traditional frequency and voltage controllers to improve the system frequency response after disturbances by taking advantage of the characteristic of voltage-sensitive loads. Therefore SGs and voltage-sensitive loads are essential for the proposed control scheme. Next, we will give a brief review of the dynamics of the SG and characteristic of voltage-sensitive loads.

The dynamics of an SG can be described by the classical swing equation as follows [10]:

$$2H\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e - D\Delta\omega \tag{1}$$

where H is the inertia constant, $\Delta\omega$ is the rotor speed deviation, ΔP_m and ΔP_e are the mechanical input and electrical output power deviation, respectively, and D is the damping constant.

Loads in a power system are normally modeled by the following equations [10]:

$$P = P_0(\frac{V}{V_0})^{n_p} \tag{2}$$

$$Q = Q_0(\frac{V}{V_0})^{n_q} \tag{3}$$

where P and Q are active power and reactive power consumed by loads, respectively, P_0 and Q_0 are rated active and reactive power demand when the load voltages are at their nominal value V_0, respectively. The symbols n_p and n_q denote the voltage indices for the active power and reactive power, respectively. In this paper, constant impedance loads are used in the test system, therefore, both n_p and n_q are equal to 2. Note that although Q may also affect the frequency in MGs, this paper only utilize the $P - V$ relationship for frequency control for simplicity.

For a load with $n_p = 2$, a change ΔV in its voltage will lead to an active power demand change ΔP as follows:

$$\Delta P = \left((V_0 + \Delta V)^2 - V_0^2 \right) \frac{P_0}{V_0^2} \tag{4}$$

Assuming that the load was operating at its nominal voltage prior to any change, i.e. $V_0 = 1$, therefore, (4) can be rewritten as follows:

$$\Delta P = \left((1 + \Delta V)^2 - 1 \right) P_0 \tag{5}$$

From (5), it follows that a 5% decrease in load voltage can lead to a 10.25% decrease in load consumption. Thus the FRM of the proposed VFC is designed by utilizing this characteristic of voltage-sensitive loads. By adjusting the terminal voltage of the generator to change the load operating voltage and therefore the load demand, the FRM of the proposed VFC can quickly restore the system frequency. The proposed control strategy also increases the system damping since it established a relationship between the frequency deviation and load operating voltage, and finally the load demand. Therefore, the proposed controller can effectively regulate the system frequency, and the effect is instantaneous.

III. CONVENTIONAL FREQUENCY AND VOLTAGE CONTROL IN POWER SYSTEMS

This section gives a brief introduction to conventional frequency and voltage control in power systems, considering they are an essential part of the proposed frequency control scheme.

A. Frequency Control in Power Systems

To eliminate frequency deviations, traditional power systems adopt a three-layer hierarchical frequency control structure [10]. The primary frequency control, also known as droop control, uses the frequency deviation signal as the feedback input to determine the proper load sharing among generators; the amount of load picked up by each generator therefore depends on the following droop characteristic:

$$\Delta P_m = \Delta P_{ref} - \frac{\Delta \omega}{R} \tag{6}$$

where ΔP_{ref} is the change in the power set point which is used for the secondary frequency control, and R is the droop constant specified by each generator.

The secondary frequency control, also referred to as automatic generation control (AGC), is responsible for eliminating the frequency steady state error and maintaining the tie-line power between control areas at scheduled values by adjusting the active power output of selected generators. To achieve these objectives, an area control error (ACE) signal, which is made up of tie-line power flow deviation and frequency deviation is used to regulate the active power set point ΔP_{ref} of each SG described before. The specific control strategy in a two-area system can be described as follows:

$$\begin{aligned} ACE_1 &= \Delta P_{12} + \beta 1 \Delta \omega \\ ACE_2 &= -\Delta P_{12} + \beta 2 \Delta \omega \\ \Delta P_{ref1} &= -K_1 \int_{t_0}^{t} ACE_1 d\tau \\ \Delta P_{ref2} &= -K_2 \int_{t_0}^{t} ACE_2 d\tau \end{aligned} \tag{7}$$

where ACE_1 and ACE_2 are the ACE signals applied to the selected SGs in each area that act on the load reference set points, ΔP_{12} is the tie-line power deviation from the scheduled value between areas, $\beta 1$ and $\beta 2$ are weighting factors, ΔP_{ref1} and ΔP_{ref2} are the derived change in the power set points of the selected SGs, and K_1 and K_2 are two integration coefficients. This supplementary control is much slower than the primary droop control.

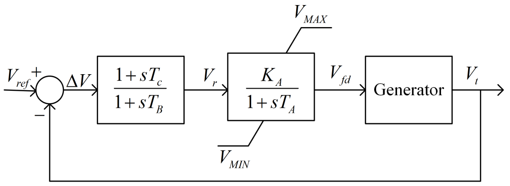

Fig. 1. The simplified IEEE type AC4A excitation system

The tertiary frequency control is responsible for the economical and reliable operation of the system, which is not considered in this paper.

B. Voltage Control in Synchronous Machines

Voltage control in a synchronous machine is implemented by the excitation system, in which the exciter provides direct current to the synchronous machine field winding, while the automatic voltage regulator (AVR) forms an appropriate control signal to the exciter [10]. The AVR aims to maintain the generator terminal voltage by regulating the generator stator terminal voltage. A simplified IEEE type AC4A excitation system model shown in Fig.1 is adopted in the paper [10]. Obtained by comparing the generator terminal voltage V_t and the voltage reference set point V_{ref}, the voltage error signal ΔV is then fed to the AVR to get the V_r signal. Afterwards, the V_r signal is applied to the exciter to get the generator field winding voltage V_{fd} and finally adjusts the generator terminal voltage to the reference value.

IV. DUAL-MODE VOLTAGE-BASED FREQUENCY CONTROLLER

Based on the characteristic of voltage-sensitive loads and the working principle of generator excitation system, a dual-mode VFC is designed in this section.

The proposed dual-mode VFC will coordinate with the primary and secondary frequency control of the SGs. The

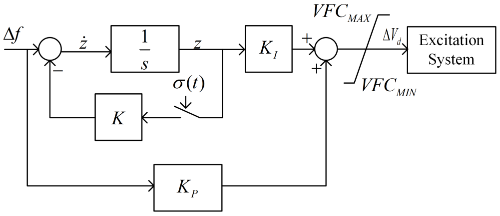

Fig. 2. Proposed dual-mode VFC for the excitation system

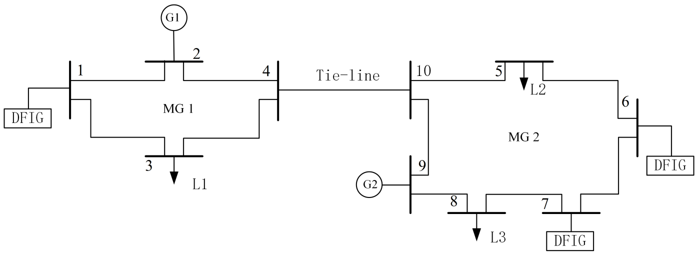

Fig. 3. The test networked MGs system

proposed controller has two operating modes: a frequency restoration mode (FRM) and a voltage restoration mode (VRM). The basic idea here is that the dual-mode VFC in the FRM regulates the generator terminal voltage to restore the frequency immediately upon the frequency deviation from the nominal value being beyond a certain limit. And MGs will help each other to restore the frequency quickly through the tie-line power exchange in the FRM. After the frequency deviation has been recovered to a satisfactory region, the VFC switches to the VRM to restore the generator terminal voltage to its nominal value so as to mitigate the negative impact on loads as well as to reserve enough voltage margin in case of the next disturbance; the AGC of selected SGs will eventually take the full power mismatch, and restore tie-line power between MGs to their scheduled values in this voltage restoration process.

Fig.2 shows the proposed dual-mode VFC which is applied to the excitation systems of the SGs for a networked MG system in this paper. The input to the VFC is the system frequency deviation signal Δf. Note that since $\Delta\omega = 2\pi\Delta f$, so $\Delta\omega$ and Δf will be used interchangeably in the rest of the paper. The switching signal $\sigma(t)$ determines if the VFC should be in the VRM ($\sigma(t) = 1$) or FRM ($\sigma(t) = 0$). Finally, the output of the VFC, which is the voltage reference deviation signal ΔV_d, adds to the reference set point of the excitation systems of SGs. The limits before the VFC output are used to ensure the terminal voltages of the SGs remain within a proper range, with the purpose of avoiding voltage collapse.

The control logic of the proposed controller can be summarized as follows:

$$\begin{aligned} \dot{z} &= \Delta f - K_{\sigma(t)} z \\ \Delta V_d &= K_p \Delta f + K_I z \end{aligned} \tag{8}$$

where $\sigma(t) = 0$ indicates the VFC is in the FRM, and $\sigma(t) = 1$ indicates the VFC is in the VRM. Let $K_{\sigma(t)} = 0$, for $\sigma(t) = 0$, and $K_{\sigma(t)} = C > 0$, for $\sigma(t) = 1$, where C is a constant to be selected.

To avoid chattering in regulating the system frequency, the switching signal is designed as follows:

$$\begin{cases} \sigma(t) = 0, \text{if } \sigma(t^-) = 1 \text{ and } |\Delta f| \geqslant \varepsilon_1 \\ \sigma(t) = 1, \text{if } \sigma(t^-) = 0 \text{ and } |\Delta f| \leqslant \varepsilon_2 \end{cases} \tag{9}$$

where ε_1 and ε_2 are two constants to be chosen satisfying $0 < \varepsilon_2 < \varepsilon_1$.

To explain the working principle of the proposed dual-mode VFC, we assume the system was operating at a steady-state operating point with $\sigma(t_0) = 1$, $z = 0$ and $\Delta V_d = 0$. Assume that an active power deficiency happens and cause $|\Delta f| \geqslant \varepsilon_1$ at $t = t_1$. Then, the switching signal $\sigma(t)$ shifts its value from 1 to 0, and results in the mode changing from the VRM to FRM. The VFC in the FRM immediately utilizes the characteristic of voltage-sensitive loads to restore the frequency, meanwhile MGs in the system will help each other through power exchange. As soon as the frequency deviation is restored to ε_2 at $t = t_2$, i.e. the frequency has been restored to an ideal region, the switching signal $\sigma(t)$ shifts its value from 0 to 1, therefore brings the mode of VFC from the FRM back to VRM so that the SGs terminal voltages can be restored to nominal values. And the AGC of selected SGs will eventually take the full power mismatch, and restore tie-line power between MGs to their scheduled values in this voltage restoration process. Therefore, the power deficiency will be fully taken over locally by SGs in the area in which the disturbance happens. In addition, following with the recovery of SGs terminal voltages, the operating voltages of loads are therefore also restored significantly, leading to a mitigation of negative impact on loads caused by the intended regulation of system voltages in the FRM.

V. CASE STUDY

The effectiveness of the proposed dual-mode VFC and superiority of the networked MG system over single MGs are demonstrated by simulations implemented in PowerFactory, based on a test networked MG system proposed in [12] with minor modifications. The block diagram of the test system is shown in Fig.3. The test system has two MGs interconnected with each other through a tie-line, where MG 1 has a constant impedance load, an SG and a doubly-fed induction generator (DFIG), and MG 2 has two constant impedance loads, an SG, and two DFIGs. The DFIGs are built using the template model in PowerFactory with full control scheme, and are set to produce constant active power with unity power factor so that a better observation and comparison of performances with different controllers under the same constant disturbances can be achieved. In order to compare and distinguish between the VFC in [6] and the improved dual-mode VFC proposed in this paper, single-mode VFC represents the prior one in the rest of the paper.

TABLE I
VFC PARAMETERS

Parameter	Value
K_p	10.5
K_I	3.5
C	0.245
ε_1	0.1
ε_2	0.02

A. Dual-Mode VFC Versus Single-Mode VFC

The effectiveness of the proposed dual-mode VFC under constant consecutive large disturbances is demonstrated by comparing the system response with three sets of different controllers: traditional AGC and AVR, single-mode VFC and AGC, and proposed dual-mode VFC and AGC. The first disturbance is a 25% increase in active power demand of L1 at $t = 20s$, and the second disturbance is a 25% increase in active power demand of L2 at $t = 140s$. Prior to the disturbances, the system is in steady-state condition. The proposed dual-mode VFC parameters are given in Table I, obtained by trial-and-error. Note that the allowable voltage range is different based on the specific system condition, a range of $0.95 - 1.05$ p.u. is set for the VFC voltage constraints in this paper.

Fig.4 presents the system frequency response and per unit line-to-line voltages for G1 and L1 with different controllers, along with the switching signal $\sigma(t)$ for the dual-mode VFC. Generator G2 exhibits similar voltage response as G1 so is omitted. Observe that for the system with traditional AGC and AVR, the system frequency drops below 49.6Hz after both disturbances, which is not desirable [11]. On the other hand, the system frequency after the first disturbance has much smaller undershoot with both single-mode VFC and dual-mode VFC. Note that after the second disturbance, the proposed dual-mode VFC can still manage to regulate the system frequency with performance as good as that for the previous disturbance. However, the single-mode VFC fails to regulate the system frequency as well as before and the frequency drops to 49.7Hz. This is due to the fact that the SGs terminal voltages reach their limits as shown in Fig.4. After the first disturbance, the single-mode VFC brings the SGs terminal voltages down to a value which are near the 0.95 p.u. limit. When the second disturbance comes, the single-mode VFC tries to bring down the voltage again in order to restore the frequency, but since a limit is included in the VFC, it avoids the SGs terminal voltages to be out of the limit. Therefore, it also constraints the frequency regulation capability of the single-mode VFC. As a result, the single-mode VFC fails to restore the frequency as quickly as before and results in a large undershoot. On the other hand, the proposed dual-mode VFC successfully restore the SGs terminal voltages before the second disturbance, therefore, the frequency can be properly regulated when the second disturbance comes. Observe that after the dual-mode VFC switches from the FRM to VRM, the system frequency shows a small drop due to the deliberate restoration of the system voltage. However, the frequency deviation is still within $\pm 0.05Hz$, which is acceptable. As a result, the proposed dual-mode VFC significantly improves the system frequency response compared with the single-mode VFC.

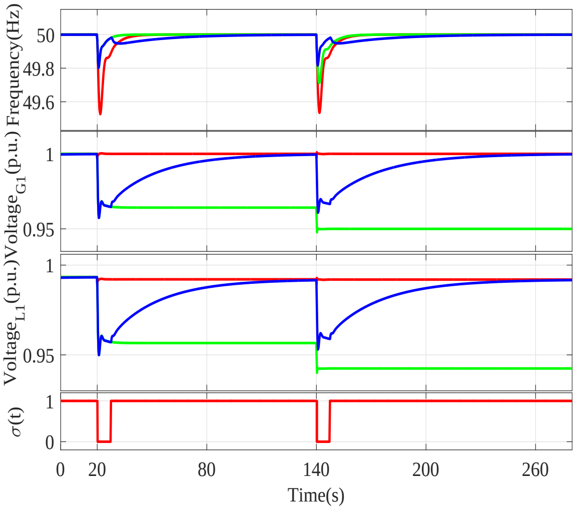

Fig. 4. System frequency response, per unit line-to-line voltages for G1 and L1 (red: AGC+AVR; green: AGC+single-mode VFC; blue: AGC+dual-mode VFC), along with the switching signal of the dual-mode VFC

Another thing to note is that although the limits in single-mode VFC can prevent the SGs terminal voltages from deviating from the nominal value too much, it cannot guarantee the voltages of every bus in the system are within the proper ± 0.05 p.u. range. It is shown in Fig 4 that with the single-mode VFC after the second disturbance, the SGs terminal voltages reach their 0.95 p.u. limits, but the operating voltage of L1 is settled to a value lower than 0.95 p.u. and remained unchanged, which is not desirable for loads. On the other hand, it has been examined that voltages of all buses are within the ± 0.95 p.u. range and can be restored with our proposed dual-mode VFC. It is due to the fact that the recovery of SGs terminal voltages results in a significant restoration of operating voltages of loads, as shown in Fig.4. As a result, a mitigation of the negative impact on loads caused by the intended regulation of system voltages in the FRM is achieved.

Note that further work can be done to incorporate local voltage measurement of every bus and communication between each bus and the SGs with the dual-mode VFC, so that once any bus voltage is out of a limit, the dual-mode VFC could be switched to the VRM accordingly to ensure a better voltage response.

B. Networked Microgrids Versus Single Microgrids

To demonstrate the superiority of the networked MGs over single MGs in terms of system response under disturbances, MG 1 is picked out from the original test system shown in Fig.1, and a disturbance of 25% increase in the active power demand of L1 is applied to both the networked MG system and single MG. Comparison in system response between the two systems is made with the same set of controllers, i.e. AGC

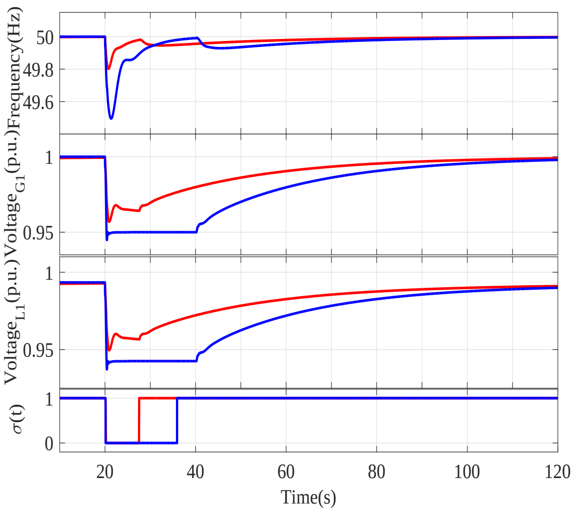

Fig. 5. System frequency response, per unit line-to-line voltages for G1 and L1, switching signal (red: networked MGs; blue: single MG)

and dual-mode VFC, and with the same parameters as in Table I. Fig.5 exhibits the system frequency response, per unit line-to-line voltages for G1 and L1, and the switching signal $\sigma(t)$. Obvious worsening in system response can be observed for the single MG. Compared with the networked MG system, the frequency and voltage deviation from the nominal value under the same disturbance are larger in the single MG, and the duration of the FRM is longer in the single MG due to the larger frequency deviation.

One important reason that the networked MG system can achieve a better system response under disturbances compared with single MGs is that each MG in the whole interconnected system can sense disturbances through the frequency fluctuation, and thereafter offers help to each other through the corresponding response of frequency controllers. As a result, the whole interconnected system becomes more reliable and robust to disturbances. Fig.6 shows the tie-line power of the networked MG system. It is shown that with the networked MG system, the disturbance happens in MG 1 leads to an increase in power transfer from MG 2 to MG 1, therefore the system frequency response is surely better than the single MG. Since the VFC in the FRM regulates system voltage according to frequency deviations, therefore the voltage response is also better in the networked MGs system. Also, it is shown that the tie-line power is finally restored to the initial scheduled value by AGC.

VI. CONCLUSIONS

Based on the characteristic of voltage-sensitive loads, a novel dual-mode VFC is proposed in this paper for a networked MG system, which cooperates with the conventional primary and secondary frequency controllers to mitigate the negative impact on loads, as well as to improve frequency response under consecutive disturbances. The proposed VFC has two modes: a fast acting FRM to quickly restore the system frequency upon a frequency deviation from the allowed limits, and a relatively slow VRM to gradually return the generator terminal voltage back to its nominal value after the frequency has been restored to a proper region. The effectiveness of the proposed controller and superiority of the networked MG system over single MGs in terms of system response under disturbances have been tested and validated through various simulations in PowerFactory.

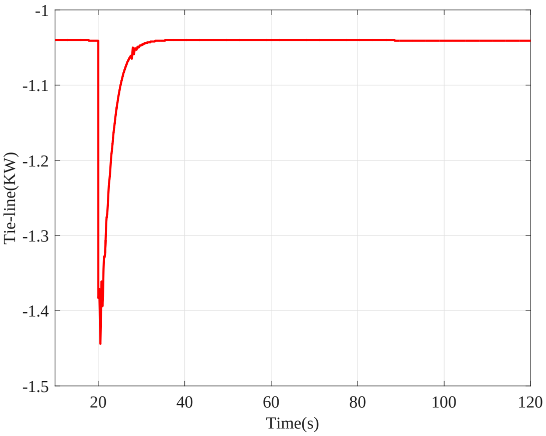

Fig. 6. Tie-line power

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