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New Control Strategy of Interlinking Converters as The key Segment of Hybrid AC-DC Microgrids

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Abstract: This paper is concerned with presenting control strategy for interlink converters in hybrid microgrids. When both ac microgrids (AC-MG) and dc microgrids (DC-MG) are in the vicinity of each other, they can be interconnected via ac-dc converters, known as interlinking converters (ICs), making it possible to exchange energy between two grids. Common methods employed in IC control strategy use frequency variation and current-controlled method (CCM) in their structure. This method requires the frequency variation at IC ac-side to be large, leading to poor power quality and stability of AC-MG. Furthermore, CCM does not directly regulate the IC ac-side voltage, which again deteriorates the IC ac-side voltage quality. The proposed strategy is based on droop method, similar to what is used in the autonomous control of sources in an AC-MG. This technique uses voltage-controlled method (VCM) and does not need frequency measurement in its structure. This considerably improves the voltage quality of AC-MG. The derivation of appropriate droop characteristic is explained. Time domain simulation is used to verify the performance of the proposed method. The small-signal stability of the system is studied. It is shown how by introducing a proper virtual impedance, the small-signal stability of the system can be improved.

1. Introduction

Distributed energy resources (DER) and microgrids are two new concepts in power systems which have attracted great attention in recent years [1, 2]. A microgrid is a part of a distribution network with at least one DER which can operate independently as an island when necessary [2]. Many types of DERs such as photovoltaic (PV) panels, fuel cells (FC) and microturbines (MT) produce energy in the form of dc and thus need an dc-ac power converters to be connected to ac grid. On the other hand, many existing loads such as variable-speed drives, compact fluorescent lamps and computers which constitute a major part of grid load are dc load in nature and convert ac power to dc before utilizing it. Therefore, in order to reduce energy conversion stages and improve efficiency, dc grids and consequently dc microgrids (DC-MG) have been recently attracted the attention of researchers [3, 4]. As ac loads and ac microgrids (AC-MG) still are the majority of grid loads, a structure consisting of both AC-MG and DC-MG, also known as hybrid microgrid (HMG), has been proposed [4-7].

In a HMG, as shown in Fig. 1, two microgrids are connected together via interlinking converters (ICs). In standalone mode of operation, which is the subject of this research work, and when decentralized control strategy is employed, the existing sources in both microgrids are responsible for maintaining acceptable voltage/frequency and supply-demand balance. The most common method to accomplish this task is to use droop control strategy [4, 8]. When two microgrids are connected together, the supply-demand balance and power sharing can be expanded throughout HMG by exchanging power between two microgrids [9, 10]. This results in many advantages such as lower chance of an overstressed source located somewhere in HMG, lower reserving capacity requirement and lower variation in sources power demand [9, 11].

Power-frequency droop characteristic is conventionally used in AC-MG sources to realize adequate power sharing among them. Similarly, power-voltage droop characteristic is employed in DC-MG sources to achieve desirable power sharing among them. When it comes to a HMG, a proper strategy is needed for ICs such that power sharing between two microgrids takes place. In [9-13], it has been suggested to use per-unit frequency and voltage in order to determine the reference active power for ICs and consequently balance supply-demand between two microgrids. However, sensing these variables is rather difficult due to the small range of their variation. Consequently, the overall control system performance may not be adequate [9, 11]. It should be noted that such limitations are not prominent in each microgrid because source droop control strategy requires the sensing of wider power variations through its terminal voltages and currents [9, 11]. In order to reduce this sensitivity in power sharing, the slope of P-V and P-f droop characteristics respectively in DC-MG and AC-MG has set to 5% or higher [9, 11, 12, 14]. However, such a large slope results in large frequency variation which is usually not acceptable with regards to power quality standards [15]. Secondary control can be used to recover the frequency to its nominal value [4], but the delay associated with secondary control [16] may not be acceptable. Furthermore, secondary control impose more cost on system due to the need to communication links.

Large slope of P-f droop characteristic also lead to inadequate stability [17]. Using virtual impedance is a well-known method in alleviating this problem [18]. However, the large slope of P-f characteristic and consequently the large frequency variation requires a large virtual impedance which could result in high voltage drop and angle instability.

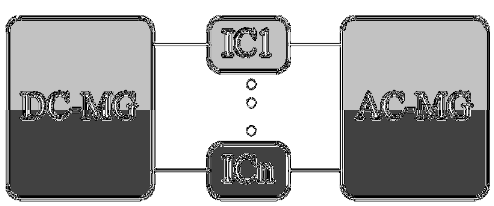


Fig.1. *HMG general structure*

In a control strategy proposed for IC [9, 11-13], the ac-side active and reactive power references are calculated and usually realized using current controlled method (CCM) [19]. This strategy may lead to unacceptable voltage quality at IC ac bus.

In this paper, a new control strategy for ICs has been proposed for proportional power sharing among all sources in a HMG. In the proposed strategy, which has been inspired by AC-MG control strategy, the power injected by ICs to AC-MG terminal and dc voltage at DC-MG terminal are measured. Based on these information, and using a modified droop characteristic, the voltage and frequency of IC is calculated. The determined frequency and voltage references are realized by voltage controlled method (VCM). Such a strategy does not need the AC-MG frequency variation measurement and thus the slope of P-f characteristic can be chosen small, leading to small and acceptable frequency variation and better voltage quality due to VCM.

This paper is organized as follows. Section 2 explains conventional control methods in AC- and DC-MGs. The general approach of power sharing in HMGs proposed by some other researchers has been briefly described in Sec. 3. Section 4 presents the proposed control strategy for ICs in a HMG. Simulation results are shown in Sec. 5. In section 6, the stability and dynamic analysis of proposed strategy is presented.

2. Conventional control strategy of AC- and DC-MGs

In this section, conventional control strategies associated with AC- and DC-MGs are explained. This paves the way for explaining IC control strategy and power sharing method in a HMG in the next sections.

2.1. Conventional control strategy of an AC-MG

A common technique for the decentralized control of AC-MGs is to use droop control method [2, 4, 8]. This technique results in proper voltage and frequency control throughout an AC-MG and maintains supply-demand balance and power sharing among ac sources. Droop characteristics for the i*th* ac source is given by

$$f_i = f_0 - m_{ac,i} \times P_{ac,i} \qquad (1)$$

$$V_{ac,i} = V_{0ac} - n_{ac,i} \times Q_{ac,i} \qquad (2)$$

where f_i and $V_{ac,i}$ are the frequency and amplitude of the output voltage reference, f_0 and V_{0ac} are respectively the frequency and voltage at no load, $P_{ac,i}$ and $Q_{ac,i}$ are active and reactive generated powers and $m_{ac,i}$ and $n_{ac,i}$ are droop slopes in i*th* ac source. In (1), $m_{ac,i}$ is calculated as the ratio of intended frequency variation range to the rated source power, $P_{ac,i}$. Similarly, the slope of Q-V droop characteristic is determined. Such an strategy will result in desirable power sharing among ac sources [20, 21].

In the conventional control of ac sources in an AC-MG, the active and reactive power are measured and low-pass filtered to calculate f_i and $V_{ac,i}$ based on (1) and (2). Consequently, VCM is employed to realize f_i and $V_{ac,i}$ [4, 8, 19]. Fig. 2a illustrates the general structure of a converter-based three-phase ac source. The general block diagram associated with the conventional control of such converter is shown in Fig. 2b. Furthermore, Fig 2c shows how VCM is realized in synchronous rotating frame. The parameters associated with these block diagrams are shown in Fig. 2a.

2.2. Conventional Control Strategy of a DC-MG

Using droop characteristic is also common in the decentralized control of dc sources in a DC-MG [3, 4]. Droop characteristics for the i*th* dc source in a DC-MG is given by

$$V_{dc,i} = V_{0dc} - m_{dc,i} \times P_{dc,i} \qquad (3)$$

where $V_{dc,i}$ is the amplitude of the output voltage reference, V_{0dc} is voltage at no load, $P_{dc,i}$ is active generated power and $m_{dc,i}$ is droop slope in i*th* dc source. Again, similar to AC-MG, the slop of P-V characteristic is calculated as the ratio of intended voltage variation range to the rated source power, $P_{dc,i}$.

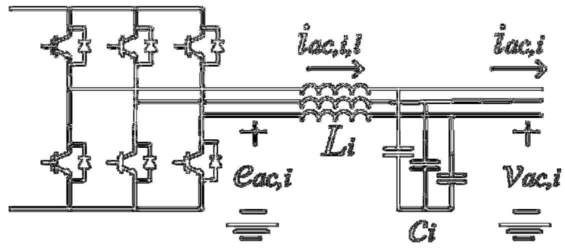
3. Power sharing in a HMG

The advantages of forming a HMG by interconnecting two DC- and AC-MGs via ICs was stated in the introduction. In this section, a strategy proposed for the control of ICs is explained.

Frequency is a global parameter and is the same throughout an AC-MG. Based on (1), any increase in power demand in an AC-MG will follow by a decrease in grid frequency, *f*. Therefore, the relative amount of frequency deviation with respect to the intended frequency variation range is a good indication of the relative occupied capacity of sources in an AC-MG. In this way, the per-unit frequency in the AC-MG is defined as

$$f_{pu} = \frac{f - f_{ave}}{\Delta f / 2} \qquad (4)$$

where Δf is the intended frequency variation range and f_{ave} is $f_0 - \Delta f/2$. Similarly, the relative amount of voltage deviation with respect to the intended voltage variation range is a good indication of the relative occupied capacity of sources in a DC-MG. Therefore, the per-unit dc voltage in the DC-MG is defined as



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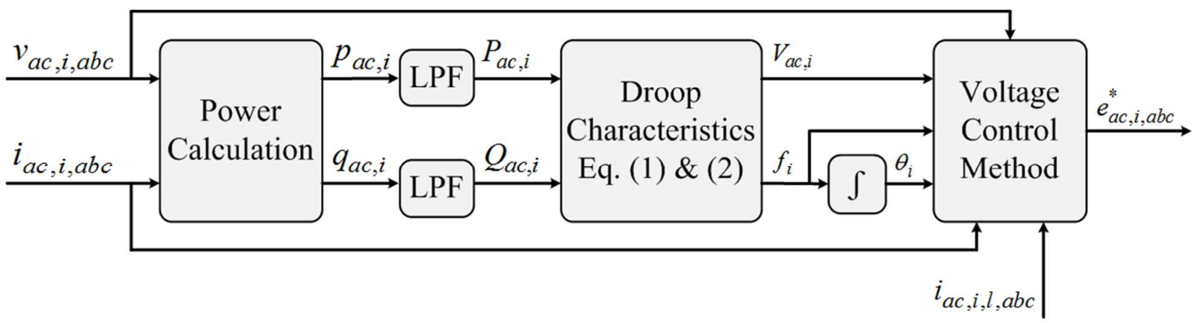

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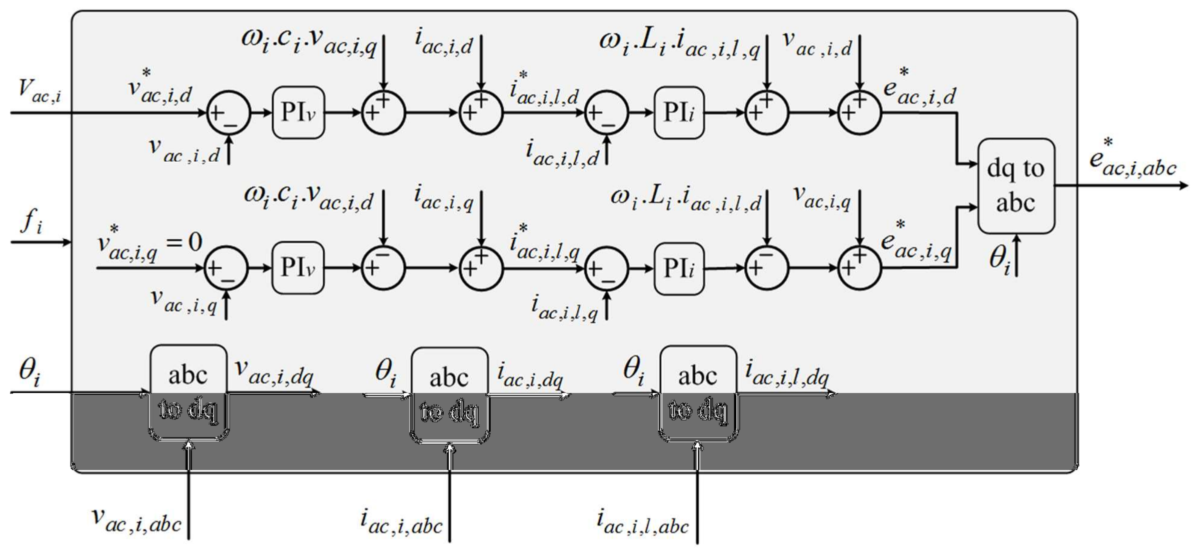

c

Fig. 2.
a Structure of a three-phase converter used in a converter-based ac source
b General block diagram of the converter shown in Fig. 2a
c VCM realization

$$V_{dc,pu} = \frac{V_{dc} - V_{ave,dc}}{\Delta V_{dc}/2} \quad (5)$$

where ΔV_{dc} is the intended voltage variation range of DC-MG and $V_{ave,dc}$ is V_{0dc}-$\Delta V_{dc}/2$.

By setting the per-unit frequency and per-unit dc voltage equal in a HMG, the relative occupied capacity of sources on both microgrids are equalized. In other words, the total active power demanded by both AC- and DC-MGs are shared among all ac and dc sources proportional to their power rating [9, 11-13].

4. Proposed IC control strategy

As explained in Sec. 3, the main function of IC is to properly manage the power transfer between AC- and DC-MG such that proportional power sharing throughout HMG is taken place. Besides, the IC control strategy must be coordinated with each MG taking into account the requirements mandated by them. In other words, the IC control strategy must be compatible with the control strategy on both AC- and DC-MG.

The proposed IC control strategy is inspired from an ac source control strategy in an AC-MG. In this strategy, especial droop characteristics are implemented to obtain the frequency and voltage reference values for IC ac-side (Fig. 3b). As will be shown shortly, the dc-side voltage is also used in defining the proposed droop characteristics. The calculated frequency and voltage reference values are realized by VCM, similar to an ac source in an AC-MG. In this control strategy, no frequency measurement is required and consequently there is no need to have large frequency deviation. Furthermore, using VCM results in higher voltage quality at IC ac terminals.

To explain the proposed control strategy, first assume that IC has ac-side droop characteristics, called primary droop characteristic, similar to ac sources in AC-MG given by

$$f_{ic} = f_{0ic} - m_{ic} \times P_{ic} \quad (6)$$

$$V_{ac,ic} = V_{0ac} - n_{ic} \times Q_{ic} \quad (7)$$

where f_{ic} and $V_{ac,ic}$ are the frequency and amplitude of the output voltage reference values, P_{ic} and Q_{ic} are IC active and reactive powers and m_{ic} and n_{ic} are droop slopes which is determined in a manner similar to ac sources. Based on (6) and (7), IC contributes to the active and reactive power demand of AC-MG similar to other ac sources. Note that in general, the active power demand by an AC-MG in a HMG could be either positive or negative. By changing f_{0ic}, the amount of IC contribution to active power can be controlled. This basic strategy, however, lacks the ability of maintaining proportional power sharing throughout the HMG. In the following section, the modifications made on active power droop characteristic to overcome this problem are explained.

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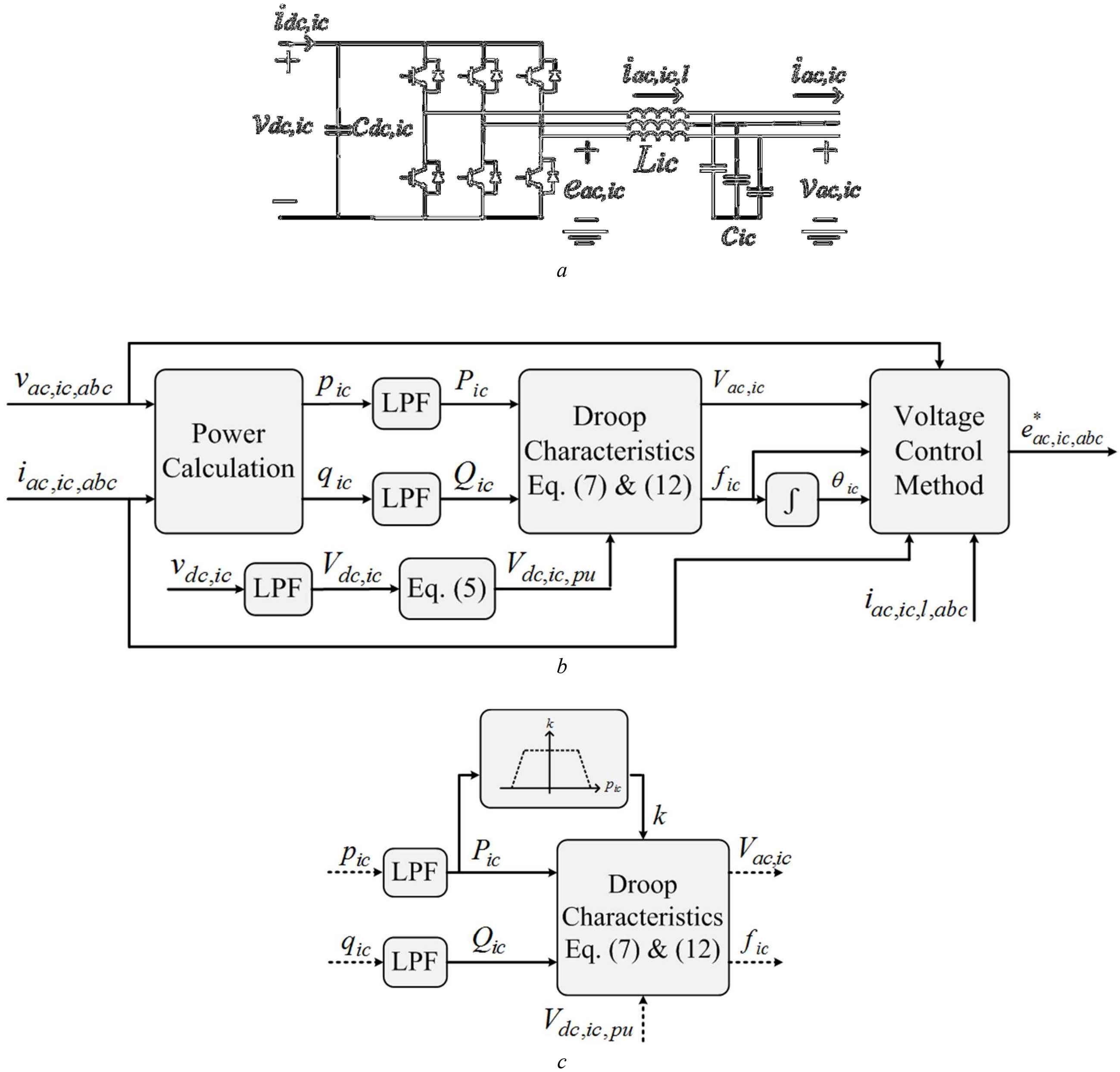


Fig. 3.
a Structure of IC converter and the definition of parameters
b Proposed control structure of IC
c Overload protection strategy by reducing k

4.1. Proportional Power Sharing throughout an HMG

It was explained in Sec. 3 that how by equating the per-unit values of the ac-side frequency and dc-side voltage amplitude, proportional power sharing throughout an HMG can be achieved. In this section, it is shown that how by selecting proper f_{0ic}, power transfer via IC is calculated such that proportional power sharing is realized.

Let us define a cumulative droop characteristic for the AC-MG as [9]

$$f = f_0 - m_{ac,cum} \times P_{ac,cum} \qquad (8)$$

where $P_{ac,cum}$ is the total active power generation in the AC-MG and $m_{ac,cum}$ is the droop slope. Active power balance in an AC-MG implies

$$P_{ac,load} = P_{ac,cum} + P_{ic} \qquad (9)$$

where $P_{ac,load}$ is total AC-MG power demand. Substituting frequency as a global parameter from (6) in (8) and substituting $P_{ac,cum}$ from (9) in (8) yields

$$P_{ic} = \frac{f_{0ic} - f_0 + m_{ac,cum} \times P_{ac,load}}{m_{ac,cum} + m_{ic}} \qquad (10)$$

Based on (10), for a given $P_{ac,load}$, the IC throughput power, P_{ic}, can be controlled via controlling f0ic. This is shown in Fig. 4a where the *P-f* droop characteristic of both AC-MG and IC are shown. It can be seen from Fig. 4a that increasing f_{0ic} will increase P_{ic} , i.e. increases the power transfer from dc to ac side, and vice versa. In other words, f_{0ic} can be used as a parameter to control the power flow between AC- and DC-MG.

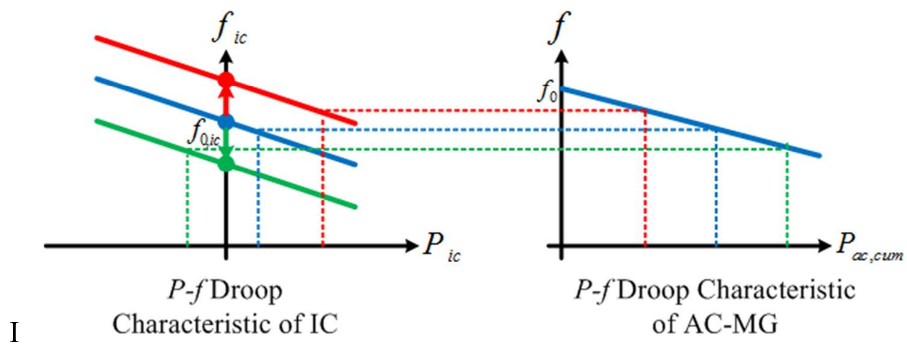
The above strategy for controlling $f_{0,ic}$ suggests the idea of using this parameter as a mean to realize the requirements for proportional power sharing throughout an HMG. To explain this, consider a scenario where IC is transferring power from DC- to AC-MG and at the same time the per-unit value of ac-side frequency is larger than the per-unit value of dc-side voltage. This situation implies that the dc-side sources are generating more power than is expected, i.e. proportional power sharing is not fulfilled. Therefore, the flow of power from DC- to AC-MG must be decreased or even reversed.

This power reduction can be realized by decreasing $f_{0,ic}$. Based on this reasoning, the f_{0ic} can be changed proportional to $V_{dc,ic,pu}$-$f_{ic,pu}$ as

$$f_{0ic} = f_{ave} + (V_{dc,ic,pu} - f_{ic,pu}) \times k \; (11)$$

where k is a constant and $V_{dc,ic,pu}$ is the per-unit value of IC dc-side voltage. Now if in addition to the *P-f* droop, given by (6), (11) is also satisfied, proportional power sharing throughout HMG will be realized. Therefore, by substituting $f_{0,ic}$ from (11) and per-unit frequency from (4) in (6), the modified *P-f* droop characteristic of IC can be obtained as

$$f_{ic} = f_{ave} - \frac{m_{ic} \times \Delta f}{\Delta f + 2k} \times P_{ic} + \frac{\Delta f \times k}{\Delta f + 2k} \times V_{dc,pu} \; (12)$$



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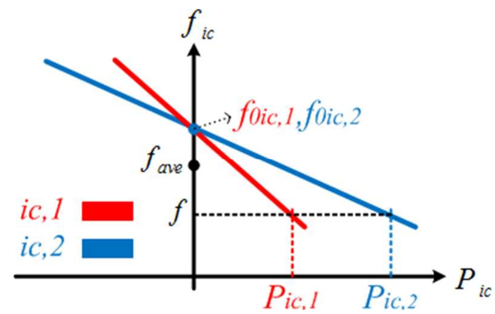

b

Fig. 4.
a $f_{0,ic}$ affect on P_{ic}
b Active power sharing among ICs

In realization of (12), the ac-side active power and the dc-side voltage must be measured. Therefore (12) and (7) indicate the final droop characteristics of IC. Fig. 3a and 3b show the structure of IC along with the proposed control strategy. The ac-side quantities are used to calculate the active and reactive power associated with IC. After proper low-pass filtering, the calculated powers and per-unit voltage of dc bus are applied to (12) and (7) to generate the reference for IC output voltage. A conventional VCM (similar to Fig. 2b) is then used to generate voltage command value for switching pattern realization.

As mentioned in the beginning of this section, an important feature of the proposed strategy is that it does not need any ac-side frequency measurement, leading to small ac-side frequency variation. Furthermore, VCM ensures superior voltage support. Both these features will improve the power quality in AC-MG.

4.2. Power sharing among ICs

In a HMG with several ICs, it is desirable to share the exchanged power among ICs proportional to their rating. To achieve this goal, one may choose the slope of ICs primary P-f droop characteristics (m_{ic}) in reverse proportion to their rating, and also choose k in (11) equal for all ICs. Similar k for all ICs results in their f_{0ic} to be very close to each other. Considering that the frequency is a global parameter and based on Fig. 4b, the exchanged power is shared among ICs proportional to their rating.

4.3. Impact of k and m_{ic} on sharing performance

It was shown in Sec. 4.1 that by the appropriate control of f_{0ic}, proportional power sharing can be realized in an HMG. Based on (11), for a specific f_{0ic} corresponds to the desired P_{ic}, larger k results in smaller difference between $V_{dc,ic,pu}$ and $f_{ic,pu}$, i.e. better proportional power sharing throughout HMG. Furthermore, k also affects the power sharing among ICs.

As stated in Sec. 4.2, the power sharing among ICs results from setting their f_{0ic} very close to each other. Based on (11), larger k magnifies any difference between $V_{dc,ic,pu}$ and $f_{ic,pu}$, resulting in larger difference between f_{0ic} of different ICs, which consequently degrades sharing among them.

The effect of m_{ic} on sharing performance is explained using (10), which shows that any increase in m_{ic} results in lower impact of f_{0ic} on P_{ic}. In other words, the larger the m_{ic}, the larger change of f_{0ic} is needed for a given change in P_{ic}. Consequently, larger f_{0ic} calls for larger ($V_{dc,ic,pu}$ - $f_{ic,pu}$), i.e. the sharing performance is deteriorated.

In addition, m_{ic} variation affects the power sharing quality among ICs. As stated in the above, (10) shows that larger m_{ic} results in lower impact of f_{0ic} on P_{ic}. Under this circumstances, any difference between the f_{0ic} of different ICs will have lower impact on power sharing among them.

As discussed above, k and m_{ic} will have impact on both proportional power sharing and power sharing among ICs, and their values must be chosen based on required performance.

4.4. Overloading protection

When the difference between two microgrid loading is high, the demanded active power exchange for proportional power sharing could become higher than the rating of IC. In this situation, proportional power sharing must be violated to limit active power exchange and protect IC.

The influence of k on sharing can be exploited to protect IC from overloading. This is shown in Fig. 3c where an additional block has been added to fulfil IC protection. As can be seen, P_{ic} is monitored and compared with a preset value. As soon as any overloading is detected, parameter k is reduced such that P_{ic} is limited.

5. Simulation results

In this section, time domain simulation is used to verify the analytical studies presented in the previous sections and show the performance of the proposed control strategy. The simulations have been carried out using PSIM software. Fig. 5 shows the structure of the HMG used for the simulation studies. In this circuit, all sources and loads in both AC- and DC-MG are aggregated and modelled as a single source and load. The HMG parameters are shown in Table I.

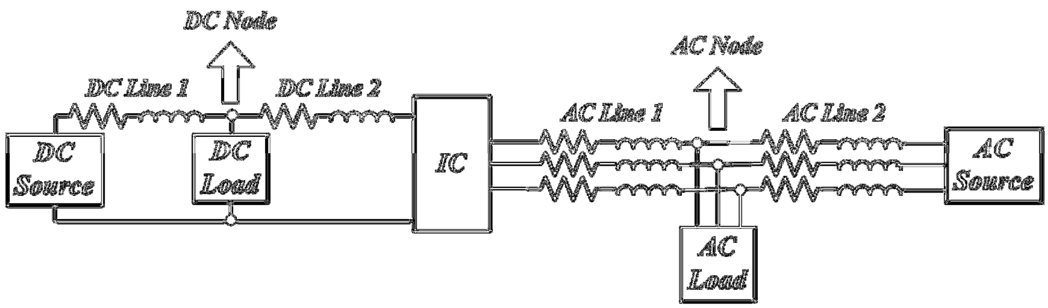

Fig. 5.*HMG structure used for studies*

Table 1 HMG parameters

AC Line 1	R=0.2 Ω, L=0.5 mH
AC Line 2	R=0.3 Ω, L=0.7 mH
f_0, Δf	50 Hz, 0.2 Hz
V_{0ac}, ΔV_{ac}	260 V, 26 V
AC Source	P_{rated}=10 kW, Q_{rated}=5kVAR Output Filter: L=1.5 mH, C=50 µF Voltage Controller: k_p=0.2, k_i=100 Current Controller: k_p=5, k_i=33000
DC Line 1	R=0.35 Ω, L=0.4 mH
DC Line 2	R=0.25 Ω, L=0.3 mH
V_{0dc}, ΔV_{dc}	570 V ,630 V
DC Source	P_{rated}=10 kW Output Filter: L=3 mH, C=25 µF Voltage Controller: k_p=0.03, k_i=15 Current Controller: k_p=33, k_i=220000
IC	P_{rated}=6.5 kW, Q_{rated}=3.3 Kvar, k=2.5 Hz Ac Side Output Filter: L_{ic}=1.5 mH, C_{ic}=50 µF Dc Side Output Filter: $C_{dc,ic}$=2 mF Voltage Controller: k_p=0.2, k_i=100 Current Controller: k_p=5, k_i=33000
Low pass filters cut off frequency used in sources and IC droop strategy: ω_c=30 rad/s	

A typical load variation in a HMG is shown in Fig. 6. Simulation results are shown in Fig. 7. First consider results from t=1 sec. to t=9 sec. The per-unit AC-MG frequency and the per-unit IC dc-side voltage are shown in Fig. 7a. The same value of these parameters indicates the ability of the proposed controller in proportional power sharing.

Now consider results from t=9 sec. to t=12 sec. where the ac load is increased such that IC is imposed to overload. If the loading scenario in this interval is to be applied, the IC would be overloaded. This is prevented by applying a modification on droop characteristics as explained in Sec. 4.4 and shown in Fig. 3c. As can be seen in Fig. 7.b, the active power exchange of IC is limited to 6.5 kW, but at the same time the per-unit AC-MG frequency and the per-unit DC-MG voltage are no longer equal due to the intervention of protection strategy.

AC system frequency is shown in Fig. 8a. A small deviation of frequency relative to the nominal value (50 Hz) shows the quality of frequency control. It should be noted that frequency deviation more than ±0.1 Hz is known as the power quality phenomenon [15] and can damage the frequency sensitive devices.

The rms voltage at the ac-side of IC bus is shown in Fig. 8b. As can be seen, even during transitions, the voltage in this bus remains within standard levels [15]. This is due to the continuous voltage support via VCM used in the proposed control structure of IC.

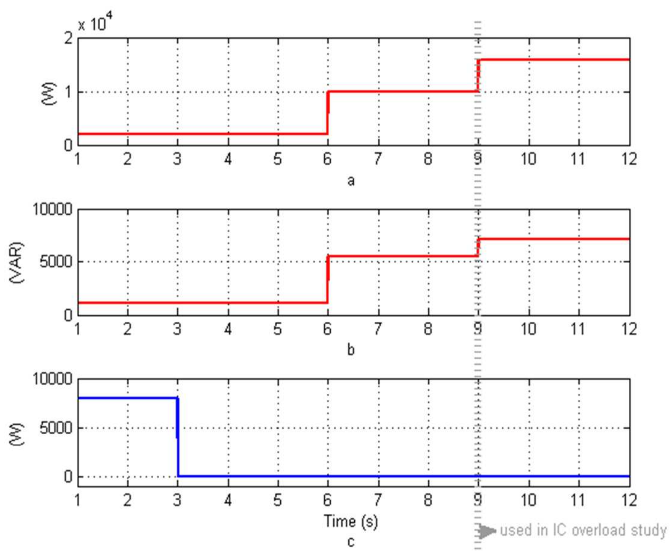

Fig. 6. Load variation scenario
a ac load active power
b ac load reactive power
c dc load active power

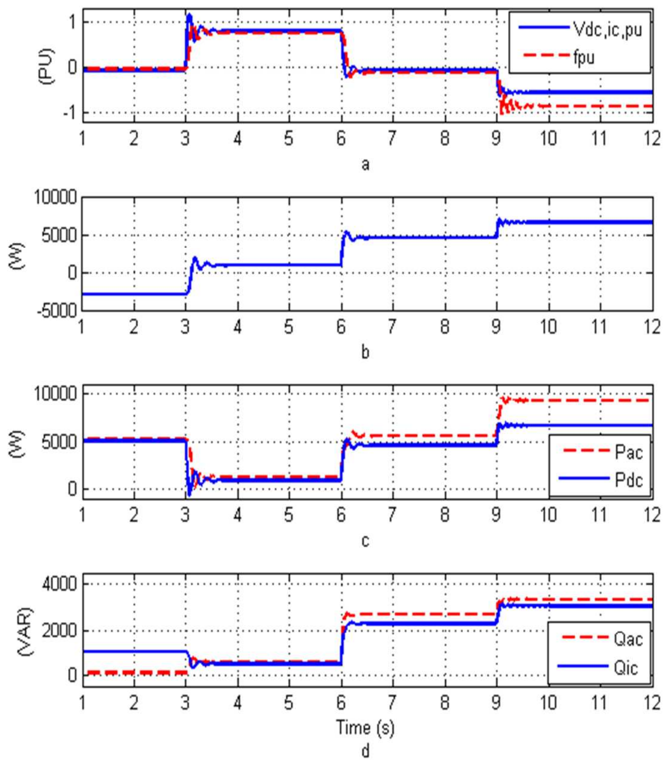

Fig. 7. Simulation results showing
a Per-unit AC-MG frequency and per-unit IC dc-side voltage
b IC active power from dc to ac
c ac and dc sources active power generation
d ac source and IC reactive power generation

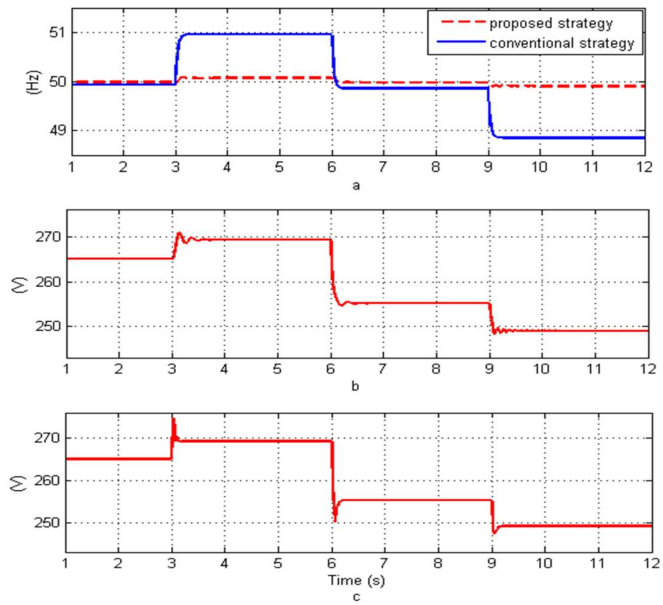

Fig. 8.*Simulation results showing*
a IC ac bus frequency in the proposed and conventional strategies
b IC ac bus voltage (proposed strategy)
c IC ac bus voltage (conventional strategy)

In Fig. 8, the frequency and ac-side voltage variation has been compared between the proposed and conventional strategies. It can be seen that the frequency variation is much lower in the proposed strategy. Furthermore, voltage over/undershoots have been disappeared during load change which is the result of using VCM.

The effect of m_{ic} and k on sharing quality is investigated using the HMG shown in Fig. 5 with an additional IC connected to ac and dc nodes. The parameters associated with this new structure are shown in Table II. Fig. 9 and 10 illustrate the results when m_{ic} and k are changed. These results verify the studies presented in Sec. 4.3.

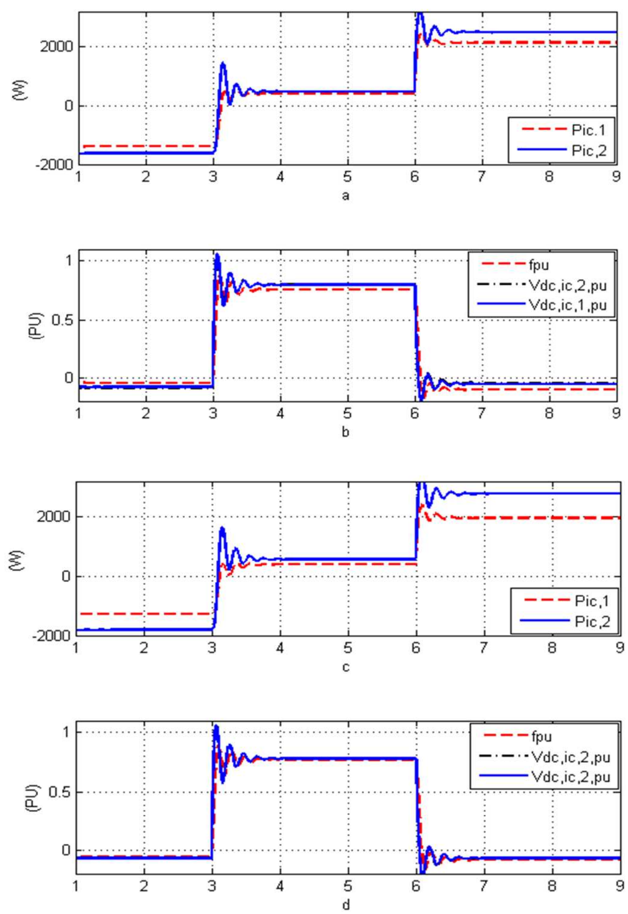

Fig. 9. Simulation results showing the effect of k on system performance
a ICs active power exchange (k=2.5, m_{ic}=6.15×10^{-5})
b Per-unit AC-MG frequency and per-unit ICs dc-side voltage (k =2.5, m_{ic}=6.15×10^{-5})
c ICs active power exchange (k =6, m_{ic}=6.15×10^{-5})
d Per-unit AC-MG frequency and per-unit ICs dc-side voltage (k =6, m_{ic}=6.15×10^{-5})

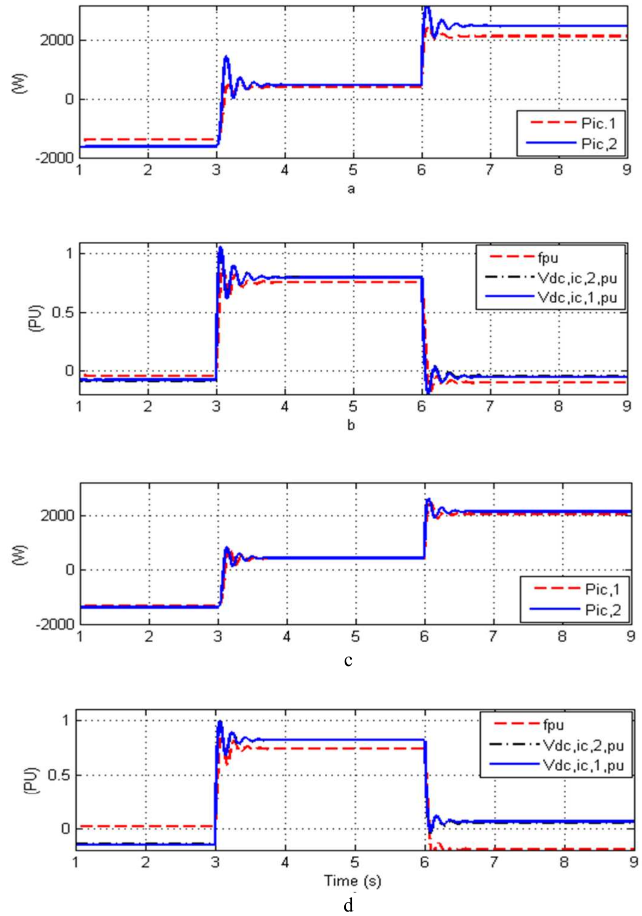

Fig. 10. *Simulation results showing the effect of m_{ic} on system performance*
a ICs active power exchange (k=2.5, m_{ic}=6.15×10^{-5})
b Per-unit AC-MG frequency and per-unit ICs dc-side voltage (k =2.5, m_{ic}=6.15×10^{-5})
c ICs active power exchange (k =2.5, m_{ic}=3.08×10^{-4})
d Per-unit AC-MG frequency and per-unit ICs dc-side voltage (k =2.5, m_{ic}=3.08×10^{-4})

Table 2 HMG parameters used in m_{ic} and k variation study

IC 1 (IC in Fig. 5)	P_{rated}=3.25 kW, Q_{rated}=1.6 kVAR
IC 2	P_{rated}=3.25 kW, Q_{rated}=1.6 kVAR AC Line: R=0.1 Ω, L=0.25 mH DC Line: R=0.15 Ω, L=0.2 mH

6. Small signal stability

This section deals with the stability analysis of the proposed system. As the starting point of this analysis, the small signal model of a typical HMG was obtained similar to the approach presented in [17, 18, 22, 23]. Table 3 shows the eignvalues associated with the HMG shown in Fig. 5. As can be seen, all eignvalues are on left half plane, meaning that the system is inherently stable.

For small-signal stability studies, the system root locus versus k, m_{ic} and the inductance of ac lines are extracted and shown in Fig. 11. As can be seen, k increment results in little stability decrement. In addition the inductance increment results in significant stability and damping increment.

As shown in Table 3, the dominant poles of under study system (-4.7±30j shown by asterisk) have small damping which results in undesirable dynamic performance during IC power transfer. This situation and significant impact of ac lines inductance, brings up the idea of using virtual impedance in IC and ac source control strategies in order to improve dynamic performance of HMG. For virtual impedance implementation the output current is measured and the voltage drop corresponding to the required virtual impedance is subtracted from the voltage reference [4, 18]. Table 4 shows the dominant poles without and with virtual impedance implementation. Adding virtual inductances equal to 1.9 mH in IC and ac source considerably improves the damping of poles. Corresponding dynamic performance improvement in time domain simulation is shown in Fig. 12.

Table 3 HMG eigenvalues

-3.09×10^{4}	$(-6.52\pm3.15j)\times10^{2}$
$(-0.52\pm1.21j)\times10^{4}$	$(-5.76\pm0.01j)\times10^{2}$
$(-1.13\pm8.28j)\times10^{3}$	$(-3.19\pm1.35j)\times10^{2}$
$(-1.03\pm7.82j)\times10^{3}$	-2.49×10^{2}
$(-0.26\pm5.93j)\times10^{3}$	-1.07×10^{2}
$(-0.12\pm5.70j)\times10^{3}$	-3.93×10^{1}
$(-2.45\pm0.05j)\times10^{3}$	-3.06×10^{1}
$(-2.07\pm8.37j)\times10^{2}$	-3×10^{1}
$(-8.70\pm6.65j)\times10^{2}$	-3×10^{1}
$(-4.45\pm5.89j)\times10^{2}$	$*(-0.56\pm2.81j)\times10^{1}$
-8.25×10^{2}	

Table 4 Dominant poles without and with virtual impedance

virtual inductances	Dominant Poles	Damping ratio
0 (uncompensated)	-5.6±28.1j	0.19
1.9 mH	-9.4±12.6j	0.6

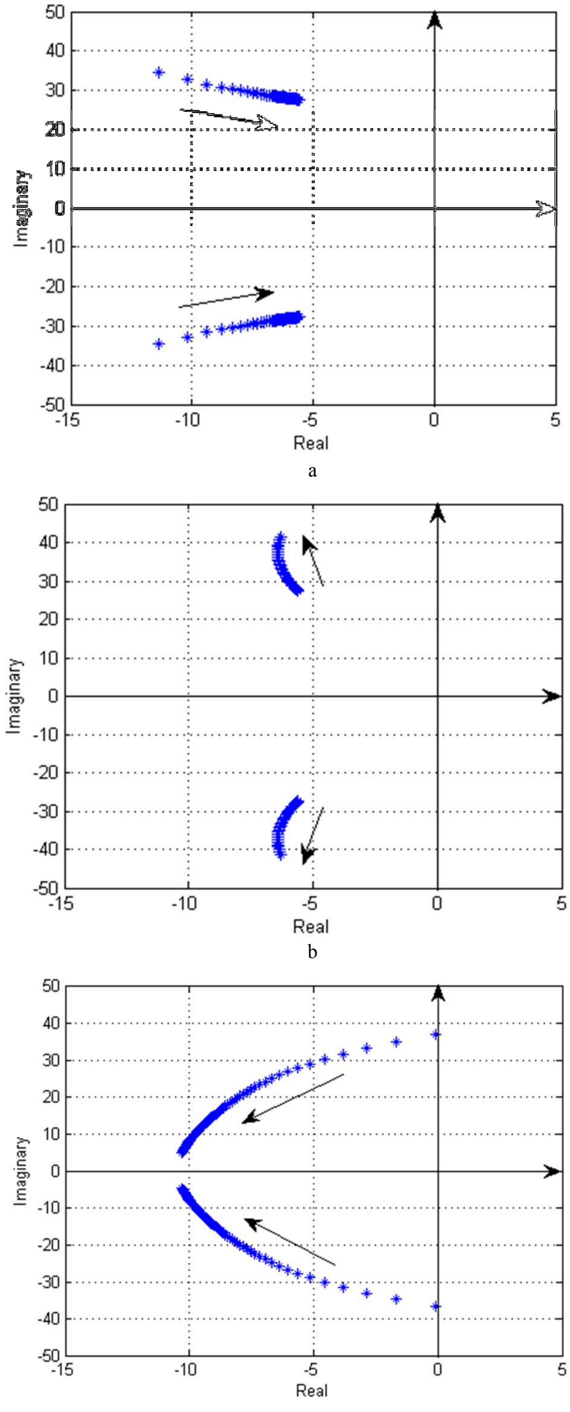

Fig. 11. *System root locus versus*
a k changing from 0 to 6
b m_{ic} changing from 4×10^{-6} to 4×10^{-4}
c ac lines inductance changing from 0.5 mH to 10 mH

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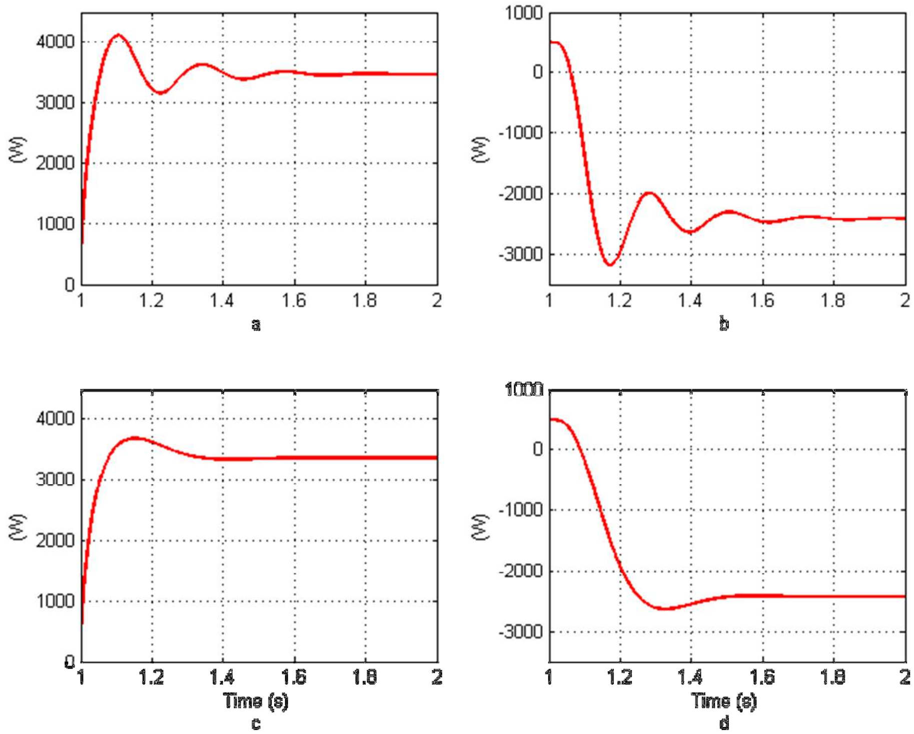

Fig. 12. IC active power flows from dc to ac
a Ac side load increase (uncompensated system)
b Dc side load increase (uncompensated system)
c Ac side load increase (compensated system)
d Dc side load increase (compensated system)

7. Conclusion

This paper presents a control strategy for interlink converters (ICs) used as the power electronic interface between ac and dc microgrids in a hybrid microgrid (HMG). The proposed strategy does not use frequency variation in its structure. This makes it possible to use smaller slop for P-f droop characteristic and thus smaller frequency variation and better power quality at ac side. Furthermore, using voltage control method (VCM) allows direct control of ac terminal voltages and hence better the voltage quality. The impact of various parameters on the performance of the proposed controller was discussed. The modification of droop parameter to prevent IC overloading was explained. The performance of the proposed strategy is verified using time-domain simulation. The small-signal stability of the proposed technique is studied using the small-signal model and eigenvalue analysis. It is shown that how by introducing a virtual inductance in the ac-side of IC, the stability of the system can be improved.

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