

# A Suitable Power Transfer Control System for Interconnection Converter of DC Microgrids

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**Abstract.** The operation and control strategies for interconnection of DC microgrids have not been studied in previous researches. In this paper, an electrical model has been developed for DC microgrids and a suitable control system has been proposed for a DC/DC converter connecting two DC microgrids. Simulation results indicate the effectiveness of the proposed control strategy in power flow control and the cancellation of interactions between two DC microgrids.

## Keywords

DC Microgrid, Distributed Generation, Droop Control, Hysteresis Current Control.

## 1. Introduction

The interest in Distributed Generation (DG) is increasing due to technical, economical, reliability and environmental merits. As a result, a significant share of electricity will be generated and consumed locally in future electric power systems. Local aggregation of DG systems and electrical loads results in a Microgrid ( $\mu$ G). In order to meet energy, reliability, power quality, power back-up and peak shaving needs and to allow sharing of resources within a common infrastructure, multiple  $\mu$ Gs could be interconnected resulting in a power park [1]. The DC Microgrid (DC $\mu$ G) concept and consequently, DC power parks have provided a new paradigm for future distribution power systems. This is due to the fact that modern DG systems (e.g., fuel cells, microturbines, photovoltaic arrays and wind power systems) and modern electrical loads (e.g., sensitive loads, electronic loads and AC drives) have DC link stages for interconnection to the AC distribution network. As a result, DC $\mu$ Gs provide the best solution for the aggregation of these devices by integrating their DC power link stages. Previous researches have shown that DC $\mu$ Gs are preferable to both power frequency and high frequency AC  $\mu$ Gs from various technical, economical and reliability viewpoints [2]-[7].

The interconnection of DC $\mu$ Gs has not been studied in previous researches. A possible solution for interconnection of DC $\mu$ Gs could be the use of DC cables as their direct DC links. However, these links will result in the following disadvantages:

- Effective control of the DC link power flow will require considerable modifications in the design of controllers in both DC $\mu$ Gs and a supervisory control system to monitor the DC voltage changes at both DC $\mu$ Gs.
- Disturbances in one DC $\mu$ G will instantaneously affect the other DC $\mu$ G through the DC link.
- Design of controllers in each DC $\mu$ G will considerably be affected by dynamic properties of the DC link and the other DC $\mu$ G.
- $\mu$ Gs will be designed and controlled to meet local requirements according to their own independent operational standards and reliability and power quality guidelines [1], [4]-[7]. As a result, DC $\mu$ Gs will most probably have different DC voltage levels. DC $\mu$ Gs with different DC voltage levels can not be connected to each other by direct DC links.

As a result, DC cables are not an acceptable solution for interconnection of DC $\mu$ Gs. A modern solution for the interconnection of power systems has been the Power Electronic Conversion System (PESC) which provides the following benefits as compared to the direct DC link interconnection method:

- Added power flow control,
- Increased system flexibility and controllability,
- Improved system stability.

Consequently, a DC/DC converter named Interconnection Converter (ICC) has been used in this paper for the interconnection of two DC $\mu$ Gs. The DC/DC ICC can simply interconnect two DC $\mu$ Gs with different DC voltage levels. The main goal of this research is to develop a suitable control system for the DC/DC ICC which should

provide proper power flow control and the cancellation of interactions between the DC $\mu$ Gs.

## 2. Operation and Control of a DC $\mu$ G

The typical structure of a DC $\mu$ G is shown in Fig. 1.

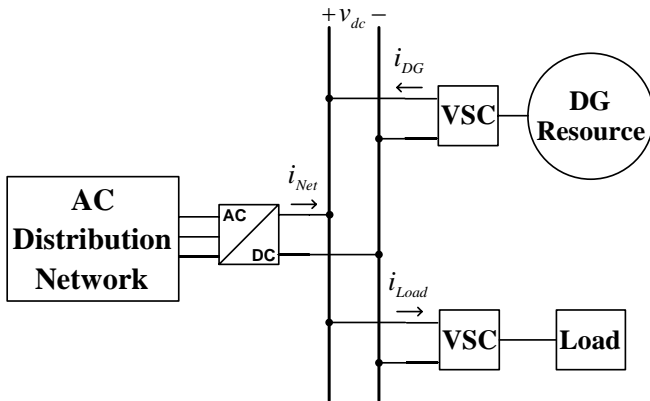


Fig. 1. General structure of DC $\mu$ G

All power electronic converters of the DC $\mu$ G are Voltage Source Converter (VSC) systems. Note that in order to avoid a cut set of voltage or current sources at converter switching, one side of a VSC should have a capacitive termination and the other side of the VSC should have an inductive termination. The DC $\mu$ G has a common capacitive DC terminal for its VSCs. The AC distribution network, the DG system and the load are connected to the inductive terminals of their interface VSCs. In this paper, each converter of the DC $\mu$ G is named considering its inductive side subsystem, i.e. the network converter, the DG converter and the load converter.

Previous researches have developed several operation and control strategies for subsystems of a DC $\mu$ G. Considering technical and economical issues, the following operation and control strategies have been selected for DC $\mu$ Gs of this paper:

- The DC bus voltage should be adjusted within its specified limits in order to meet the VSCs requirements [4]-[7].
- The DG system controller should be designed to meet its technical and economical constraints such as maximum/optimum power/efficiency operation [4], [5].
- The load voltage should be regulated to meet its requirements [4]-[7].
- The DC $\mu$ G operation and control should be independent from fast communication systems [4]-[6].
- The DG and the load should be decoupled from disturbances of the neighboring subsystems [7].

To achieve all the above characteristics, the following control systems have been proposed in [2] and [3]:

- The network converter incorporates a Hysteresis Current Control (HCC) Pulse Width Modulation (PWM) system whose reference current is specified by a DC $\mu$ G bus voltage droop controller.
- The DG converter incorporates an HCC PWM system whose reference current is specified by a local DG controller which considers the DG resource technical and economical generation requirements.
- The load converter incorporates a linear PWM system whose reference signal is specified by a local load controller which considers the load technical and economical supply requirements.

Note that each local controller of a  $\mu$ G should be coordinated by the  $\mu$ G central controller which is responsible for the optimization of the  $\mu$ G operation [1], [8].

## 3. DC $\mu$ G Modeling

According to the load-generation voltage control concept in DC distribution systems, the original and large signal values of the DC $\mu$ G bus voltage are the same [3]. This is due to the fact that the capacitive terminals of VSCs do not include high frequency switching waveforms. As DC $\mu$ G bus voltages are the only signals from the DC $\mu$ Gs which interact with the DC/DC ICC, detailed and large signal modeling of the DC $\mu$ Gs would provide the same results for studying the DC/DC ICC. As a result, the large signal model of the DC $\mu$ G has been developed in this paper. Note that the large signal model of a power electronic system is derived from its detailed model by time averaging of high frequency switching waveforms.

The HCC reference currents of the network converter and the DG converter are smooth PWM signals due to slower dynamics of the DC $\mu$ G voltage droop controller and the local DG controller in comparison to the HCC fast switching operation. Thus, the HCC VSC current error is normally maintained within the hysteresis band. As a result, the HCC VSC current is equal to its reference current at frequencies much lower than the switching frequency. In other words, the large signal value of the HCC VSC output current is equal to its reference current. Thus, the large signal behavior of the network converter and the DG converter are merely determined by the DC $\mu$ G voltage droop controller and the local DG controller, respectively.

The PWM reference voltage of the load converter is a smooth signal due to implementation of linear regulators and slower dynamics of the local load controller in comparison to the voltage PWM fast switching operation. Thus, the load terminal voltage is equal to its reference voltage at frequencies much lower than the switching frequency. In other words, the large signal value of the load voltage is equal to its reference voltage. As a result, the large signal behavior of the load converter is merely determined by the local load controller.

As modeling of the local DG and load controllers is not required for purposes of this research, the DG and the load systems have been modeled as independent current sources in the large signal modeling of the DCμG. The capacitive DC bus is assumed to be lossless and has been modeled by an equivalent capacitor named DC bus capacitor  $C_{dc}$  which represents the total required DC bus capacitor for the DCμG VSCs. As a result, for the DCμG shown in Fig. 1 we have:

$$i_{Net} = \frac{V_{ref} - v_{dc}}{R_d} = C_{dc} \frac{dv_{dc}}{dt} + i_{Load} - i_{DG} \quad (1)$$

where  $i_{Net}$  is the network converter current,  $V_{ref}$  is the reference DC bus voltage,  $v_{dc}$  is the DC bus voltage and  $R_d$  is the droop coefficient. Using (1), we have:

$$P_{Net} = V_{dc} \cdot \left( \frac{V_{ref} - V_{dc}}{R_d} \right) = \frac{\delta(1-\delta)}{R_d} \cdot V_{ref}^2 \quad (2)$$

where  $P_{Net}$  is the steady state active power of the network converter,  $V_{dc}$  is the steady state DC bus voltage and  $\delta$  is the voltage droop.

The droop coefficient is selected to obtain an acceptable  $\delta$  at rated power condition of the network converter. Thus, using (2),  $R_d$  can be obtained by the following equation:

$$R_d = \frac{\delta_n(1-\delta_n)}{P_{Net,rated}} \cdot V_{ref}^2 \quad (3)$$

where  $\delta_n$  is the nominal voltage droop and  $P_{Net,rated}$  is the rated power of the network converter.

Unexpected changes of active power in DCμG can result in out of range DC bus voltage and the shutdown of the DCμG. In order to prevent unexpected unbalancing of active power in a DCμG, the installation of power leveling units such as flywheels has been proposed in [4]. Power leveling units are costly and have complicated system operation and control. A new design approach is used in this research which eliminates the need for power leveling units in a DCμG. In this paper,  $P_{Net,rated}$  is proposed to be selected equal to maximum possible change of active power in the DC bus considering all operating conditions of DG systems and loads. In other words, the maximum value of the power injected to and absorbed from the DC bus is chosen for  $P_{Net,rated}$ . In this way, the DC voltage droop controller would maintain the DC bus voltage within the specified limits in all conditions. In previous papers [2], [3] of the authors, the rated power of the network converters have been selected equal to maximum value of total DG power and total load power which has resulted in effective active power balancing in all operating conditions of DG resources and loads without requiring power leveling units. In interconnected DCμGs of this research, the power transfer between DCμGs is proposed to be considered in

the selection of the rated power of network converters in order to take all possible operation condition into account.

Using (1), the characteristic polynomial of the DCμG voltage control system is obtained as follows:

$$R_d C_{dc} s + 1 = Ts + 1 \quad (4)$$

where  $s$  is the Laplace transform operator and  $T$  is the time constant of the DC voltage droop controller. Using (4),  $C_{dc}$  is designed to give the DC voltage droop controller a specified  $T$  as follows:

$$C_{dc} = \frac{T}{R_d} \quad (5)$$

The developed large signal model of the DCμG is illustrated in Fig. 2.

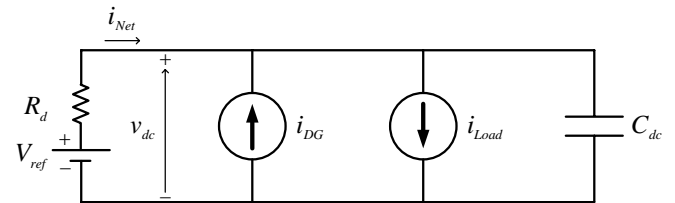


Fig. 2. DCμG model

As shown in Fig. 2, the network converter is modeled using (1) as a DC voltage source of  $V_{ref}$  in series with a resistor of  $R_d$ . The DG and load systems are modeled as independent current sources of  $i_{DG}$  and  $i_{Load}$ , respectively. As explained before, the large signal modeling of the DCμGs in this paper is just for simplification and it is not an approximation.

#### 4. DC Power Park

Fig. 3 illustrates the DC power park which has been studied in this paper.

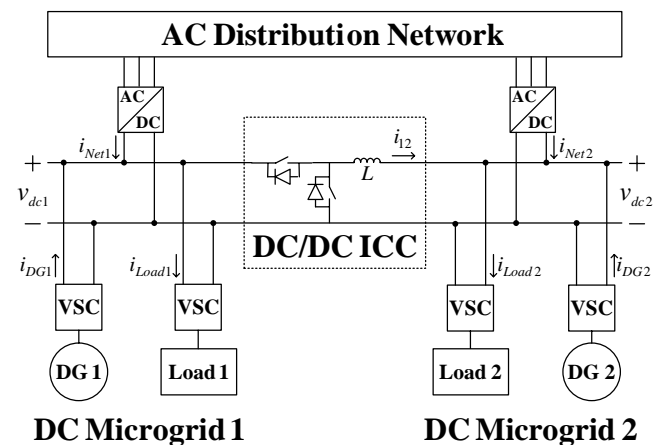


Fig. 3. DC power park

This DC power park includes two DC $\mu$ Gs named DC $\mu$ G1 and DC $\mu$ G2 which have been connected by a DC/DC ICC. A suitable control system should be developed for the DC/DC ICC in this section. DC $\mu$ G1 and DC $\mu$ G2 are assumed to have the general structure of DC $\mu$ Gs and DC $\mu$ G1 is assumed to have a higher DC voltage level than DC $\mu$ G2. The DC/DC ICC has a DC/DC VSC topology with IGBT switches. For proper switching, operation and control of a DC/DC VSC, the DC voltage level at the capacitive terminal must be higher than the DC voltage level at the inductive terminal. As a result, the inductor  $L$  in Fig. 3 has been installed in the DC $\mu$ G2 side of the DC/DC ICC.

Fig. 4 illustrates the DC power park model. The losses of the connecting DC cables have not been considered for the interconnection of DC $\mu$ Gs. DC $\mu$ G1 and DC $\mu$ G2 have been modeled using the large signal model of DC $\mu$ Gs. According to the goals of this research, operation and control of the DC/DC ICC should be studied. As a result, detailed model of the DC/DC ICC has been used for modeling of the DC power park in this paper.

Considering technical and economical issues which are generally taken into account for power systems, the following points are assumed to design a suitable control system for the DC/DC ICC:

- Proper regulation of power flow between the DC $\mu$ Gs
- Cancellation of interactions between the DC $\mu$ Gs

### 5. Proposed Control System for DC/DC ICC

The control system of the DC/DC ICC controller should have a fast dynamic response to changes of scheduled transfer power reference in order to properly regulate the power flow between the DC $\mu$ Gs. Furthermore, considering the possible DC voltage changes, the control system of the DC/DC ICC should be insensitive to these variations in both DC $\mu$ Gs. As a result, the DC/DC ICC control system should have the following characteristics:

- Fast dynamic response
- Insensitivity to system parameters variations

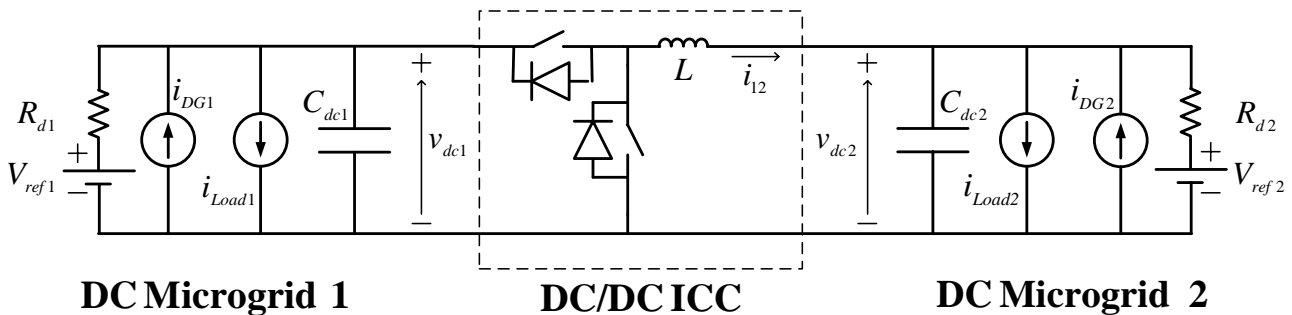


Fig. 4. DC power park model

HCC is the simplest PWM system which has the above characteristics [9]. Thus, HCC has been used for the DC/DC ICC and its reference current is proposed to be calculated as follows:

$$i_{12,ref} = \frac{P_{12,ref}}{v_{dc2}} \quad (6)$$

where  $i_{12,ref}$  is the HCC reference current and  $P_{12,ref}$  is the scheduled transfer power reference.

It must be noted that  $i_{12,ref}$  is the reference current for control of  $i_{12}$  shown in Fig. 3.  $i_{12,ref}$  and  $i_{12}$  are the inputs of a two level hysteresis comparator in the HCC system. As it can be seen, (6) is based on an instantaneous power regulation resulting in faster dynamic response than average power regulation methods.

The switching frequency of HCC systems is variable. Thus, the maximum switching frequency of the DC/DC ICC should be limited to an acceptable value. This issue is considered in the design of the inductor  $L$  in Fig. 4. In an arbitrary switching cycle of the DC/DC ICC, the following equation is obtained according to the HCC concept:

$$h = i_{12,max} - i_{12,min} = \frac{V_{dc1} - V_{dc2}}{Lf_{sw}} D \quad (7)$$

and

$$D = \frac{V_{dc2}}{V_{dc1}} = \frac{1 - \delta_2}{1 - \delta_1} \cdot \frac{V_{ref2}}{V_{ref1}} \quad (8)$$

where  $h$  is the fixed hysteresis band,  $i_{12,max}$  is the maximum value of  $i_{12}$ ,  $i_{12,min}$  is the minimum value of  $i_{12}$ ,  $f_{sw}$  is the switching frequency and  $D$  is the duty ratio.

Thus, switching frequency of the DC/DC ICC is obtained as a function of  $\delta_1$  and  $\delta_2$  by the following equation:

$$f_{sw} = \frac{(1 - \delta_2)V_{ref2}}{Lh} \cdot \left( 1 - \frac{1 - \delta_2}{1 - \delta_1} \cdot \frac{V_{ref2}}{V_{ref1}} \right) \quad (9)$$

Using (9), the maximum value of  $f_{sw}$  is obtained considering the following conditions:

$$\begin{cases} \delta_1 = -\delta_{n1} \\ \delta_2 = 1 - \frac{1 + \delta_{n1}}{2} \cdot \frac{V_{ref1}}{V_{ref2}} \end{cases} \quad (10)$$

Substituting (10) into (9), the inductor  $L$  can be obtained as follows:

$$L = \frac{V_{ref1}}{4hf_{sw,n}} \cdot (1 + \delta_{n1}) \quad (11)$$

where  $f_{sw,n}$  is the acceptable switching frequency of the DC/DC ICC.

## 6. Simulation Results

The system shown in Fig. 4 has been modeled and simulated by PSCAD/EMTDC. The parameters given in Table I have been selected for DC $\mu$ Gs. The parameters of the DC/DC ICC are given in Table II. The system parameters calculated from the design procedure of this paper have been listed in Table III.

TABLE I. - Parameters of DC $\mu$ Gs

Parameter	DC $\mu$ G1	DC $\mu$ G2
$V_{ref}$	600 V	270 V
$\delta_n$	0.05	0.05
$T$	20 ms	20 ms
DG rated power	60 kW	10 kW
Load rated power	30 kW	20 kW

TABLE II. - Parameters of DC/DC ICC

$P_{12,ref}$	(-15) to (+35) kW
$h$	5 A
$f_{sw,n}$	10 kHz

TABLE III  
CALCULATED SYSTEM PARAMETERS

Parameters			Equation
DC $\mu$ G1	$R_d$	0.228	(3)
	$C_{dc}$	87.72 mF	(5)
DC $\mu$ G2	$R_d$	0.07695	(3)
	$C_{dc}$	259.91 mF	(5)
ICC	$L$	3.15 mH	(11)

Note that considering the proposed design approach of this paper, the rated powers of the network converters have been selected as follows:

$$P_{Net1, rated} = \max\{60 + 15, 30 + 35\} = 75 \text{ kW}$$

and

$$P_{Net2, rated} = \max\{10 + 35, 20 + 15\} = 45 \text{ kW}$$

### A. Changes in Scheduled Transfer Power Reference

In this section, the system performance under changes of  $P_{12,ref}$  is studied. The DG and load powers in both DC $\mu$ Gs are assumed to have rated values of Table I. Fig. 5 illustrates  $P_{12,ref}$  and the instantaneous active power of the DC/DC ICC.

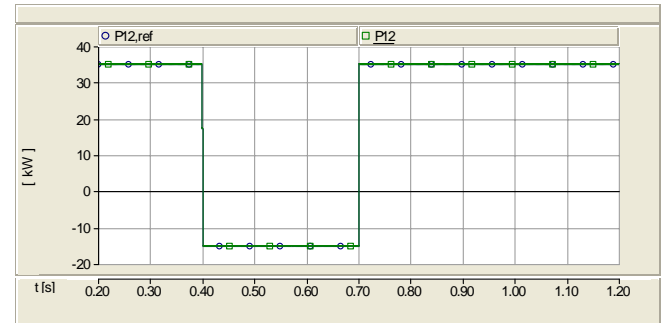


Fig. 5. Transfer power reference and power of DC/DC ICC

The DC bus voltages of DC $\mu$ G1 and DC $\mu$ G2 are illustrated in Fig. 6. Instantaneous active powers of the network converters in DC $\mu$ G1 and DC $\mu$ G2 are shown in Fig. 7.

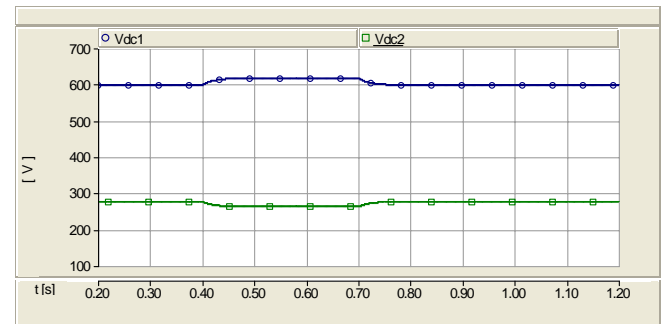


Fig. 6. DC bus voltage of DC $\mu$ G1 and DC $\mu$ G2

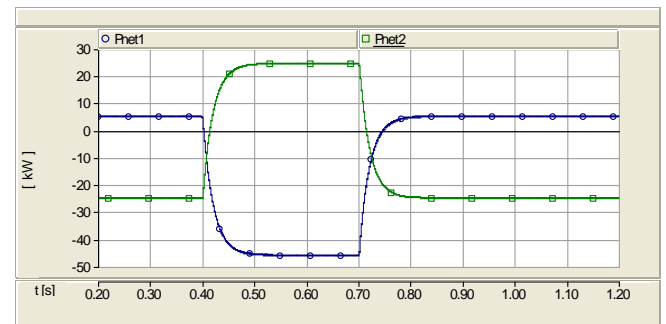


Fig. 7. Active power of the network converters

In the steady state condition, we have  $P_{Net1} = 5.25 \text{ kW}$ ,  $V_{dc1} = 597.97 \text{ V}$ ,  $P_{Net2} = -24.75 \text{ kW}$  and  $V_{dc2} = 278.35 \text{ V}$ . These results can be verified by (2). As shown in Fig. 6, the DC bus voltages are maintained within specified limits. This indicates the good performance of the DC voltage droop controller. As shown in Fig. 5, the active power of

the DC/DC ICC effectively follows the scheduled transfer power reference. This indicates the effectiveness of the proposed control system for the DC/DC ICC.

### B. Changes in DG and Load Power of DCμGs

In this section, the system performance under changes in active powers of the DG resource and the load in both DCμGs is studied. The scheduled transfer power reference is assumed constant. Fig. 8 illustrates  $P_{12,ref}$  and the instantaneous active power of the DC/DC ICC.

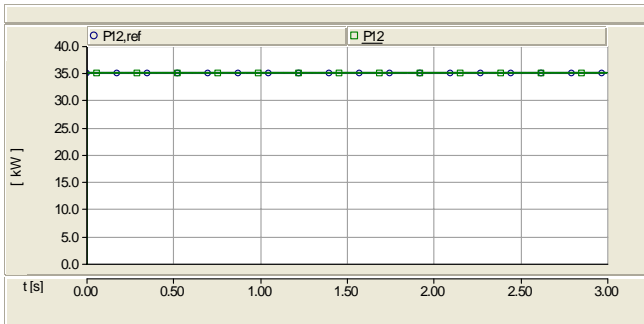


Fig. 8. Transfer power reference and power of DC/DC ICC

The active powers of the DG resource, the load power and the network converter of DCμG1 and DCμG2 are illustrated in Fig. 9 and Fig. 10, respectively.

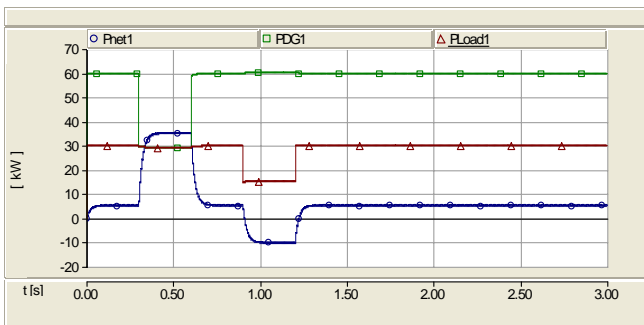


Fig. 9. Power of DG, load and network converter of DCμG1

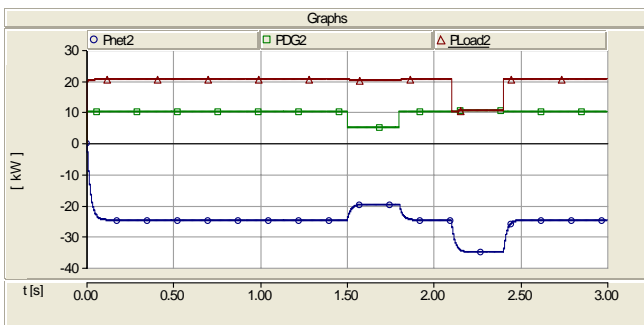


Fig. 10. Power of DG, load and network converter of DCμG2

The DC bus voltages of DCμG1 and DCμG2 are shown in Fig. 11.

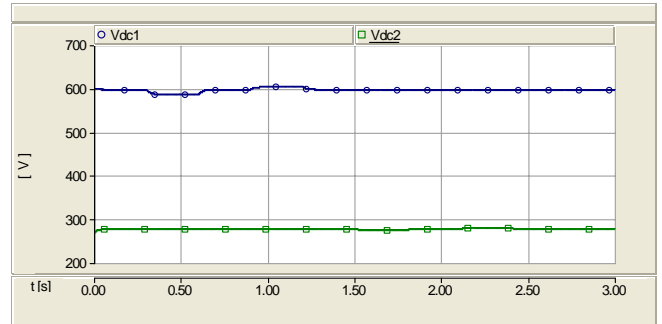


Fig. 11. DC bus voltage of DCμG1 and DCμG2

In the steady state condition, the obtained results are the same as the previous simulation and therefore they are also verified by (2). As shown in Fig. 11, the DC bus voltages are maintained within specified limits. This indicates the effectiveness of the DC voltage droop controller. Furthermore, it can be seen that the DC bus voltage of either DCμG is not changed due to changes in the DG or load power in the other DCμG. As a result, disturbances in one DCμG have no effect on the other DCμG. This indicates the good performance of the proposed control system for the DC/DC ICC in the cancellation of interactions between DCμGs. As illustrated in Fig. 8, the instantaneous active power of the DC/DC ICC is constant during changes in DG or load power of both DCμGs. This indicates the effectiveness of the proposed control system for the DC/DC ICC in the exact regulation of power transfer between the DCμGs.

## 7. Conclusion

The operation and control strategies for the interconnection of DCμGs have not been studied in previous researches. In this paper, a suitable control strategy has been developed for a DC/DC voltage source converter which interconnects two DCμGs. The proposed control system for this converter incorporates an instantaneous power-based reference current calculator for a two level hysteresis current regulator. Also, a large signal model of DCμGs has been developed which can effectively be used to study the interactions of DCμGs in a DC power park. This paper also proposes a new approach to design the AC network interface converter controller which eliminates the need for costly power leveling units and overcomes unexpected power changes in DCμGs. Simulation results indicate that the proposed control strategy can properly regulate the instantaneous power transfer and can eliminate the interactions between interconnected DCμGs.

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