

Autonomous Operation of a Hybrid AC/DC Microgrid with Multiple Interlinking Converters

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Abstract— Applying conventional dc-voltage based droop approaches for hybrid ac/dc microgrids interconnected by a single interlinking converter (IC) can properly manage the power flow among ac and dc subgrids. However, due to the effect of line resistances, these approaches may create a circulating power as well as overstressing the ICs in the case of employing multiple ICs for interconnecting the ac and dc subgrids. This paper proposes an autonomous power sharing approach for hybrid microgrids interconnected through multiple ICs by introducing a superimposed frequency in the dc subgrid. Hence, a suitable droop approach is presented to manage the power among the dc and ac sources as well as ICs. The outcomes are proportional power sharing, preventing circulating power and overstressing the ICs as well as acceptable dc voltage regulation. Furthermore, the maximum transferred power by the ICs can be improved by employing the proposed approach. The effectiveness of the proposed approach is evaluated by simulation.

Index Terms— hybrid microgrid, droop method, power sharing, interlinking converter, frequency droop.

I. INTRODUCTION

PROLIFERATION of Distributed Generations (DGs) introduces higher reliability, stability, and quality as well as lower power losses and operational costs to the power systems. Integrating smart-grid and microgrid technologies to the power systems will further improve the overall performance of the system [1]–[3]. Moreover, dc microgrids create an infrastructure to supply dc loads by dc sources such as photovoltaic arrays, fuel cell modules, as well as storages, which in case, increases the energy conversion efficiency [1]. Operating dc microgrids together with ac microgrids, therefore, will form a new distribution systems called hybrid ac/dc systems [4], [5], in which the dc side is dynamically decoupled from the ac side [6], [7].

Operating hybrid microgrids requires stable and appropriate power management strategies in order to control the load sharing among ac and dc sources. A variety of research works have been performed on the power sharing control in dc and ac microgrids. However, so far, a few efforts have been made on the power management among ac and dc sources in hybrid systems, especially in the case of an islanded ac side.

A reliable power sharing approach, inspired from droop control of governor system of conventional synchronous

generators, is employed for power sharing control in ac microgrids [8]–[11]. A frequency-droop characteristic is defined for a converter working together with other converters, in order to determine the corresponding reference power. Based on the droop control theory, all droop controlled converters participate in load sharing following the corresponding droop slope [9].

Like the frequency-droop method, a dc-voltage based droop concept is also introduced for power management in dc grids [1], [8], [12], where a virtual resistor is emulated in the control system to manage the loading of converters. However, unlike the frequency droop in ac grids, the dc link voltage is not a global variable, and the line resistances will affect the sharing accuracy. Furthermore, the virtual resistor results in a voltage drop in the microgrid. These two issues deteriorate the performance of the dc-voltage droop method which is resolved by a secondary controller reinforced by a communication network. In fact, the information of voltage and current of converters are shared among them to improve the sharing accuracy and voltage regulation [1], [13]. Furthermore, an enhanced approach employing the information of neighboring converters is presented to improve the sharing accuracy, voltage regulation and overall reliability based on consensus protocol using a sparse communication network [14]–[16]. A power sharing approach utilizing only the information of output currents of the converters is presented in [17]. Moreover, frequency-based power sharing approaches are presented to improve the overall reliability and stability without utilizing an extra communication network [18]–[20].

Besides the power sharing approaches for ac and dc microgrids, a few studies have been performed for power sharing in hybrid microgrids. Power flow control among dc microgrid interlinked to the utility is discussed in [11]. A droop-based control strategy is presented for power sharing between ac/dc microgrid intertied by a back-to-back converter [21], in which only one Interlinking Converter (IC) between the ac and dc grid is considered. Power sharing approach between two ICs in a hybrid microgrid is also presented in [22] addressing the circulating current between the ICs. However, the given strategy is only suitable for controlling the power flow from dc to ac side, and there is no mechanism to support the dc grid by ac sources. Another general droop-based approach is presented in [4] for ac subgrids interconnected to dc subgrids. However, the approach is validated for only one IC between dc and ac microgrid. Interconnected ac and dc subgrids by multiple ICs introduce some issues including overstressing the ICs and circulating

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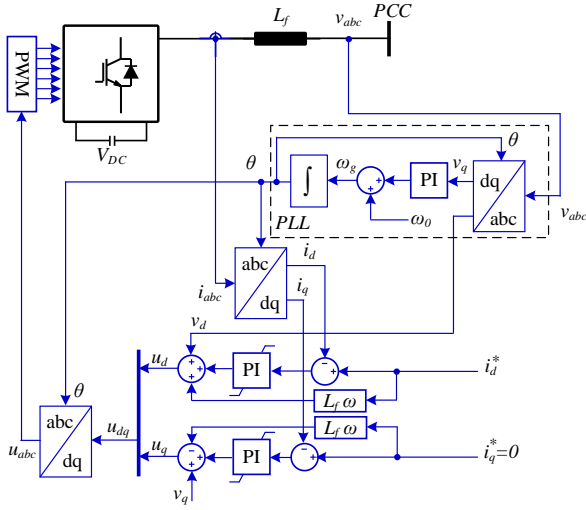


Fig. 2. Control structure of an Interlinking Converter (IC).

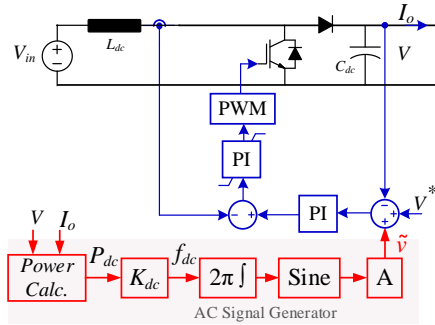


Fig. 3. Control structure of a dc/dc boost converter.

When the normalized power of the ac side is equal to that of the dc side, $V_{pu} = f_{ac,pu}$, hence $P_d = 0$. If the dc load (/ac load) increases, V_{pu} ($f_{ac,pu}$) decreases, and according to (7), the power should be transferred from the ac (/dc) to the dc (/ac) subgrid.

The control block diagram of the IC is shown in Fig. 2. In the dq reference frame, the active power can be found as:

$$P_d = \frac{3}{2} v_d i_d, \quad (8)$$

where i_d and v_d is the d-axes component of ac current and voltage of the IC.

By combining (7) and (8), the reference current (i_d^*) of the IC can be obtained as:

$$i_d^* = \frac{2}{3} \frac{K_{ic}}{v_d} (V_{pu} - f_{ac,pu}). \quad (9)$$

Employing the presented interlinking droop can properly share the ac and dc loads among ac and dc sources interconnected by a single IC or multiple ICs connected to a common dc bus. However, in the case of multiple ICs distributed through a grid, the above mentioned approach will face some challenges including circulating active power between the two subgrids and overstressing the converters due to the effect of line resistances. In such a case, the dc voltage of different ICs does not have the same value, and hence according to (9), the ICs cannot share the load proportional to the corresponding droop gains (K_{ic}). Furthermore, due to the

line resistances and dc subgrid topology, for one IC V_{pu} may be lower than $f_{ac,pu}$ and the other way around for another one. Therefore, one IC transfers active power from the ac to dc grid, while another one transfers power from the dc to the ac grid which in fact means an active power circulates between ac and dc subgrids. Circulating power will increase the losses on the system and ICs, decreases the lifetime of ICs, and occupies the ICs' capacity.

In order to overcome the aforementioned issues, a superimposed frequency-based droop approach is proposed to control the active power sharing among ICs. The frequency-droop approach is conceptually explained in [19], [29], [30] for power sharing control in dc microgrids. In this approach, the dc converters superimpose a small ac voltage signal on the dc voltage, where the frequency of the ac signal is proportional to the corresponding output power. Therefore, the converters are coordinated together with the superimposed frequency based droop method, and hence, they can be operated without any communication network. Furthermore, since the injected signal frequency has a same value for all converters, the sharing will not be affected by the line resistances. Moreover, the dc voltage can properly be regulated at the reference value in the absence of virtual resistors. The frequency droop approach in dc microgrids are discussed in [19], [29], [30]. In this paper, without losing the generality and for simplicity, one dc/dc converter is considered in dc side.

The frequency-droop control of a dc/dc converter, boost one in this paper, is shown in Fig. 3. A small ac voltage with a small amplitude of "A" is added to the dc voltage with a frequency proportional to the corresponding output power as:

$$f_{dc} = f_{max} - K_{dc} P_{dc}, \quad (10)$$

where f_{dc} is the superimposed frequency, K_{dc} is the droop gain, and f_{max} is the maximum frequency at no load. According to [29], [30], the amplitude of the injected ac signal is very small, e.g., 2 V, which introduces a small ripple on 400 V, i.e., 0.5 %. Hence it will not affect other components of the dc system [29], [30]. Furthermore, the nominal injected frequency is 50 Hz to be modulated by the dc/dc converter [19], [29], [30].

The same as the ac droop approach, K_{dc} can be set proportional to the converter rating in order to have an appropriate sharing to take into consideration the converters rating. The coordination among multiple dc converters with frequency-droop approach has been addressed in [19]. Here, without losing generality, only one dc converter is considered, and the load sharing among the ICs are presented.

Introducing a new control parameter, i.e., f_{dc} , in the dc subgrid brings an opportunity to coordinate the ICs by a modified interlinking droop characteristics given in (11), where $f_{dc,pu}$ can be defined as (12).

$$P_d = K_{ic} (f_{dc,pu} - f_{ac,pu}) \quad (11)$$

$$f_{dc,pu} = \frac{f_{dc} - 0.5(f_{max} + f_{min})}{0.5(f_{max} - f_{min})} \quad (12)$$

f_{dc} in (12) is the superimposed frequency in the dc side, and f_{max} and f_{min} are like the ones considered for the ac subgrid. Therefore, the ICs can be autonomously operated without being affected by the line resistances.

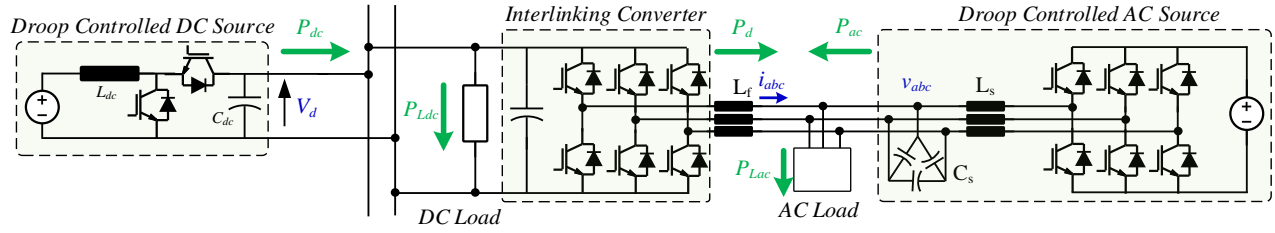


Fig. 4. Block diagram of a hybrid ac/dc microgrid with single Interlinking Converter (IC), and local ac and dc loads.

Hence, the issues like overstressing the ICs and circulating power between the grids will be appropriately controlled. The maximum transferred power by the IC utilizing the conventional and proposed interlinking approach is discussed in the next section. In the following section, the simulation results will be given to demonstrate the effectiveness of the proposed approach in comparison to the conventional one.

III. MAXIMUM TRANSFERRED POWER BY THE IC

In this section, the maximum transferred power by an IC in the droop control mode is calculated. A hybrid microgrid with dc and ac sources as well as a single IC is shown in Fig. 4. From (7) and (11), the transferred power can be rewritten as:

$$P_d = K_{ic} (X_{pu} - f_{ac,pu}) \quad (13)$$

where X_{pu} is the control parameter of the dc subgrid which can be $f_{dc,pu}$ or $V_{dc,pu}$, and it can be defined as (14).

$$X_{pu} = \frac{X - 0.5(X_{max} + X_{min})}{0.5(X_{max} - X_{min})} \quad (14)$$

Furthermore, X which is the dc voltage in the conventional approach and dc frequency in the proposed approach, can be defined as:

$$X = X_{max} - K_{dc} P_{dc}, \quad (15)$$

where X_{max} is the maximum value of X , and

$$K_{dc} = \frac{X_{max} - X_{min}}{P_{dc,n}}. \quad (16)$$

Substituting (6) and (14) into (13), the IC power can be found as:

$$P_d = K_{ic} \left(\frac{X - 0.5(X_{max} + X_{min})}{0.5(X_{max} - X_{min})} - \frac{f_{ac} - 0.5(f_{max} + f_{min})}{0.5(f_{max} - f_{min})} \right) \quad (17)$$

Furthermore, substituting (1) and (15) in (17) results in:

$$P_d = K_{ic} \left(\frac{-K_{dc} P_{dc}}{0.5(X_{max} - X_{min})} - \frac{-K_{ac} P_{ac}}{0.5(f_{max} - f_{min})} \right) \quad (18)$$

Combining (2), (16) and (18), the IC power is rearranged as:

$$P_d = 2K_{ic} \left(\frac{P_{ac}}{P_{ac,n}} - \frac{P_{dc}}{P_{dc,n}} \right). \quad (19)$$

From Fig. 4, the relation among the power of the dc source (P_{dc}), the ac source (P_{ac}) and the IC power with the ac and dc loads (P_{Lac} and P_{Ldc}) can be found as:

$$P_{dc} = P_{Ldc} + P_d, P_{ac} = P_{Lac} - P_d. \quad (20)$$

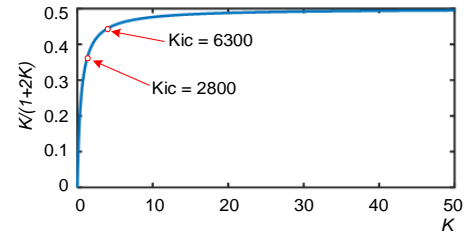


Fig. 5. Maximum transferred power of the IC in terms of $K = 2K_{ic}/P_{ac,n}$.

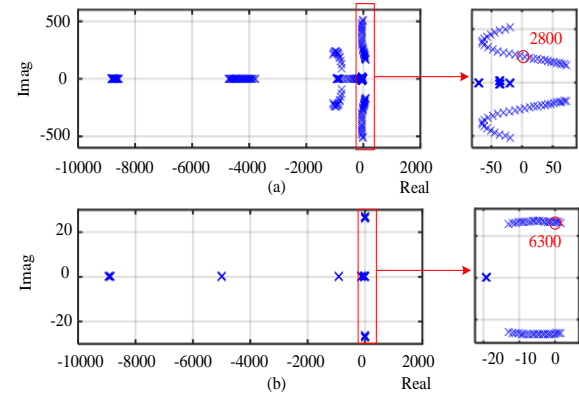


Fig. 6. Trace of eigenvalues for the closed loop system in terms of K_{ic} , with the (a) conventional interlinking droop, and (b) proposed interlinking droop.

TABLE I
PARAMETERS OF THE POWER SYSTEM AND CONTROLLERS

Converter	Parameter	Symbol	Value
DC Source Boost Converter	DC Inductor, Capacitor	L_{dc}, C_{dc}	200mH, 500μF
	Inner Current Regulator	$K_{p1} + K_{i1}/s$	0.05+1/s
	Inner Voltage Regulator	$K_{p2} + K_{i2}/s$	0.45+20/s
	DC Voltage Droop Gain	K_{dev}	0.005 V/W
	Frequency Droop Gain	K_{dcf}	0.00025 Hz/W
	Nominal Power	P_{dcn}	4 kW
AC Source Three Phase Inverter	Filter Inductor, Capacitor	L_s, C_s	2 mH, 30 μF
	Inner Current Regulator	$K_{p3} + K_{i3}/s$	0.1+2/s
	Inner Voltage Regulator	$K_{p4} + K_{i4}/s$	2+100/s
	Frequency Droop Gain	K_{ac}	0.00025 Hz/W
Interlinking Converter Three Phase Inverter	Filter Inductor	L_f	2 mH
	Inner Current Regulator	$K_{p5} + K_{i5}/s$	0.1+2/s
	Droop Gain IC1	K_{ic1}	2000 A
	Droop Gain IC2	K_{ic2}	1000 A
	Droop Gain IC3	K_{ic3}	2000 A
	Nominal Power IC1	$P_{ICn,1}$	1.6 kW
	Nominal Power IC2	$P_{ICn,2}$	0.8 kW
	Nominal Power IC3	$P_{ICn,3}$	1.6 kW
Grid parameters	Nominal ac voltage	V_{ac}	200 V
	Nominal dc voltage	V_{dc}	400 V
	Nominal ac frequency	f_{ac}	50 Hz
	Nominal dc frequency	f_{dc}	50 Hz
	Injected ac voltage	v_{ac}	2 V

Substituting (20) into (19) yields:

$$P_d = \frac{\left(\frac{2K_{ic}}{P_{ac,n}}\right)P_{Lac} - \left(\frac{2K_{ic}}{P_{dc,n}}\right)P_{Ldc}}{1 + \frac{2K_{ic}}{P_{ac,n}} + \frac{2K_{ic}}{P_{dc,n}}} \quad (21)$$

Without losing the generality, considering the same rating for the ac and dc sources, and defining K as:

$$K = \frac{2K_{ic}}{P_{ac,n}} = \frac{2K_{ic}}{P_{dc,n}}, \quad (22)$$

then, the transferred power by the IC can be found as:

$$P_d = \frac{K}{1+2K} (P_{Lac} - P_{Ldc}). \quad (23)$$

According to (23), the maximum power of the IC is limited by K_{ic} . The variation of $K/(1+2K)$ in terms of K is shown in Fig. 5. For instance, considering $P_{dc,n} = 4$ kW, $P_{ac,n} = 4$ kW, $P_{Lac} = 4$ kW, and $P_{Ldc} = 0$ kW, P_d can be calculated as 1.5 kW for $K_{ic} = 3000$, 1.7 kW for $K_{ic} = 6000$, and ideally 2 kW if $K_{ic} = \infty$. Therefore, increasing K_{ic} from 3000 to 6000 will increase the sharing accuracy by 10%.

However, K_{ic} cannot approach infinity due to the stability restriction. Following the control system of the ac source, dc source, and the IC given in Fig. 1, 2, and 3, and employing the interlinking droop approaches with the control parameters given in TABLE I, the closed-loop system poles in terms of K_{ic} can be found as shown in Fig. 6. As it can be seen, the maximum K_{ic} in the proposed approach is almost three times higher than that in the conventional approach. Increasing the droop gain will increase the control loop gain, and hence creates stability limitations. Therefore, the proposed interlinking approach increases the maximum transferred power capability of the ICs in the droop mode operation.

IV. SIMULATION RESULTS

The performance of the proposed strategy is demonstrated through different simulation case studies. In Case I, a hybrid microgrid with a single IC is considered, and the transferred power capability of the IC employing the proposed and conventional droop approach is investigated. In Case II, the effectiveness of the proposed approach in terms of the circulating power is evaluated in a hybrid microgrid with two ICs. The performance of the load sharing between the ICs are further investigated in Case III. The system specifications and control parameters are given in TABLE I. Furthermore, the simulations have been performed by PLECS (Plexim®) software. The simulations are done in Z-domain with sampling frequency of 100 kHz, and switching frequency of 20 kHz for all converters. The converters are simulated using IGBTs with non-ideal parameters for dc, ac, and interlinking converters as shown in Fig. 4. The sensor gains are modeled as a first order delay with time constant of 2.5 μ s for all measurements.

A. Case I: Transferred Power Capability

In this case, the hybrid microgrid shown in Fig. 4 with a single IC is considered. A 6 kW dc load is connected to the dc grid. The load sharing among the dc source, the IC and the ac source employing the conventional and proposed droop approach are shown in Fig. 8-a and -b respectively. When the ac load is disconnected, the ac source only supports the

requested power by the IC. Therefore, the dc load should be supported by the dc source and the ac source through the IC. As shown in Fig. 4(a1 and a2), increasing K_{ic} will increase the participation of the ac source. With $K_{ic} = 2000$, the output power of the dc and ac sources are 4 kW and 2 kW respectively. However, the IC power cannot be higher than 2800 due to the stability limitation shown in Fig. 6(a).

Despite limitation of the conventional droop approach, in the proposed strategy, K_{ic} can be increased up to 6300 as shown in Fig. 6(b). The simulation results employing the proposed strategy with $K_{ic} = 1000, 2000, 3000, 5000$ are shown in Fig. 8(b). As it can be seen, increasing K_{ic} will increase the participation of the ac sources. When K_{ic} is 5000, the output power of the dc and ac sources are 3.3 kW and 2.7 kW respectively. As it is demonstrated in this case study, the maximum transferred power by the IC can be increased by decreasing K_{ic} . Therefore, the load sharing accuracy among the dc side sources and the ac side sources can be improved employing the proposed control strategy.

The dc link voltages are shown in Fig. 8(a4 and b4) for the conventional and the proposed control approach. As this figure indicates, better voltage regulation is achieved using the proposed method. If the voltage droop controller, the dc link voltage drops below 390 V in Fig. 8(a4). However, the dc link voltage can be properly regulated at the reference value (400 V in Fig. 8(b4)) using the proposed control system.

B. Case II: Circulating Power Demonstration

In this Case, a hybrid microgrid with two ICs is considered with the rating powers of 1.6 and 0.8 kW for the first and second ICs. Therefore, the corresponding droop gains are set to 2000 and 1000 respectively. The microgrid topology with the line impedances and the direction of reference power flow is shown in Fig. 7. The simulation results employing the conventional and the proposed droop are shown in Fig. 9.

At first, the dc and ac loads are equal to 0.5 kW and 3.25 kW respectively. As shown in Fig. 9(a3), the per-unit dc voltage of the ICs are higher than the per-unit ac frequency. Therefore, according to (7), the power should be transferred from the dc side to the ac side. The output power and the current of the sources and the ICs are shown in Fig. 9(a1, a2). The transferred power of IC1 and IC2 from the dc side to the ac side is 622 W and 193 W respectively. Since the dc voltage of IC1 is not equal to that of IC2 due to the line resistances, the transferred power of the ICs are not proportional to the rating of the converters. However, employing the proposed approach, the per-unit dc side frequency has the same value for both ICs as shown in Fig. 9(b3), and hence, the transferred power of the ICs are equal to 587 W and 294 W (as shown in Fig. 9(b1, b2)), which are proportional their ratings. As a result, employing the proposed approach will improve the power sharing accuracy of the ICs.

At $t = 1$ s, the dc load is increased to 2 kW. As shown in Fig. 9(a3), the per-unit voltage of IC1, i.e., $V1$ is higher than the ac frequency, and therefore, IC1 transfers the power from the dc side to the ac side. Moreover, the per-unit voltage of IC2, i.e., $V2$ is lower than the ac frequency, and consequently, the power is transferred from the ac to the dc side by IC2.

Therefore, the active power is circulating between the two grids through the ICs. However, by employing the proposed approach, the dc side frequency, which is the same for both ICs, according to Fig. 9(b3), is higher than the ac side per-unit frequency. Therefore, both ICs transfer active power from the dc grid to the ac grid as shown in Fig. 9(b1, b2). As a result, employing the proposed approach can resolve the circulating power issue between the two grids through the ICs.

The dc load voltages in both cases are shown in Fig. 9(a4, b4). The ac current of IC1 in both cases are shown in Fig. 9(a4, b4) in order to show the dynamic response of the inner control loops of the ICs.

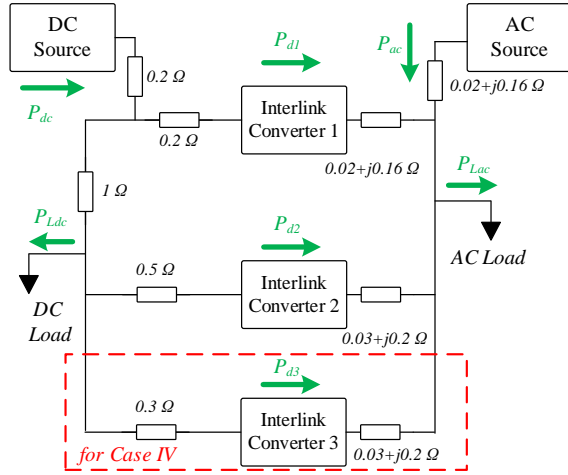


Fig. 7. Single line diagram of the hybrid ac/microgrid with corresponding reference power flow directions.

C. Case III: ICs Overstressing Demonstration

In Case II, it was shown that the load sharing accuracy is not proportional to the converters ratings if the conventional droop approach is employed due to the voltage drops on the line resistances. This case shows the load sharing error between ICs can cause overstressing the ICs in some loading conditions due to effect of the line resistances. As Fig. 10 shows, during $0 < t < 0.8$ s, the dc and ac loads are 1 kW and 3.25 kW. According to Fig. 10(a1), the ICs powers are 532 W and 95 W, where the power of IC1 is 5 times higher than that of the IC2, while the rated power of IC2 is 2 times larger than IC1. This is because of the voltage drop across the line resistance as shown in Fig. 10(a2), where the per-unit voltage of IC1 (V_1) is not equal to the per-unit voltage of IC2 (V_2), which generates incorrect power references for the ICs. However, by using the proposed approach, as shown in Fig. 10(b1), the power of IC1 is 479 W which is two times that of IC2, i.e., 239.

During $1.2 < t < 2$ s, the ac load is disconnected and the dc load is equal to 4.5 kW. As shown in Fig. 10(a1), the ICs powers are 0.87 kW and 0.8 kW. Therefore, IC2 is overstressed, even though IC1 is operating almost at half of its rated power. In order to find out this issue, the per-unit voltage and frequency of ac and dc microgrid is shown in Fig. 10(a2). Due to the line resistances, the difference between V_2 and f_{ac} is almost two times that of between V_1 and f_{ac} . Following (7) and considering $K_{ic1} = 2 \times K_{ic2}$, the reference power of IC2 is almost equal to IC1, even though the rated power of IC1 is two times that of IC2.

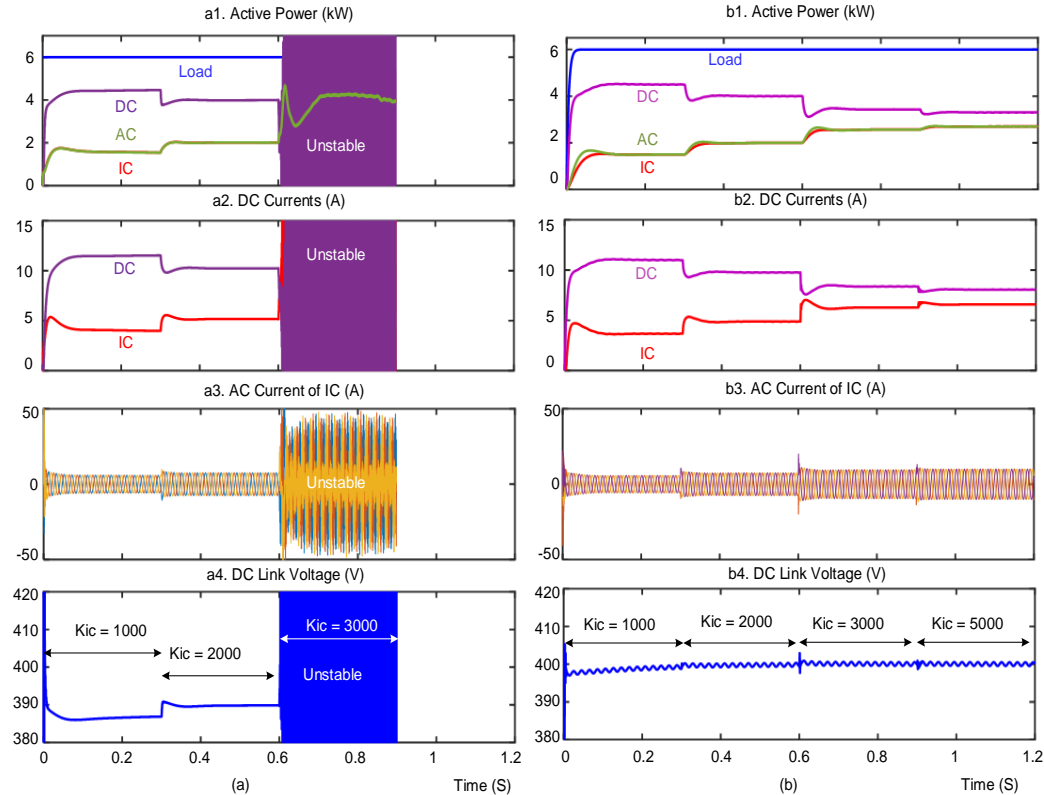


Fig. 8. Simulation results in Case I: the transferred power capability of an Interlinking Converter (IC) with (a) voltage-based droop controller, and (b) frequency-based droop controller.

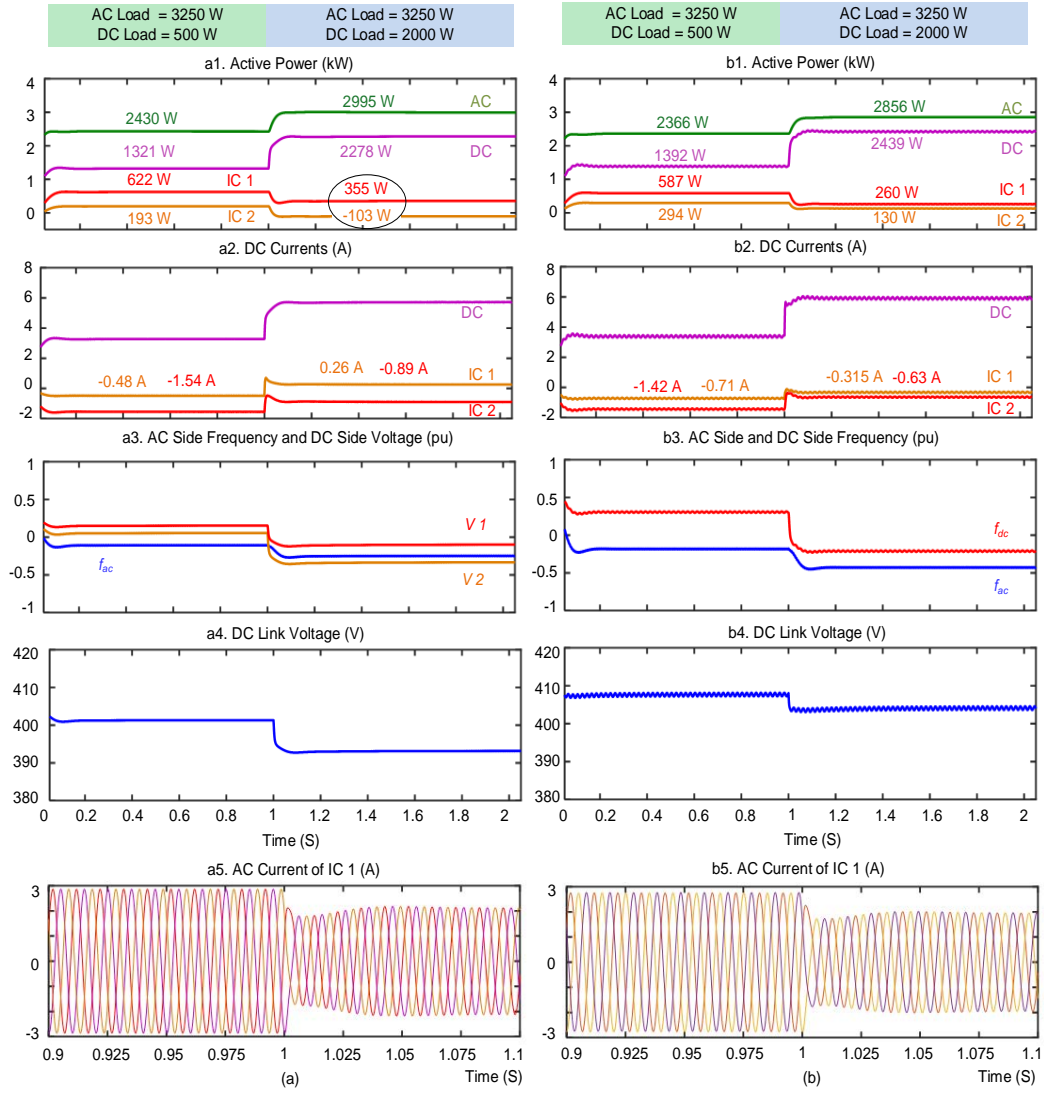


Fig. 9. Simulation results in Case II; (a) Voltage based droop control: the circulating power between the two Interlinking Converters (ICs) occurred at $t > 1$ s., (b) the transferred power by the ICs are proportional to the corresponding ratings and the circulating power does not exist in the case of applying proposed approach.

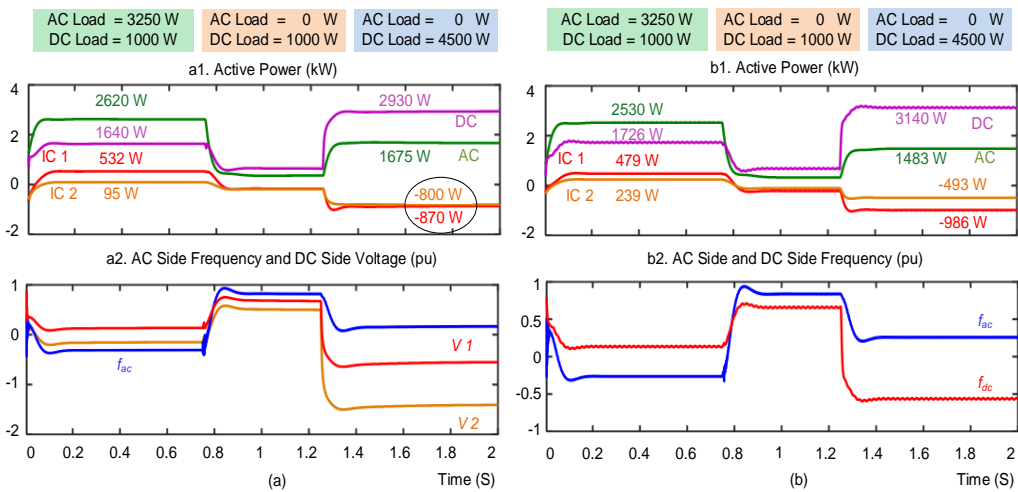


Fig. 10. Simulation results in Case III for illustrating the overstressing of the ICs employing (a) voltage based droop control, and (b) proposed droop approach.

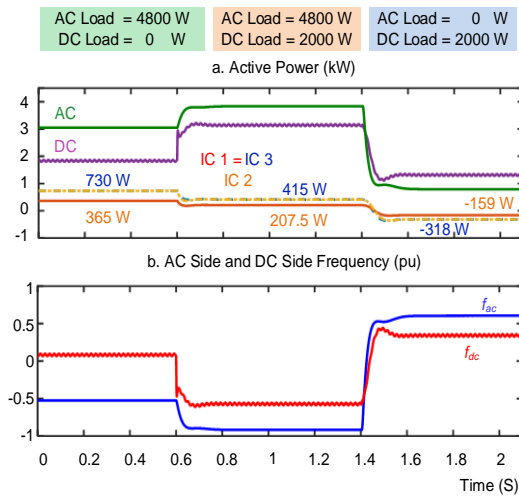


Fig. 11. Simulation results in Case IV for illustrating the power sharing among the three ICs employing the proposed approach.

However, in the case of utilizing the proposed approach, the dc side frequency is the same for both ICs as Fig. 10(b2) shows, and hence following (11) and considering $K_{ic1} = 2 \times K_{ic2}$, the transferred power by the ICs are proportional to their rated powers. As shown in Fig. 10(b1), the powers of IC1 and IC2 are equal to 986 W and 493 W respectively. As a result, the load sharing between the ICs can be properly carried out preventing overstressing the ICs.

D. Case IV: Operating of three ICs

In this case, three ICs are considered as shown in Fig. 7, where the rated power of the second IC is half of the other ICs. At first, the ac load is equal to 4.8 kW. As it can be seen from Fig. 11(a), the output power of ac source is 2.85 kW and the remaining ac load is shared among the three ICs following their rated power. Furthermore, as shown in Fig. 11(b), the ac frequency is lower than the dc frequency and hence, the power should be flowed from the dc side to the ac grid. At $t = 0.6$ s, a 2 kW dc load is connected. As shown in Fig. 11(a), both ac and dc loads are appropriately supplied by the ac and dc grids. Furthermore, the output power of ICs is proportional to their rated powers. Moreover, at $t = 1.4$ s, the ac load is disconnected. As shown in Fig. 11(b), the dc frequency is lower than the ac frequency, and hence the power needs to be flowed from ac side to the dc grid. The output power of the sources as well as the ICs are shown in Fig. 11(a) implying appropriate power sharing among them.

V. CONCLUSION

In this paper, power sharing control issues in hybrid ac/dc microgrids are discussed. The drawbacks of the conventional voltage droop approach are explained, and a new frequency-droop based strategy is proposed for suitable power sharing in hybrid microgrids. In the proposed approach, the Interlinking Converters (ICs) and the dc sources are coordinated by the frequency of an injected ac ripple in the dc grid. Introducing a global variable in the dc microgrid provides an opportunity to accurately coordination the power of the ICs. Employing this

method achieves proper load sharing without being affected by the line resistances. The proposed approach, also, prevents the circulating power among the ac and the dc grids as well as overstressing the converters. Furthermore, the maximum transferred power capability by the ICs can be increased by employing the proposed approach. Moreover, due to the lack of virtual resistors as compared to a voltage droop controller, the dc link voltage can be precisely regulated. The effectiveness of the proposed approach is evaluated by the simulations, and the load sharing performance is compared with that achieved if the conventional voltage-based droop approach is used.

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