Distributed Control and Power Management Strategy for an Autonomous Hybrid Microgrid with Multiple Sub-Microgrids

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***Abstract*— This paper proposes an improved approach of distributed coordination control for multiple Sub-Microgrids (SMGs) within the hybrid AC/DC microgrid. The conventional control approach for managing power flow between AC and DC microgrids is based on the proportional power sharing principle that results from merging the normalized voltage at the DC side and the frequency at the AC side for any interfaced hybrid microgrids. The proposed method suggests a distributed control system that ensures a global controllability for the interlinking converters (ILCs), thus avoiding the total dependency on a specific variable for power exchange. The proposed method not only able to control the power flow between SMGs but also ensures continuity of transferring power in case of failure in any single microgrid. Three case studies are presented to demonstrate the validity and capability of the proposed approach using MATLAB/Simulink software. From results it is found that the proposed control system provides high level of flexibility in managing the power flow among sub-microgrids.**

***Index Terms*—Droop method, hybrid microgrid, distributed control,**

I. INTRODUCTION

The microgrid is gaining momentum in the power system research field due to their economic, environmental, and sustainable incentives. Moreover, such a system is considered to be the solution for the complexity of integrating diverse renewable energy technologies [1]. Distributed generators (DGs), storage elements (SEs) and loads are considered to be the main elements in the microgrid. The cooperation of these elements under suitable control system supervision can ensure a seamless and secure operation of such system. DGs can be segmented into renewable energy sources (photovoltaic, wind, and wave energy sources) and non-renewable ones (nuclear, diesel and coal-powered systems). The SEs have a wide range of classifications according to the capacity and charging specifications. Ultra-capacitors, batteries, and flywheels are the most common SEs used in the modern electrical systems. There are three main structures of microgrids: AC, DC, and hybrid AC/DC microgrid. These structures are categorised based on how the DGs of the DC and AC microgrids are connected to the loads [2-4].

AC microgrids have been the focus of research in the resent decade due to the advantages of using clean and sustainable energy sources. They also have the ability to integrate the renewable energy sources with non-renewable ones, all within the main grid without the need for power conversion [5-7]. However, there is an increased interest to build a DC microgrid. Not only to suit lots of renewable energy sources that naturally generate power in the DC form (photovoltaic and fuel cell), but also to meet the growing penetration of modern DC loads. This interest in the DC and AC microgrids is promoting to link these systems together by a bidirectional power converter and form the third structure (hybrid microgrid). Such a system is strongly recommended to overcome the power shortage in any part of the hybrid system. Most of the literature proposes a hybrid microgrid structure that consists of a single interfaced AC and DC microgrid. However, the trend for linking multiple microgrids with different voltage and frequency levels is gaining an increased interest in the power industry. This is due to the many benefits of such arrangement [8].

The microgrid can work in two operation modes: the grid-connected mode where the voltage and frequency are regulated by the main grid and the autonomous mode which is a more realistic situation in rural areas. The main challenge in the autonomous arrangement is the power management and control coordination [9]. This can be achieved by the local controller in every SMG regulating the voltage and frequency at the AC bus and the voltage at the DC bus. These controllers are also responsible for managing the power flow within the SMG. On the other hand, the transferable power from SMG to another is controlled through the bidirectional converters (ILCs) which play a critical role in increasing the stability and reliability of the system [10, 11].

Conventionally, droop control technique is widely used as a decentralized control method of the three microgrids structures mentioned before. In the case of the hybrid microgrid which is our focus in this paper, many researches use the droop characteristic as indicators (representatives) of the power conditions in AC and DC microgrids [12-16]. This implies that the frequency and voltage should slightly vary when the active power changes at the AC and DC side. Depending on this variation, a sequential process are used so that the results of such process are used as references to the ILCs. Thus, every individual SMG cooperates with the other SMG and share active power proportionally to its total capacity.

In the case of the hybrid microgrid with multiple sub-microgrid, the droop technique is used for every interfaced microgrid. Thus, the AC bus works as a common bus and mediates the power flow from SMG to another according to the microgrid power condition. The frequency works as a transferable indicator between the SMGs even when power flow from DC to DC SMG [17]. Although this method obtains a high level of flexibility and reliability, it has many drawbacks that limit its implementation. For instance, the conventional droop method is not suitable when the hybrid microgrid consists of multiple SMGs. Moreover, once the AC SMG is disconnected from the HMG, there will no longer be any power transfer in the system as the frequency of the AC SMG triggers the ILCs.

This paper proposes a new approach of control strategy to manage the power flow between SMGs without relying on one single variable for each ILC. The organization for the rest of this paper is as follows: Section II illustrates the hybrid microgrid structure used in this work. Section III discusses the conventional control method and its advantages and disadvantages. Section IV presents the Proposed Control Methodology approach. Section V includes the case studies and simulation results that clarify the performance of the proposed system. Finally, the conclusions are presented in VI.

II. ISLANDED HYBRID MICROGRID STRUCTURE

Fig 1 shows a schematic diagram of the hybrid AC/DC microgrids with multiple SMGs. In the AC SMG, every DG is emulated by a DC/AC converter that is linked to the local AC bus and directly connected to the common AC bus. The DC SMG is linked to the DC bus via voltage source inverter (VSI), and each DC SMG is linked to the common AC bus by an ILC. The AC common bus links all the SMGs and mediates the power exchange that may occur. Each ILC act as a bi-directional converter and operates in two modes depending on the direction of the power flow. When the HMG works in the grid connected mode, the intelligent transfer switch or the circuit breaker remains closed in the normal state. The switch opens, and the HMG operates in the islanded mode if there is any planned switching maintenance or unplanned one such as emergency breakdowns. Adopting such structure would boost system efficiency through a reduction in the conversion stages. Also, the power sharing in this structure increases the total power rating of the HMG and improves the system reliability.

III. CONVENTIONAL CONTROL METHODOLOGY

Droop control method is widely utilized in the primary control level for AC and DC and AC/DC microgrids. The commonly used droop control methods are explained below.

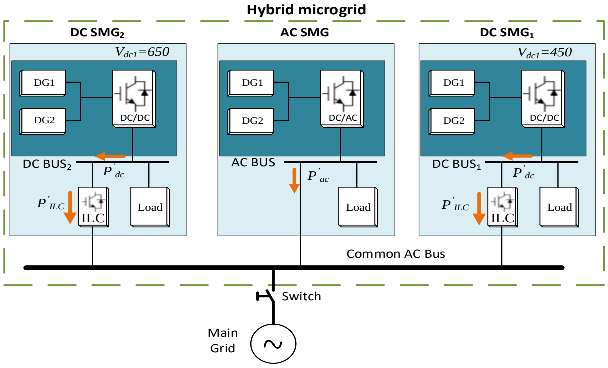

Figure 1. Hybrid MG structure with multi SMGs

A. *Droop control among AC SMG*

In AC SMG the main aim of the control system is to regulate the voltage and frequency at the AC bus. Moreover, to manage the power flow and ensure sufficiently accurate power sharing between the DGs. This can be obtained by using (*P-f*) and (*Q-V*) droop control loops. The basic concept of this method is to mimic the behaviour of synchronous generators. These loops are adapted to ensure an inductive output impedance and connect parallel inverters without using any physical communication links. The *P/f* and *Q/V* curves (Fig. 2) define the characteristic equations of the amplitude (V_i) and frequency (f_i) of the output voltage for the i^{th} DG (DG_i) as the following:

$$f_i = f_{\max} - \alpha_i . P_{ac,i}; \quad V_i = V_{\max} - \beta_i . Q_{ac,i} \qquad (1)$$

where V_{max} and f_{max} are the maximum voltage and frequency magnitude which are obtained at the no load condition. $P_{ac,i}$ and $Q_{ac,i}$ are the calculated output active and reactive power respectively. α_i and β_i are the droop control gain factors and are usually tuned carefully after taking into account the maximum and minimum allowable voltage and frequency deviations (V_{max}, f_{max}, V_{min}, & f_{min}). This is given as:

$$\alpha_i = \frac{f_{\max} - f_{\min}}{P_{i,\max}}; \quad \beta_i = \frac{V_{\max} - V_{\min}}{Q_{i,\max}} \qquad (2)$$

B. *Droop control among DC SMG*

In the DC SMG, the control system is almost similar to the AC one except that it only involves the active power. The (*p-v*) droop control is also adopted to regulate the voltage that slightly varies with the active output power. Virtual output impedances loop is also utilized with the droop loop to avoid the circulation current and insure an inductive output

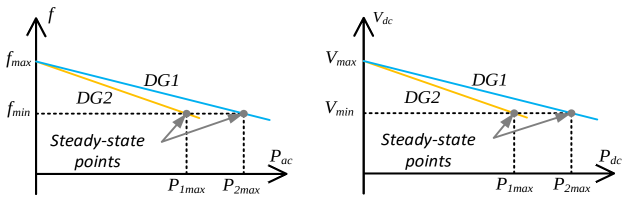

Figure 2. Active power droop characteristics of AC and DC SMGs

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impedance of the converter. The mathematical form that represents the p-v droop control is given as:

$$V_{dc,i} = V_{dc}^{\max} - \lambda_i . P_{dc,i} \tag{3}$$

where V^{max}_{dc} is the maximum DC voltage at the no load condition, λ_i is the droop control gain factor which reflects the rate of deviation in the output voltage ($V_{dc,i}$), and should be tuned carefully as a slight increase of the droop gain factor results in a wide voltage range which might not be accepted for some applications. However, such increase in the voltage range yield more accurate power sharing. The droop gain is given mathematically by:

$$\lambda_i = \frac{V_{dc,i}{}^{\max} - V_{dc,i}{}^{\min}}{P_{dc,i}{}^{\max}} \tag{4}$$

C. Droop control among hybrid AC/DC SMG

Once the voltage and frequency have been regulated in accordance with the power management strategy in each single SMG, the ILCs energise in the system and link each DC SMG with the common AC bus. Not only to manage the transferable power between SMGs but also to increase the whole system stability by reducing the voltage and frequency variations in each SMG. The conventional method for managing the power flow in HMG basically depends on the characteristics of the droop curves ((*p-f*) in AC SMG and (*p-V*) in DC SMGs)since these curves reflect the amount of active power in each SMG. This is further shown through the merge of all the individual droop curves of all DGs into one curve for each SMG. The new droop curves with output frequency f_S at the AC SMG and the voltage $V_{S,i}$ at the DC SMG$_i$ can be given as follows:

$$\begin{aligned} f_S &= f^* - \alpha_S P_{ac,S}, \quad \alpha_S = \frac{1}{\sum_{i=1}^{n} \frac{1}{a_i}} \\ V_{S,i} &= V^* - \lambda_{S,i} P_{dc,S,i}, \quad \lambda_{S,i} = \frac{1}{\sum_{i=1}^{n} \frac{1}{\lambda_i}} \end{aligned} \tag{5}$$

where α_S and $\lambda_{S,i}$ are the combined droop gain of the total output active power ($P_{ac,S}$ and $P_{dc,S,i}$) of the AC SMG and the ith DC SMG (DC SMG$_i$) respectively. Then, these droop curves undergo a normalization process so that it could be compared to each other as a standardized indicator of the power condition. The following expression represents the normalized frequency f' in AC SMG and voltage at DC SMG*i* V_i'.

$$\begin{aligned} f' &= (f_S - f_{\min}) / (f_{\max} - f_{\min}) \\ V_i' &= (V_S - V_{\min}) / (V_{\max} - V_{\min}) \end{aligned} \tag{6}$$

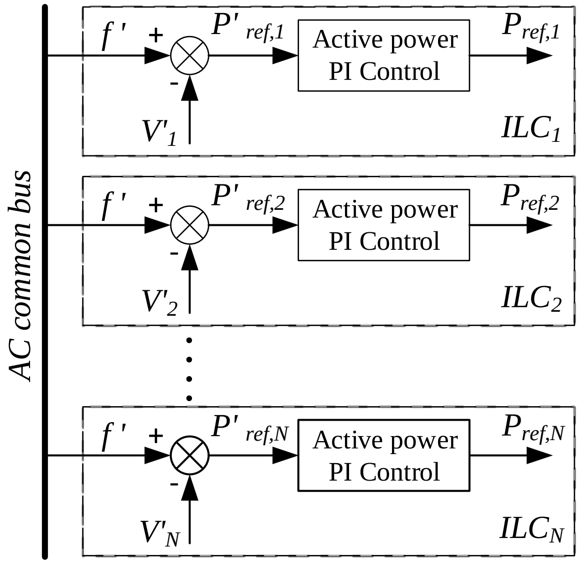


Figure 3. ILCs Conventional control method.

Now the normalized parameters are comparable since they have the same range scale which varies from 0 to 1. According to this range, when the SMG has the maximum output power, the normalized value will be 0, and consequently, the output voltage will be the minimum allowable value.

Once the normalized parameters (f', V_i') are equalized, these parameters are simultaneously utilized as an input of the power management strategy, and the interfaced SMGs share an active power proportional to their ratings. Thus, the interlinking converter manages the power flow between the involved SMGs and at the same time maintain the stability of the AC and DC SMGs. The per- unit transferred power can be achieved by merging f' and V_i' obtained from (9) and can be given as:

$$P'_{ref,i} = f' - V_i' \tag{7}$$

A similar approach can be adopted for the hybrid microgrids with a multiple SMGs structure. The difference here is that the normalized frequency is compared with each normalized voltage as shown in Fig.3 and each DC SMG will deliver or absorb power from/to the AC bus based on Ṕ. The conventional control approach presented above can achieve an accurate power sharing between SMGs without any communication links between DGs or ILCs. On the other hand, the problem in such approach is that it can easily fail if the AC SMG disconnects for a planned (maintenance process) or unplanned condition (faults). In such case, the power transfer will no longer take place.

IV. PROPOSED CONTROL METHODOLOGY

In order to avoid the transferring power discontinuity between SMGs that would results from isolating AC SMG from the whole system, a distributed control system approach is proposed in this work. The main idea is to implement an outer control loop (primary loop) as a local controller considering the normalized factor ($\acute{f}_i$, $\acute{V}_1$, $\acute{V}_2$, .., $\acute{V}_N$) of all SMGs together in each ILC. Fig.4 shows the schematic diagram of the proposed ILCs distributed control system.

In the proposed control strategy the controller of each ILC collects all the measured parameters (DC voltages $V_{dc,i}$ and AC frequency f_i) in every sample time. Send them to other ILCs by using communication link and then, the collected factors are normalized with accordance to (9). Once the normalization step is completed, the resulted indices ($\acute{f}_i$, $\acute{V}_2$, $\acute{V}_3$, .., $\acute{V}_N$) are given by a typical factor name as $y_{SMG,i}$. The new factor represents the normalized variable of ith SMG. For example, y_{SMG} is same to $\acute{f}$ and y_{SMG1} is same to $\acute{V}_1$ and so on. Then, the collected variables ($y_{SMG,N}$) are averaged and produce the appropriate control signal that would be send to the primary control loop of each ILC. This can mathematically be expressed as follow:

$$\bar{y}_{SMG_i} = \frac{\sum_{i=1}^{N} y_{SMG_i}}{N} \qquad (8)$$

where $y_{SMG,i}$ represents the normalized parameter of the ith SMG and range from 0 to 1. Here, i= 1, 2, . . . , N, where, N is the number of the participated SMGs. The outcome variable $\bar{y}_{SMG,i}$ should be forced to be equalized with each SMG corresponding normalized factor y_{SMGi} and this can be done by feeding the error ($P_{ref,i}$) to a PI controller as in (9) whose output represents the transferred active power reference through the ILC. This reference triggers the ILC to share the active power proportionally with its rating where the sign of merging process gestures the direction of the power flow. The active power reference ($P_{ref,i}$) can be obtained as:

$$p_{ref_i} = k_p(\bar{y}_{SMG_N}) - (y_{SMG_i}) + k_i \int (\bar{y}_{SMG_N}) - (y_{SMG_i}) \qquad (9)$$

where the k_p and k_i represent the PI control parameters of the outer loop for the ILC. Once the reference power ($P_{ref,i}$) is found through (9) then it can be converted to the active reference current ($I^*_{i,d}$) according as:

$$I^{*}_{i,d} = \frac{2 \times P_{ref,i}}{3 \times \left|V_{i,abc}\right|} \qquad (10)$$

where, $P_{i,ref}$ and $|V_{i,abc}|$ represent the delivered power and the AC voltage magnitude of ith SMG, respectively. The active current reference ($I^*_{i,d}$) is then supplied to the inner control loop which has a current and voltage control loop. These control loops are used in conjunction with the modified vector decoupling control technique which is implemented by feed-forwarding the line voltage components. This not only facilitates decoupling the active and reactive power control but also allows operation at a unity power factor when the reference value of the reactive reference current ($I^*_{i,q}$) is set to zero. The final step in control process is to transform the *dq* components of the reference voltage into its corresponding *abc* components.

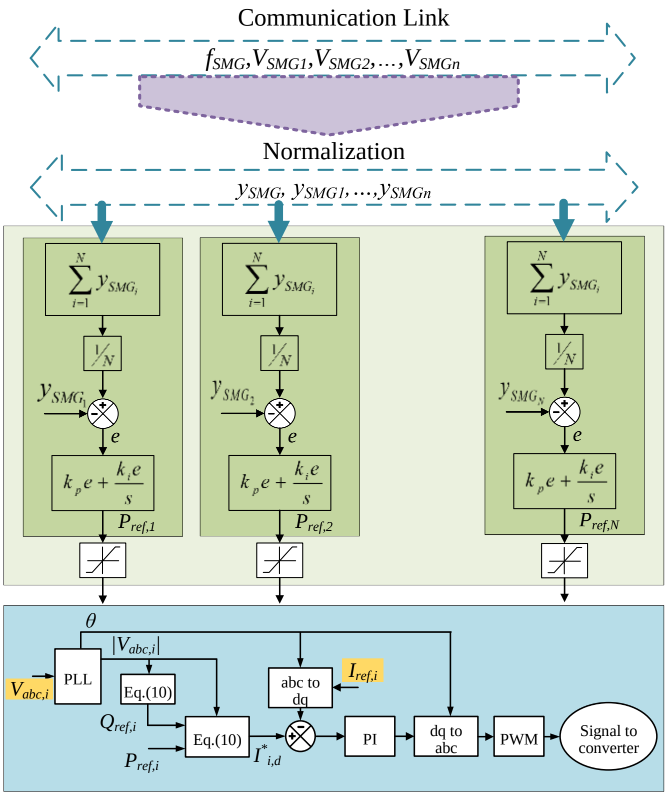


Figure 4. The proposed control approach diagram

In the normal condition, the proposed approach can lead to a similar function of the conventional one. However, if the AC SMG is disconnected from the system the transferred power in the conventional method will no more take place even when the remaining SMGs is still connected to the HMG. On the other hand, the proposed method would overcome this weakness and keep transferring power between SMGs that still connected to the AC common bus. One last step to consider for the proposed scheme is that in the case of AC SMG disconnection; the voltage and frequency at the AC common bus are regulated by one of the ILCs to maintain the function of the AC common bus as a transfer channel between DC SMGs while the other ILCs utilized to manage the power flow.

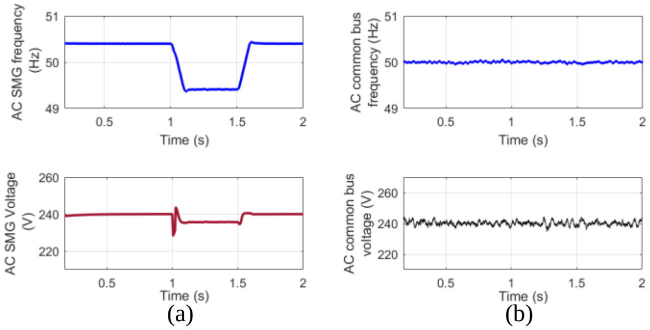
V. CASE STUDIES AND DISCUSSION

For verifying the performance and validity of the proposed control approach and power management strategy, a Matlab/Simulink simulation was executed with the designed multi-SMG structure shown in fig.1. DC SMG1 consist of two DGs that is formed by a DC/DC converter and three-phase DC/AC converter for the AC SMG. One DG represents each DC SMG2 and AC SMG. The total output rating power of all SMGs was selected to be 6 kW so that their droop factor given in (5) would intentionally tuned to ensure their generated powers always balanced. The dc voltage range is 600<V<650 for DC SMG1 and 400<V<450 for DC SMG2 while the frequency range for AC SMG is 49<f<51. The proposed HMG is tested by carrying out simulation for different loading condition in each SMG so it can demonstrate the bidirectional power flow. Three case studies are presented to validate the performance of the proposed approach and make a comparison with the conventional method.

A. *Case A: power exchange in the normal condition using the proposed control strategy:*

In this case, three SMGs are connected to the HMG where the DC SMGs are linked to the common AC bus through the ILCs and power exchange between these SMG according to the load condition in each SMG. The waveforms of the active power flow of loads, sources, and ILCs are shown in Fig.5. (a). Before t=2.5sec, the SMGs are similarly loaded. Therefore, no power exchange occurs at this event. The first load step-up transient takes place in DC SMG1 at t=2.5 sec when the corresponding load demand is increased to 4.3 kW. This trigger the interlinking converter to transfer active power from the common AC bus to the DC SMG2 which in turn is transferred from AC SMG and DC SMG1. At t=5sec a load step transient takes place in the AC SMG

B. *Case B: power exchange when AC SMG isolated using conventional control method:*



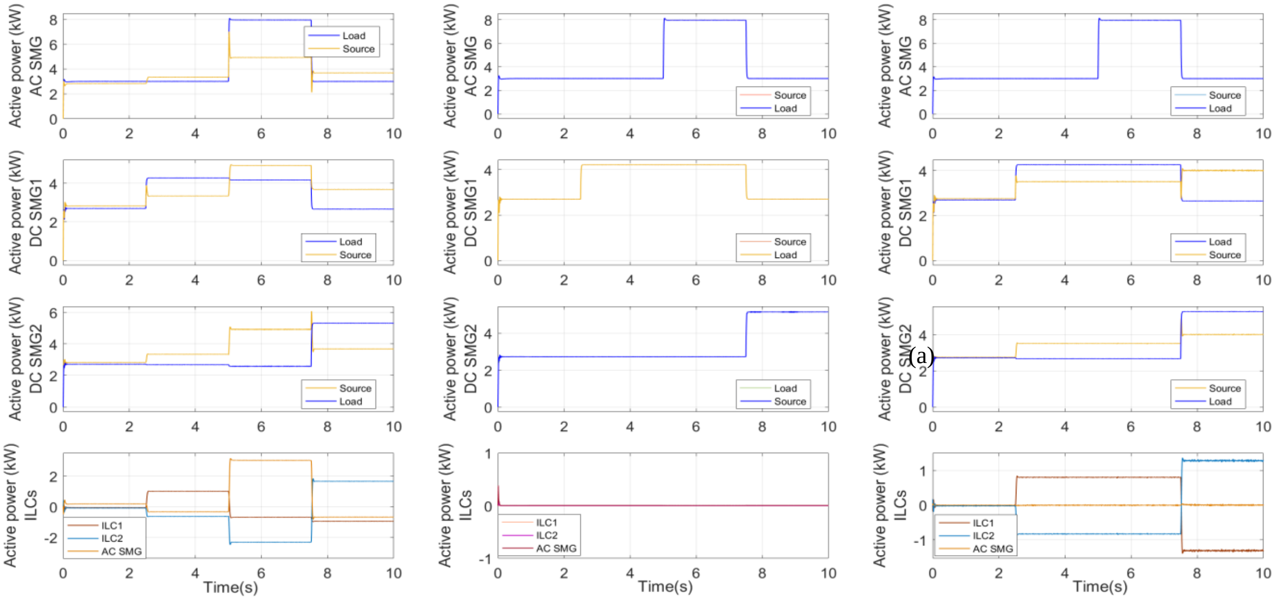
(a) (b)

Figure 6. Comparison between AC SMG and AC common bus for case C.

Meanwhile, the AC SMG may need to switch from hybrid microgrid during a contingency. Fig.5.(b) shows the power flow waveforms for all the SMGs and it can be noted that in each SMG the demand power is similar to the generated power and the transferred power between SMGs is eliminated due to the reasons discussed above and hence no more discussion needed for this case.

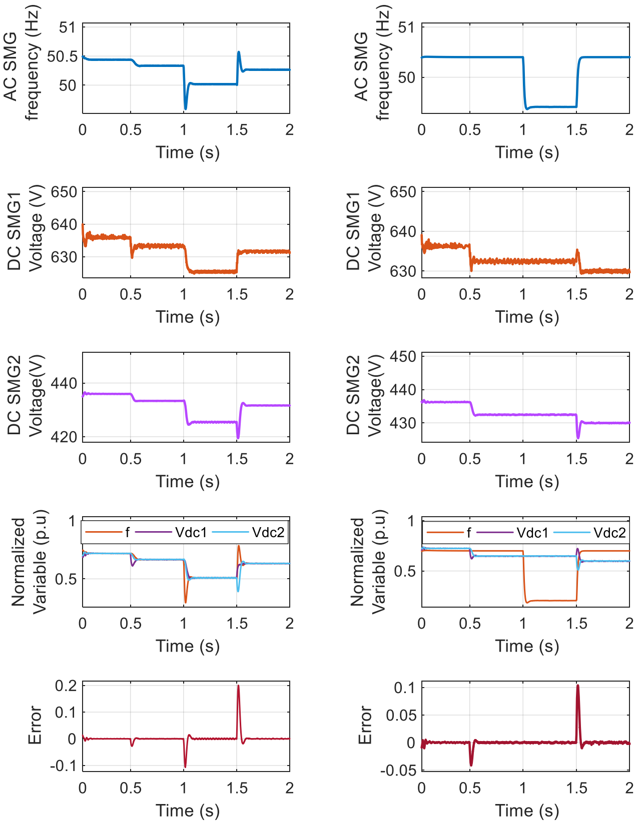
C. *Case C: power exchange when AC SMG is isolated using the proposed control method:*

This case study demonstrates the flexible performance of the proposed method. Fig.5. (c) illustrates the continuity of transfer power between DC SMG1 and DC SMG2 while the AC SMG is isolated and manage its own power flow. According to this Fig.5 (c), the controller sense two load transient at t=2.5 and at t=7.5 and the ILC is triggered to transfer power , the ILC reverses the power flow direction so that the current and voltage is now out of phase (inverter mode) due to a load spike from 2.65 kW to 5.3 kW for the DC SMG2 and from 4.6 to 2.7 for DC SMG1 until balance the generated output power in these SMGs. Due to the inversely proportional relation between power and frequency, the load



(a) (b)

Figure 5. Simulated power waveforms within hybrid MG for four load step scenarios during three case study (a) case A, (b) case B, (c) case C.



(a) (b)

Figure 5. Frequency and voltage waveforms for (a) case A, and (b) case C

increase for the AC SMG triggers its frequency decrease. The corresponding values for the dc subgrid

Fig.6 shows the difference in voltage and frequency between the AC SMG and the AC common bus during case study C where the AC SMG is isolated from the HMG. It also can be noted that the frequency and voltage in AC SMG (Fig.6 (a)) is regulated by its local controller with accordance to droop control while in the case AC common bus it is regulated by one of the ILCs with a standard external reference. The main aim of such coordination is to maintain the AC common bus as a power transfer channel.

Fig.7. shows the voltage and frequency waveforms of all SMGs for case study A in Fig.7 (a) and case study C in Fig.7 (b) through the four load transients. It also shows the normalized variable of the three SMGs and it can be clearly seen that in case A all the variables were forced to be equalized and since the generated power were always balanced. However, in Fig.7 (b) the normalized variables are only equalized for SMG1 and SMG2 as these SMGs are remained connected to the HMG. Moreover, Fig. 7 shows the positive side effect that can be achieved of sharing active power between SMGs. For instance, voltage and frequency variation would be decreased in each SMG since linking SMGs together would increase the total power rating. Accordingly, the whole system stability will improve. This explains the different in the AC SMG frequency between Fig.7 (a) and Fig.7 (b).

VI. CONCLUSIONS

In this paper, a new control method approach and accurate active power sharing are presented.for hybrid AC/DC microgrids with multiple SMGs at different voltage level within an autonomous mode. The proposed method suggests a distributed control system that ensures global controllability for the interlinking converters (ILCs), especially in the case of using multiple SMG, thus avoiding the total dependency on a specific variable for power exchange. The proposed control method has been compared with the conventional one. Various simulation results verify that the proposed scheme ensures continuity and seamless transfer power in case of failure in any single microgrid.

REFERENCES

[1] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Transactions on industrial electronics*, vol. 53, no. 5, pp. 1398-1409, 2006.

[2] F. Nejabatkhah and Y. W. Li, "Overview of power management strategies of hybrid AC/DC microgrid," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 7072-7089, 2015.

[3] M. Abuhilaleh, L. Li, M. Begum, and J. Zhu, "Power management and control strategy for hybrid AC/DC microgrids in autonomous operation mode," in *Electrical Machines and Systems (ICEMS), 2017 20th International Conference on*, 2017, pp. 1-6: IEEE.

[4] E. Unamuno and J. A. Barrena, "Hybrid ac/dc microgrids—Part II: Review and classification of control strategies," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1123-1134, 2015.

[5] J. M. Guerrero, J. C. Vasquez, J. Matas, D. Vicuna, L. García, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158-172, 2011.

[6] X. Liu, P. Wang, and P. C. Loh, "A Hybrid AC/DC Microgrid and Its Coordination Control," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 278-286, 2011.

[7] J. C. Vasquez, J. M. Guerrero, M. Savaghebi, J. Eloy-Garcia, and R. Teodorescu, "Modeling, analysis, and design of stationary-reference-frame droop-controlled parallel three-phase voltage source inverters," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1271-1280, 2013.

[8] N. Eghtedarpour and E. Farjah, "Power control and management in a hybrid AC/DC microgrid," *IEEE transactions on smart grid*, vol. 5, no. 3, pp. 1494-1505, 2014.

[9] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of AC microgrids," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 200-215, 2016.

[10] M. S. Rahman, M. Hossain, and J. Lu, "Coordinated control of three-phase AC and DC type EV–ESSs for efficient hybrid microgrid operations," *ENERG CONVERS MANAGE*, vol. 122, pp. 488-503, 2016.

[11] J. M. Guerrero, M. Chandorkar, T.-L. Lee, and P. C. Loh, "Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1254-1262, 2013.

[12] M. Nehrir *et al.*, "A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 392-403, 2011.

[13] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, "Autonomous control of interlinking converter with energy storage in hybrid AC–DC microgrid," *IEEE Trans. Ind. Appl.*, vol. 49, no. 3, pp. 1374-1382, 2013.

[14] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, "Autonomous operation of hybrid microgrid with AC and DC subgrids," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2214-2223, 2013.

[15] P. Wang, C. Jin, D. Zhu, Y. Tang, P. C. Loh, and F. H. Choo, "Distributed control for autonomous operation of a three-port AC/DC/DS hybrid microgrid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 1279-1290, 2015.

[16] Q. Xu, J. Xiao, P. Wang, and C. Wen, "A Decentralized Control Strategy for Economic Operation of Autonomous AC, DC, and Hybrid AC/DC Microgrids," *IEEE Transactions on Energy Conversion*, vol. 32, no. 4, pp. 1345-1355, 2017.

[17] L. Che, M. Shahidehpour, A. Alabdulwahab, and Y. Al-Turki, "Hierarchical coordination of a community microgrid with AC and DC microgrids," *IEEE Transactions on smart grid*, vol. 6, no. 6, pp. 3042-3051, 2015.