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Hierarchical Control for Multiple DC-Microgrids Clusters

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***Abstract*—DC microgrids (MGs) have gained research interest during the recent years because of many potential advantages as compared to the ac system. To ensure reliable operation of a low-voltage dc MG as well as its intelligent operation with the other DC MGs, a hierarchical control is proposed in this paper. In this hierarchy, primary control level is used to regulate the common bus voltage inside each MG locally. A voltage secondary control (VSC) is designed to eliminate the dc bus voltage deviation produced by primary level while guarantees proper operation of tertiary level. This secondary control acts not only as a central controller for the each MG individually, but also as a decentralized controller when dc MGs are connected together. This way, VSC maintains the dc bus voltage around the voltage reference using an averaging method. This allows the power flow control to be achieved at the same time since it can be accomplished only at the cost of having the voltage deviation inside the system. Neighboring communication is employed to exchange the voltage output of MGs to the neighbors using low bandwidth communication (LBC) network. Finally, a power flow control (PFC) is proposed to control the tie-line current between the MGs. The effectiveness of the proposed scheme is verified through detailed hardware-in-the-loop (HIL) simulations.**

I. INTRODUCTION

Microgrid (MG) has become an important conceptual electric power systems for smooth integration of distributed generations (DGs) and energy storage systems (ESS). Ac and dc MGs as well as hybrid MGs have been proposed for different applications in recent years [1]–[15]. While much of interest has largely focused on ac MGs [1]–[5], dc MGs are researched recently to facilitate integrating of modern electronic loads and alternative energy sources with dc output type such as photovoltaic (PV) system, fuel cell, and energy storages (e.g., secondary battery and super capacitor) [7]–[15]. Normally, dc MGs are proposed for power supply of applications with sensitive and/or dc loads like consumer electronics, electric vehicles, naval ships, space crafts, submarines, telecom systems and rural areas [8] to be benefited from increased power quality, and higher reliability and efficiency.

The advantages of dc MGs are summarized as 1) the conversion losses from sources to loads are reduced, thus enhancing the system efficiency; 2) there is no need for control of frequency and phase, reactive power, and power quality which are all big challenges in ac MGs. Furthermore, synchronization requirements for connection of DGs and ESSs to the bus and the main grid are not an issue in dc MGs; 3) in the grid connection mode, any blackout or voltage sag that may happen from the grid side does not affect the units inside the dc MG. Nevertheless, protection is still a big challenge in this new concept for dc systems and it is normally needed to construct new dc distribution lines while implementing dc MGs [15].

Although there is a significant increase of dc MG projects nowadays, we can still find lack of study about the overall control of these systems. A hierarchical multilevel control strategy has been introduced for dc MGs with three level of primary, secondary and tertiary control [1]. The primary control which is strictly local, deals with the inner voltage and current control loops and droop control of the dc sources. In this level, droop control which is a resistive virtual loop, provides the voltage reference to the inner control loops. However, droop control is not always the best control strategy specially when using renewable energy sources (RESs) and it is better to use the MPPT algorithms in order to absorb available free power from them [8]. The secondary control, which is conventionally based on a central controller, sets the reference of primary control such that deviations produced by the droop control are restored to maintain the dc MG voltage within the acceptable values. The tertiary control is responsible for managing the current flow from/to an external dc source, which can be a dc distribution system, another dc or ac MG, or dc/ac converter connected to the main grid.

As aforementioned, reliability improvement is a key point for dc MGs which has been addressed in some recent literatures [8]–[13]. In [9], bus selection strategies are introduced for redundancy in order to increased reliability in emergency operation. In [10], [11], distributed strategies based on dc bus signaling method have been proposed for controlling distributed generations such that the dc bus voltage level is employed as a carrier to perform different operation modes. However, use of this control strategy might be limited since voltage level varies due to resistive drop in different locations. A distributed control strategy is proposed in [8] for coordination of an autonomous low-voltage dc MG using power-line signaling method. In this method, frequency of small ac signal which is injected over the dc signal acts as a communication. Furthermore, low-bandwidth communication based distributed strategies have been proposed for secondary control of dc MGs recently in [12], [13] in order to enhance the load current sharing accuracy and regulate dc output voltage inside the dc MG.

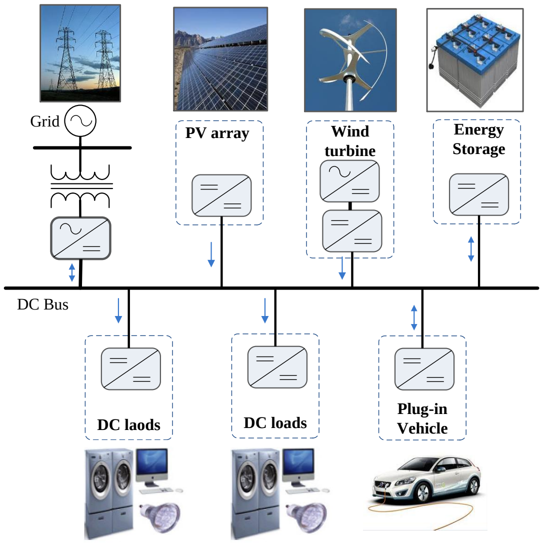


Fig. 1. Typical configuration of a low-voltage dc microgrid.

Another alternative to increase the reliability is to interconnect multiple dc MGs establishing dc MG clusters. This way, each dc MG will be able to absorb power from the other MGs in the case of emergency situation. However, overall control of the interconnected MGs and control of power flow between dc MGs raises new challenges.

In this paper, we propose a hierarchical control for dc MG clusters in order to enhance reliability inside these systems. In this general strategy, each MG has its own local primary control to regulate the common bus voltage. A secondary control is implemented for every MG to restore the voltage deviations. The secondary control is centralized for each individual MG but acts in a decentralized way when dc MGs are connected in order to have power flow between the MGs. Finally, a power flow control (PFC) is proposed to control the tie-line current between the MGs. The proposed decentralized voltage secondary controller (DVSC) requires communication in order to exchange the information among the MGs. Neighboring communication is implemented in this paper and the effect of communication delay is examined.

II. DC MICROGRID CONFIGURATION

Normally a dc MG consists of distributed energy resources (DER) and energy storage systems (ESS) which are supplying sort of electronic loads through a common dc bus. Fig. 1 shows general configuration of a low-voltage dc (LVDC) microgrid. DERs used in a LVDC microgrid can be various types such as photovoltaic (PV) arrays, fuel cells (FC), wind-turbine (WT) generators, and microturbines. PV and FC are more appropriate to be used in dc MGs since they produce dc voltage. However, WT and microturbine which generate voltage with varying frequency, require conversion to be connected to the dc bus and used in dc MGs.

On the other hand, due to transient response of sources, and the fact that they cannot be always available (in the case of renewable energy sources (RES)), ESSs are mandatory to be connected to the dc MG. Furthermore, they can be used for ancillary services like voltage regulation, power quality improvement and emergency power supply. Normally secondary batteries, super capacitors, and flywheels are used as an ESS. Batteries and capacitors can be directly connected to the dc bus, but flywheels are connected through a machine and a converter [14]. However, it is desired to connect the ESSs to the dc bus through converters supplying high reliable power to the loads.

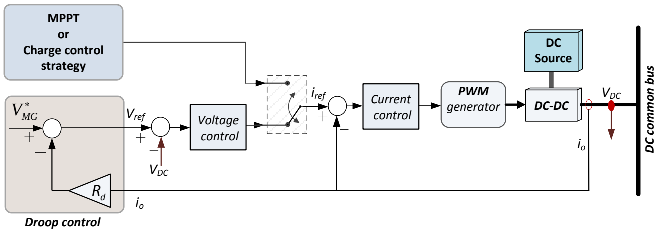


Fig. 2. Primary control of DC MGs.

DERs and ESSs are connected to a common bus establishing a dc MG. Low-voltage dc MGs are normally considered to have two dc voltage levels in the common bus: 1) low voltage (48 V) which for instance agrees with the standard telecom voltage and some home appliances like tabletop, LED lighting and entertainment systems; 2) high-voltage (380 V) which is chosen to coincide the standard intermediate dc voltage and to support some major home appliances. In these voltage dc levels, protection is not a particular concern since all power is fed from electronic power converters which are controllable and can provide active current limiting. Moreover, it provides enhanced safety, increases efficiency, and facilitates adoption when powering small appliances [16].

The common bus is linked to the sources through the power electronic interfaces. Depending on the source type and voltage, there could be one or two stages of power conversion as shown in Fig. 1. Nevertheless, last conversion stage is ordinarily a dc-dc converter. To connect different sources and loads to the dc MG, different dc-dc converters with different characteristics must be used [16]. The structure of these converters is simpler than ac-dc one, which results in higher efficiency and lower cost. Furthermore, comparing to the ac MG, dc one requires fewer power converters, and it is easier interfaced to the sources.

III. PRIMARY CONTROL

Primary control is employed locally for every source inside the MG in order to regulate the current injection into the common bus automatically. The primary control normally includes inner control loops and droop control strategy, as shown in Fig. 2. The inner loops are performed to regulate voltage and current while maintaining the system stable. These loops ensure that the actual voltage of each source is equal to its reference value. In order to connect a number of VSCs based sources in parallel, a virtual output impedance loop called droop control is needed. This control loop shares current between the units accordingly, and reduces the circulating

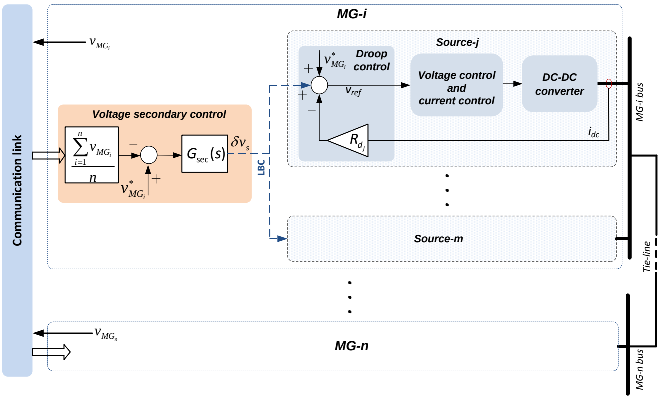


Fig. 3. Proposed voltage secondary control.

current if the voltage of the units is different. Moreover, it improves the dynamic performance of the source output voltage [1]. This control loops creates appropriate voltage reference for the voltage inner loop as follows

$$v_{ref} = v^*_{MG} - R_d \cdot i_o \tag{1}$$

with v^*_{MG} being MG voltage reference, i_o is the output current and R_d is the virtual resistance. To ensure low voltage deviation, low value of droop gain R_d is used. The larger droop gains, the more voltage deviation of the dc microgrid and better load sharing.

Although it has been proved that droop control is an efficient method for parallel operation of sources inside the MG, it is not the best solution for the RESs using the droop control and participating always in the voltage support. It is normally preferred to extract maximum available power from them when is possible using maximum power point tracking (MPPT) algorithms [17]. Moreover, appropriate methods should be considered in order to recover the state-of-charge (SOC) of the connected battery inside the dc MG. Constant voltage charging is normally applied when battery is discharged. It is worth mentioning that MPPT control of RESs and charging control of batteries act as a constant power source (CPS) and constant power load (CPL) respectively, since the bandwidth of these controllers are lower than the bandwidth of inner control loop [8]. Therefore, both control strategy are modeled as an adjustable current reference to produce set-point for the current inner loop as shown in Fig. 2.

IV. VOLTAGE SECONDARY CONTROL

As aforementioned, primary control is determined by a combination of mandatory droop control units (at least one for each MG) and optional CP units (CPS or CPL). Due to disbalanced between power consumption and production, this level of control introduces the deviation of the common dc bus voltage. In order to restore the voltage of MG to nominal value, a centralized voltage secondary control (CVSC) can be implemented. This control strategy which is usually realized with standard PI controller removes the voltage deviations inside the MG by sending an appropriate set-point (δv_s) (as shown in Fig. 3) to the primary loop of sourses using a low bandwidth communication (LBC). This signal changes the voltage reference of droop unit(s) accordingly by shifting the droop line up and down. This control loop could be also implemented in a decentralized way over the MG units using LBC to avoid having a single point failure.

On the other hand, in case that the MG is connected to the other dc MGs or another dc bus, the concept of tertiary control must be employed in order to control the power flow between them (see section V). The CVSC is used to remove the dc bus voltage steady state error, while power flow control can be accomplished only at the cost of having the voltage deviation inside the system. To cope with this, one preliminary solution is to operate secondary and tertiary levels independently. However, this is not a good solution since only one of the controllers can operate at the time. The other possibility would be to realize the tertiary control service by means of installing a dedicated converter in series with the power line through which the other MG or stiff dc grid are connected. Then, the secondary control can remain in operation, while the exchange power can be controlled by tertiary level. Although this method may solve the problem of the former solution, its implementation needs to change the system configuration which also has some cost.

In this paper, we propose a voltage secondary control (VSC) which includes both centralized and decentralized controller so that it will be able to regulate bus voltage around the nominal value while respecting the power flow control. In this strategy, if the MG operates individually it acts as a central controller for that MG, however, if it is connected to the other MGs or other dc buses it operates in a decentralized way (see Fig. 3). Needless to mention that this control strategy needs communication link between all the MGs, or at least neighbor MGs.

In this strategy which is based on averaging method, the average of all MGs voltage outputs ($\bar{v}_{MGs}$) is made based on the received voltage level of MGs buses through the communication link, compared with the voltage reference (v^*_{MG}), and the error processed through a compensator is sent to the primary level of all the units. The secondary control output signal (δv_s) can be distributed to a number of droop controlled units pass through a participation factor (α). Participation factor of batteries, for instance, can be according to their SOC ($0 < \alpha \leq 1$). The controller can be expressed as follows:

$$\begin{cases} \delta v_s = k_{Ps}\left(v^*_{MG} - \bar{v}_{MGs}\right) + k_{is}\int\left(v^*_{MG} - \bar{v}_{MGs}\right)dt \\ \bar{v}_{MGs} = \frac{\sum\limits_{i=1}^{n} v_{MG_i}}{n} \end{cases} \tag{2}$$

k_{ps} and k_{is} being the control parameters of proposed VSC, and n is number of MGs. General implementation of proposed VSC strategy is presented in Fig. 3.

In order to avoid peer-to-peer communication for the decentralized VSC, neighboring communication is one possibility

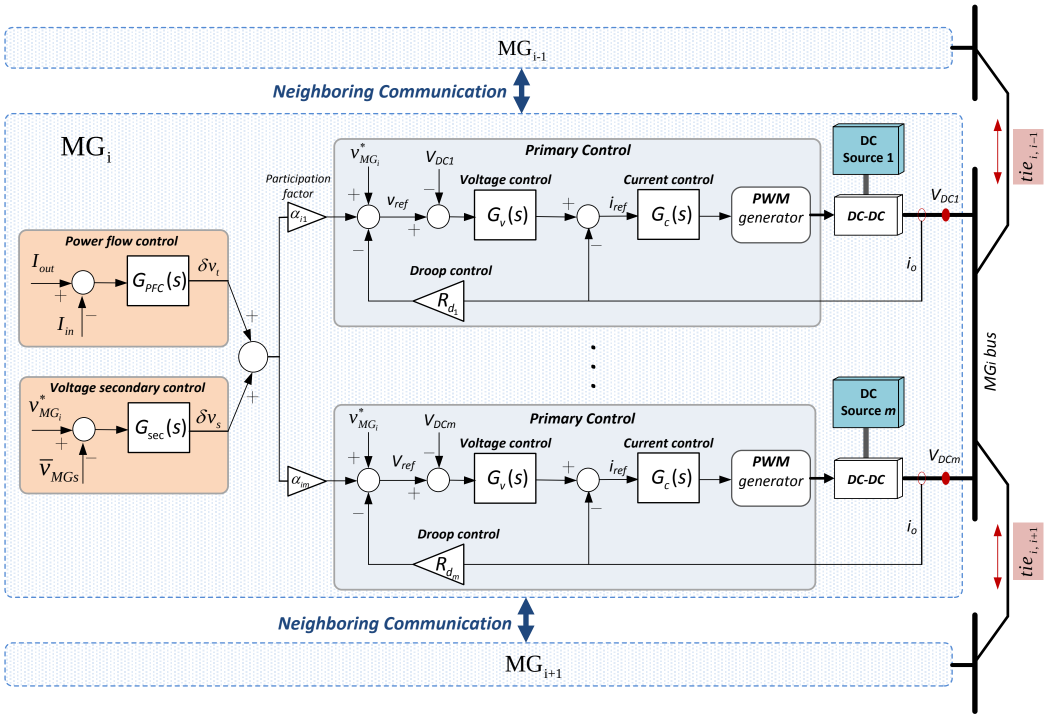


Fig. 4. Proposed Hierarchical control for multiple DC microgrid clusters.

that is proposed here. In this communication approach, every agent broadcast not only its new measurement to the other agents but also the last received measurements of its neighbor agents to those which are not neighbors together. This way, only neighbors communicate to each other and trafc jam in the network is reduced. One can notice that LBC can be used between all the MGs for redundancy just in case of having communication failure in neighboring communication.

V. POWER FLOW CONTROL

Expansion of a MG in terms of increase of load can be achieved by an expansion of energy sources and storage capacity. However, connection to the other neighbor MGs could be another good possibility in order to support the extra loads. Moreover, this can also improve the reliability of the MGs.

Once MGs are connected to each other (or to a stiff dc source), power flow can be controlled by changing the voltage inside the MG. To accomplish this goal, one solution is to employ a decentralized power flow control (DPFC) over MGs so that each MG controls the tie line with its neighbors according to a predefined reference. In this control strategy, as can be seen in Fig. 4, all imported/exported currents to/from the MG are measured, compared with the desired positive or negative current, depending whether we want to import or export energy, then pass it through a standard PI controller and send the output to droop control of sources inside the dc MG. The power flow controller can be expressed as follows:

$$\delta v_t = k_{pt}\left(I_{out} - I_{in}\right) + k_{it}\int\left(I_{out} - I_{in}\right)dt \qquad (3)$$

$$\begin{cases} I_{in} = \sum\limits_{k=1}^{n_1} i_k^* - i_k \\ I_{out} = \sum\limits_{j=1}^{n_2} i_j^* - i_j \end{cases} \qquad (4)$$

where k_{pt} and k_{it} are the PI parameters, n_1 and n_2 are number of MGs which inject and absorb power to/from the MG, respectively, and i^* is current reference which predefined by each MG to be injected or absorbed. The current reference can be also defined according to DGs power rates or SOC of batteries inside each MG. It is worth mentioning that similar to the VSC, for every droop controlled DG, different participation factor can be considered to support the power flow control. Fig. 4 presents general hierarchical control for interconnected dc MGs. Notice that the outputs of both secondary and tertiary control must be limited in order not to exceed the maximum voltage deviation.

VI. POWER HARDWARE-IN-THE-LOOP SIMULATION RESULTS

Hardware-in-the-loop (HIL) simulation results of three interconnected dc MGs is presented in order to show the feasibility of the proposed hierarchical control. As shown in Fig. 5, MGs are connected through high resistive-inductive lines, and each MG consists of four units are supporting some loads. PV and WT work in MPPT and two batteries work in droop controlled mode. For the simulation setup, the MGs voltage was selected at 48 V. Matlab/Simulink has been used for implementation of the proposed control methods, and neighboring communication method was developed in Matlab/Stateflow. However, the final code was compiled into a dSPACE ds1006 platform in order to have HIL simulations.

Fig. 6 shows a set of waveforms derived from implementation of proposed hierarchical scheme. In this figure, VSC is added in the first half of simulation, and after connecting MGs in the middle, power flow control is activated in the second half. In the first scenario of HIL simulation, only primary control operates inside the system and the MGs are disconnected having no current flow. In this period, some voltage deviations can be observed due to mismatch between production and consumption created by the droop control. Moreover, MGs are supporting different amount of loads, for instance MG_2 injects double current of MG_1. At t=0.6s, the VSC which is centralized for MGs individually starts to act in order to restore the voltage deviations. As can be seen, it is able to eliminate the MGs voltage steady state errors properly when they are not connected. Fig. 6(c) shows that MGs currents increase slightly in order to support the VSC action. Then, MGs are connected in the middle of simulation, however, no current flows between them as there is no voltage difference in the MGs. After activating the power flow controller at 3.4s, current references of 8A and 5A are imposed by this controller to be injected from MG_1 and MG_3 respectively, by producing some voltage deviation inside the MGs. At this moment, MGs currents changes accordingly as shown in Fig. 6(c) to follow the PFC action. As stated in section IV, as soon as PFC is activated VSC becomes decentralized in order to have current flow between the MGs. This way, VSC maintains the MGs voltages around the acceptable range while PFC controls the current flow.

Since the proposed VSC is implemented based on LBC, impact of communication delay is evaluated here. Performance of the VSC has been examined for different amount of fixed communication latency, 20ms, 50ms and 100ms. Fig. 7 shows the effect of mentioned communication delays on the VSC response when it tries to remove voltage deviations while the PFC is active. As can be seen, when the communication delay is set to 20 ms, there is no overshoot and oscillation in the dc output voltage. However, by considering bigger communication delays, the control system response starts to have oscillations and take the system toward instability.

VII. CONCLUSION

This paper presents a hierarchical for interconnected low-voltage DC microgrids. The primary control is a local controller which does not require any communication system, and achieves current sharing between the MGs units and regulates the dc bus voltage. A central secondary controller is implemented for restoration of MGs voltage deviations which uses low-bandwidth communication to send the appropriate reference for the droop control. Using this centralized controller, power flow control is impossible to achieve when MGs are connected due to this fact that power flow voltage is obtained at the expense of voltage deviations. In order to solve this problem, a new feature has been added to the voltage secondary control to make it decentralized when power flow control is required. This decentralized controller which is based on averaging the MGs bus voltages uses low-bandwidth

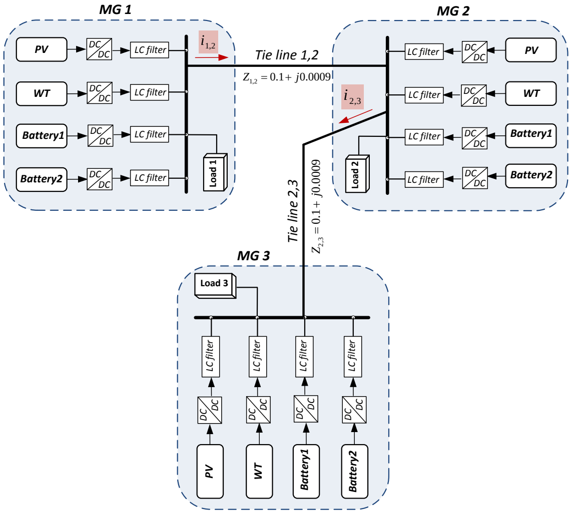
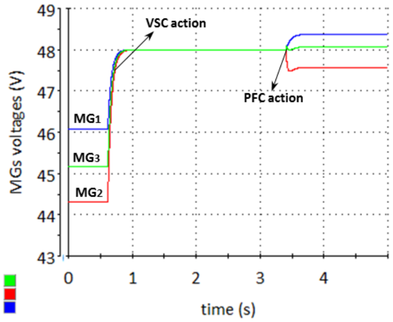
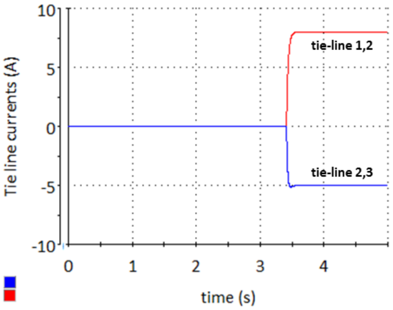


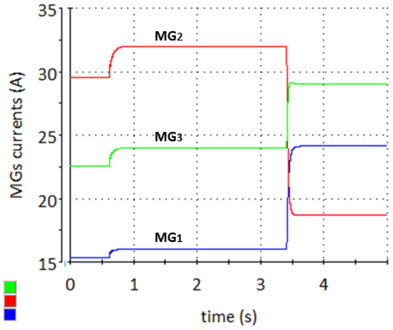
Fig. 5. HIL Simulation case study: Three interconected DC microgrids.



(a) microgrids voltages



(b) Tie line currents



(c) microgrids currents

Fig. 6. HIL simulation results .

TABLE I
ELECTRICAL SETUP AND CONTROL SYSTEM PARAMETERS

Parameter	Symbol	Value
Electrical parameters		
dc power supply	Vin	100 V
Input capacitance	C_1	2.2e-3 F
Total output capacitance	C_2	4×2.2e-3 F
Converter inductances	L	1.8e-3 H
Inductor+switch loss resistance	R_p	0.1 Ω
Switching frequency	f_{sw}	10 kHz
Primary Control		
Reference voltage	v^*_{MG}	48 V
Proportional current term	k_{pi}	2
Integral current term	k_{ii}	97
Proportional voltage term	k_{pv}	2
Integral voltage term	k_{iv}	97
Voltage secondary control		
proportional voltaage term	k_{ps}	0.1
Integral voltage term	k_{is}	20
Power flow control		
proportional power flow term	k_{pt}	0.05
Integral power flow term	k_{it}	10

communication between the MGs. The power flow control is implemented in order to conrol the tie-line current between the MGs. To verify the effectiveness of the proposed scheme, HIL simulation study is carried out.

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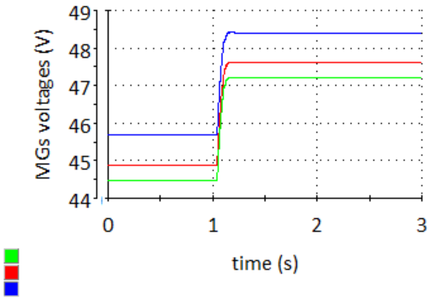
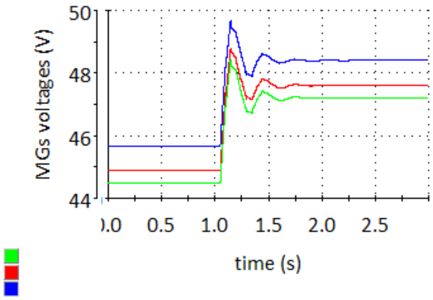
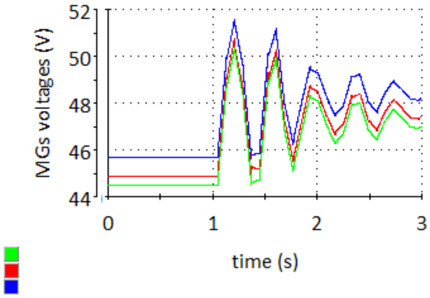


(a) 20ms delay



(b) 50ms delay



(c) 20ms delay

Fig. 7. Impact of communication delay on the proposed VSC performance.

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