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Control of Interlinking AC-DC Interface Converter Using Dual Droop Control in Hybrid Microgrid

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ABSTRACT

Due to the fast proliferation of distributed generators (DGs) in power systems, managing the power of different DGs and the grid has become crucial, and microgrid provides a promising solution. Therefore, focus on ac and dc microgrids has grown rapidly with their architectural [1], [2], modeling [3], stability analysis and enhancement [4]–[6], power quality improvement [7]–[9], power sharing control [10]–[13], and other issues. Most developments mentioned above on microgrids are, however, directed at DG control mainly within one microgrid. Autonomous operation and modified droop control schemes of such hybrid microgrids were discussed in [15] and [16] and extended in [17] and [18] by integrating an energy storage system to the dc microgrid. Another droop control scheme was followed in [19] for bidirectional power flow between the inter-tied microgrids. In [20], hierarchical control of multiple parallel ac-dc converter interfaces between ac and dc buses was proposed to achieve proportional current sharing.

In the proposed work, investigates the coordinated power sharing issues of interlinked ac/dc microgrids. An appropriate control strategy is developed to control the interlinking converter (IC) to realize proportional power sharing between ac and dc microgrids. Using the proposed scheme, the IC, just like the hierarchical controlled distributed generator units, will have the ability to regulate and restore the dc terminal voltage and ac frequency. Simulation results can be validating using Matlab/Simulink environment.

Keywords— Interlinked microgrids, interlinking converter, power sharing, dual-droop control, data-driven model-free adaptive control.

I. INTRODUCTION

The promise of the smart grid (SG) is round the corner. However, research and society cannot wait for the approval of many standards and grid codes, particularly when these codes can restrict more the independence of the electricity users from the suppliers. In this sense, the demand side management can be satisfied by using local energy storage and generation systems, thus performing small grids or microgrids. Microgrids should be able to locally solve energy problems and hence increase flexibility. Power electronics plays an important role to achieve this revolutionary technology. We can imagine the future grid as a number of interconnected microgrids in which every user is responsible for the generation and storage part of the energy that is consumed and to share the energy with the neighbors [1].

Hence, microgrids are key elements to integrate renewable and distributed energy resources as well as distributed energy storage systems. In this sense, new power electronic equipment will dominate the electrical grid in the next decades. The trend of this new grid is to become more and more distributed, and hence, the energy generation and consumption areas cannot be conceived separately. Nowadays, electrical and energy engineers have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated together into the grid. The new electrical grid, also named SG, will deliver electricity from suppliers to consumers using digital technology to control appliances at consumer's homes to save energy, reducing cost and increasing reliability and transparency. In this sense, the expected whole energy system will be more interactive, intelligent, and distributed. The use of distributed generation (DG) makes no sense without using distributed storage (DS) systems to cope with the energy balances.

Recent innovations in small-scale distributed power generation systems combined with technological advancements in power electronic systems led to concepts of future network technologies such as microgrids. These small autonomous regions of power systems can offer increased reliability and efficiency and can help integrate

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renewable energy and other forms of distributed generation (DG) [1]. Many forms of distributed generation such as fuel-cells, photo-voltaic and micro-turbines are interfaced to the network through power electronic converters [2]–[5]. These interface devices make the sources more flexible in their operation and control compared to the conventional electrical machines. However, due to their negligible physical inertia they also make the system potentially susceptible to oscillation resulting from network disturbances.

A microgrid can be operated either in grid connected mode or in stand-alone mode. In grid connected mode, most of the system-level dynamics are dictated by the main grid due to the relatively small size of micro sources. In stand-alone mode, the system dynamics are dictated by micro sources themselves, their power regulation control and, to an unusual degree, by the network itself.

A. Literature Survey

Nowadays, because of high penetration levels of renewable energy resources, the paradigms of microgrids (MGs) and distribution generation (DG) are gaining vital role in power and distribution systems. MGs are categorized as ac MGs, dc MGs, and hybrid ac–dc MGs. Since a considerable portion of renewable energy resources, such as wind turbines, photovoltaic (PV), fuel cells and energy storage systems, and many modern loads such as communication technology facilities, data centers, and motor drives is dc-type, dynamics and controls of rectifiers and dc MGs are gaining high interest [1]. However, in dc grids, many generation units such as wind turbines must
be interfaced to the utility grid via electronically interfaced (EI) rectifiers. In addition, several modern ac loads are coupled to ac grids through back-to-back rectifier-inverter to provide variable frequency operation. Based on predictions given in [2], the resistive load share will be significantly reduced whereas the EI loads share will increase to total load by 2015. The conventional control topologies for three-phase converters are the voltage-oriented vector control [3] and direct-power control [4]. The dq components of the current vector are regulated by a controller generating appropriate values for the converter dq voltage components. A phase locked-loop (PLL) is required to transform current and voltage variables from the abc frame to the dq frame. It is also feasible to implement the controller in the stationary frame or the abc frame using a proportional-resonant (PR) controller [5]. An alternative control strategy is to use direct power control in which voltage components are adjusted based on active and reactive power errors. None of these methods, however, can directly control the frequency and the load angle. One of the major challenges facing future power systems is significant reduction in grid equivalent rotational inertia due to the expected high penetration level of EI units, which in turn may lead to frequency-stability degradation. To overcome this difficulty, controlling VSCs as virtual synchronous machines is proposed for power system frequency stabilization [6] by embedding a short-term energy storage to the VSC facilitating power flow to and from to the energy storage device proportional to the variation in grid frequency. In [7], the idea of synchronverter was addressed to emulate the mechanical behavior of a synchronous generator (SG) in inverters. However, the dc-link is considered as an ideal one with infinite energy and the dynamics of dc-link voltage is not considered.

Moreover, its application to rectifiers has not been addressed. In [8]–[10], methods to emulate virtual inertia in VSCs interfacing wind turbines and HVDC systems, are presented; however, the embedded inertia does not emulate the behavior of an SG. The analogy between voltage-source inverters and SG-based MGs has also been addressed in [11], [12]. The aforementioned survey indicates the interest in developing new and improved control algorithms for VSCs to emulate the dynamic behavior of SGs.

Beside overall low inertia, future power systems and MGs will suffer from interactions between fast responding VSCs and slower SMs which may contribute to angle, frequency, and voltage instability [13]. With the expected high penetration level of power converters in future power grids; a power system may face severe difficulty in terms of frequency regulation because of lack of rotational inertia in converter-interfaced generators. Another challenge is that frequency dynamics are not known in the conventional control techniques of VSCs (e.g., voltage-oriented control and direct-power control) which makes it difficult to analyze the angle and frequency stability of a system containing several EI units and conventional synchronous machines (SMs) and line-start motors. Therefore, the development of VSCs with well-defined angle, frequency, and dc-link voltage characteristics (similar to SMs with extension to dc-link dynamics) are of high interest for future smart power systems with a high penetration of VSCs. Moreover, a general control scheme which is suitable for both rectification and inversion modes without reconfiguration is very attractive in power system applications since bidirectional VSCs can work in generative and motoring modes similar to SMs.

II. PROBLEM FORMULATION

Due to the fast proliferation of distributed generators (DGs) in power systems, managing the power of different DGs and the grid has become crucial, and microgrid provides a promising solution. Therefore, focus on ac and dc microgrids has grown rapidly with their architectural [1], [2], modeling [3], stability analysis and enhancement [4]–[6], power quality improvement [7]–[9], power sharing control [10]–[13], and other issues. Most developments mentioned above on microgrids are, however, directed at DG control mainly within one microgrid.

Enforcing ac and dc microgrids inter-tied by an interlinking power converter is a promising topology in future power networks, and has in fact been discussed recently due to some benefits, such as greater security and reliability, and reduced transmission and distribution losses [14]. Autonomous operation and modified droop control schemes of such hybrid microgrids were discussed in [15] and [16] and extended in [17] and [18] by integrating an energy storage system to the dc microgrid. Another droop control scheme was followed in [19] for bidirectional power flow between the inter-tied microgrids. In [20], hierarchical control of multiple parallel ac-dc converter interfaces between ac and dc buses was proposed to achieve proportional current sharing. Despite the progress mentioned above, some drawbacks of the previous methods can also be found. (*i*) The majority of the existing inner loop control techniques are greatly dependent on mathematical model. These techniques cannot give satisfactory results when suffering poor model. Uncertainty dynamics and disturbances [21], [22] widely exist in inverter based microgrids, and it is difficult to obtain the accurate model. Although robust control [23], predictive control [24], variable-structure control [25], and neural network [26] –based control have been proposed for power converters, some challenges still exist. Partial mathematical model and uncertainty dynamics should be known for design of robust controller and variable-structure controller. While predictive control has good performance and strong robustness, the model or structure of the plant also should be known. (*ii*) Proportional power sharing and voltage (frequency) regulation cannot be achieved at the same time. Interlinking converters in [14] and [18] can be viewed as voltage sources, but proportional power sharing between two microgrids cannot be achieved accurately. On the other hand, in [16], [17], and [19], interlinking converters can be viewed as current sources since they are current controlled converters, which implies these interlinking converters cannot participate in voltage and frequency regulation. (*iii*) Although various secondary control schemes have been developed to restore the frequency and voltage to their nominal values, the restoration of ac frequency and dc voltage has not been considered in the previous literatures for the interlinked ac and dc microgrids, such as [15]–[19]. Therefore, a new appropriate control scheme should be further developed for interlinking converts to address these issues mentioned above. Obtaining the system model information that is accurate enough is very difficult in such complicated interlinked microgrid systems. It is more important and meaningful to take advantage of the large amount of the process data produced by the system to boost the operating efficiency and cut the costs. Data-driven model-free adaptive control (DDMFAC) does not require any model information of the controlled plant and the required control performance can be achieved by using the input/output (I/O) data. It is of great significance to take advantage of the process data in such complex system particularly for the future smart grid and energy internet.

In this thesis, data-driven control (DDC) structure for interlinking converters in interlinked ac and dc hybrid microgrids. One important reason that we try to use the data-driven MFAC method to design the controller of the IC is to take the most advantage of the process data, boost the efficiency, and cut the costs on the basis of achieving required control performance. The proposed control scheme employs a data-driven model-free adaptive voltage controller (DDMFAVC) for fast and robust voltage tracking and a dual-droop controller with a secondary controller for proportional coordinated power sharing between ac and dc microgrids and restoration of frequency and dc voltage. Considering the voltage controller, model-free adaptive control (MFAC) perhaps is the best solution.

The introduced control scheme is analyzed and simulated using a MATLAB/Simulink and the results are presented.

III. HIERARCHICAL CONTROL OF MICROGRIDS

An interface is required when interconnecting dc power systems with an ac system. The design of the interface has great significance on the operation of the dc system and the impact on the ac system. A well-designed ac/dc interface shall provide a controllable dc-link voltage, high power quality and high transient performance during faults and disturbances. It must also have low losses and low cost. Moreover, bi-directional power-flow capability may be desired if generation is present in the dc system, in order to transfer power from the dc system to the ac system during low-load, high-generation conditions in the dc system. Finally, galvanic isolation is necessary to prevent having a current path between the ac system and the dc system in case of a fault.

Different designs of ac/dc converters and their control algorithms have been studied for many years. However, little research has been presented regarding converters which can be suitable to interconnect an ac system with an LV dc power system.

A. Secondary Control of Microgrids

Power electronic interfaces became prevalent through voltage source converters (VSC) to integrate emerging DGs. Depending on the objectives and the control structure, a VSC is classified to voltage-controlled VSC and current-controlled VSC. Voltage-controlled VSCs facilitate the voltage and frequency regulation of DGs, while current-controlled VSCs control the active and reactive power delivery. For instance, RESs in MPPT mode and batteries in charging mode are preferred to be used as a current-controlled VSC. However both RESs and ESSs can also participate in voltage and frequency regulation. ESSs, e.g. batteries, are better choice for use as a voltage-controlled VSC because of their bidirectional capability.

Droop control is normally employed in the primary control level to be added to the inner control loops for parallel connection of these voltage-controlled VSCs inside the MG, thus sharing power load between them. In ac systems, the droop control strategy has different forms according to the type of the output impedance. The active power-frequency, P-ω, and reactive power-voltage, Q-V, droops are used when the output impedance is inductive; the reactive power-frequency, Q-ω, and active power-voltage, P-V, droops are employed when the output impedance is resistive. However, active power-voltage droop, P-V or output current-voltage droop i_o-V is utilized for dc systems [5].

The main drawback of droop method is poor voltage and frequency (in case of ac MGs) regulation. Once the power sharing is improved among the MG units, the voltage/frequency drop increases. The larger droop gain is, the more voltage/frequency deviation and the more accurate is load sharing between the sources. Therefore, the droop method has an inherent trade-offs between voltage/frequency regulation and load sharing. As primary control is not able to return the MG to the normal operating conditions, secondary control is employed to restore the voltage and frequency. In addition, power load sharing can be also achieved between the MG sources by implementing a secondary control loop; in cases the primary control is unable to do that due to line impedances and/or different control parameters.

Centralized Secondary Control

Conventional secondary controller is unique for the whole MG, relies on centralized communication infrastructure and is, among other functions, implemented within the MG central controller (MGCC). Fig.3.1 shows centralized secondary control architecture for a MG consisting of a number of DG units controlled by local primary control and one central secondary controller, which collects measured variables transferred by means of a low bandwidth communication system. Those variables are compared with the references in order to calculate appropriate compensation signals by secondary controller, which sends them through dedicated communication channels back to primary control of each unit.

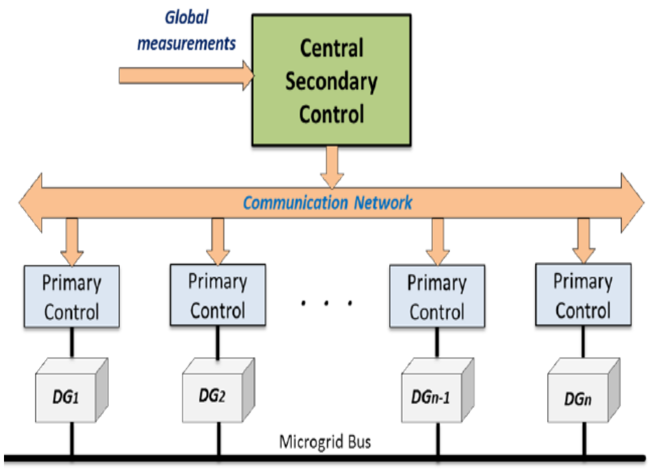

Fig.3.1 Centralized secondary control structure

The centralized approach requires point-to-point communication, which adds complexity to the system and compromises its reliability due to a single point of failure issue. Alternatively, distributed control methods have attracted a lot of interests in MG research community recently, due to their attractive features as they accommodate more reliable and sparse communication networks.

Distributed Secondary Control

Distributed secondary control (DSC) is an alternative which avoids a single centralized controller and therefore improves reliability of the MG. The idea is to merge primary and secondary control together into one local controller. However, for proper operation, these local controllers need to talk with their companions, as shown in Fig.3.2. Their conversation is typically processed through neighboring communication, resulting in a control system that is in literature generally referred to as distributed control.

The basic working principle of DSC is to exchange the information through the neighboring communication, by utilizing a distributed protocol and achieving a consensus, e.g. the average value of measured information. As opposed to frequency, voltages are local variables, implying that their restoration can be done either in selected critical buses, or on the total average level. In the latter case, DSC can be exploited to generate a common signal which is compared with a reference and passed through a local PI controller, which produces appropriate control signal to be sent to the primary level for removing associated steady state errors. It should be noted that the type of protocol, which is essential for making the secondary control distributed, influences the feasibility and performance of DSC. Several distributed control methods have been introduced in the literature out of which consensus- [46, 47] and gossip-based [48] algorithms have recently received significant attention mostly because of their implicitness and robustness for distributed information exchange over networks.

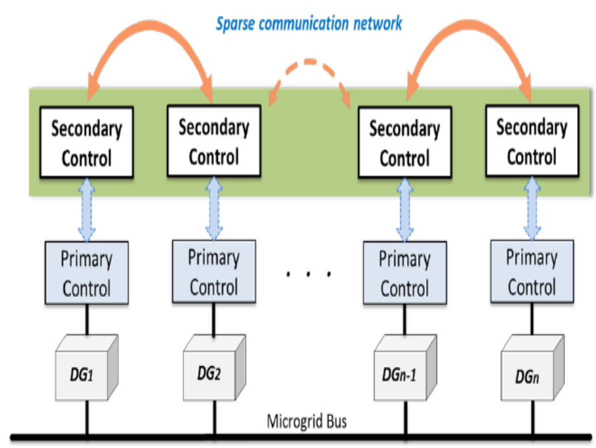

Fig.3.2 Distributed secondary control structure

B. Main Functions of Secondary Control

The main functions of secondary control are to simultaneously shift the droop characteristics of associated DGs in order to perform restorations of voltage and frequency levels to nominal values while keeping active and reactive power shared between the units. Moreover, secondary control can encompass synchronization loop, as well as power quality regulation capability, optionally. The synchronization control loop can be considered in this level of control to seamlessly connect/disconnect the MG to/from the distribution ac networks. This loop is designed to synchronize the voltage, frequency and phase of MG with the main grid. In addition, global objectives regarding voltage control and power quality of the MG, such as voltage unbalance and harmonic compensation can be also considered as a function for secondary control.

IV. SIMULATION RESULTS

This Chapter presents detailed simulation results of the proposed control system. The simulated system is shown in Fig. 4.1. Simulation studies are carried out in the MATLAB/SIMULINK environment.

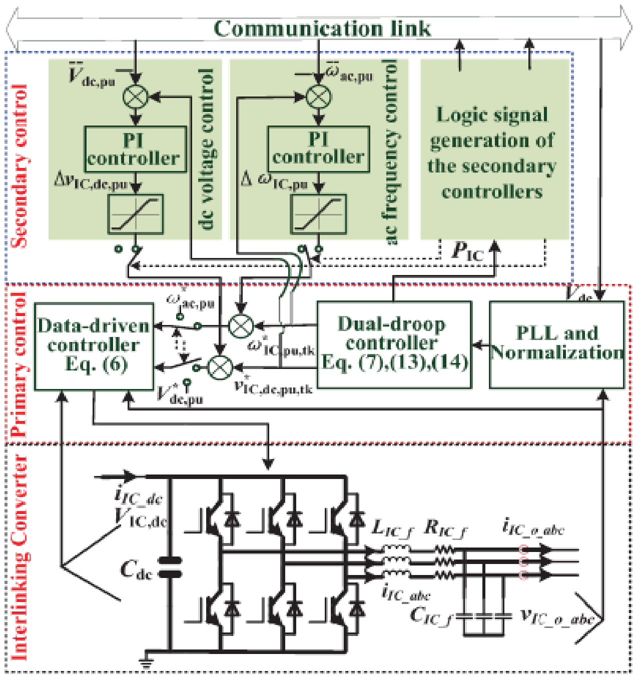

Fig.4.1 Details of the secondary controller for the interlinking converter in the hybrid microgrids

To validate the performance of the proposed control scheme for the interlinked ac/dc microgrids, the interlinked system, depicted in Fig.4.1 has been simulated in MATLAB/Simulink environment. The ac and dc microgrids have its own DGs and loads, and are emulated with a dc-ac inverter and a boost converter, respectively. A six-switch dc-ac converter with *LC* filters serving as the interlinking converter is adopted to interface the ac and dc microgrids.

A. Simulation Result Analysis

Case I:

In this case, both the ac and dc microgrids are initially experiencing a load demand of 2 kW each; this means that the wo microgrids are initially operating in light load condition. According to the proposed control strategy along with the equal measured per-unit values ($V_{dc,pu}$ = $\omega_{ac,pu}$ = 0.6) of the voltage at dc side and the frequency at ac side, no active power ($P_{IC,tk}$ =0 kW) is transferred by the interlinking converter in this condition. The interlinking converter operates in mode-3. Fig. 4.2 shows the power responses and the per unit values of the dc side voltage and the ac side frequency. After t=2 s, loads in the ac and dc microgrids are increased to 5 kW and 7 kW, respectively. In this condition, both the ac and dc microgrids are operating in normal load condition. Thus the per-unit values of the ac side frequency and dc side voltage drop to 0 p.u and -0.4 p.u, respectively. According to (13), $\eta e > \eta = 0.2$, the active power transferred by the interlinking converter is updated to -1 kW, which means the interlinking converter transfers 1 kW from the ac microgrid to the dc microgrid. The operation mode is changed from mode-3 to mode-1. Upon reaching steady-state, the ac and dc source generations are noted to be the same at about 6 kW each. And the ac and dc microgrids have the same normalized value of -0.2 p.u ($V_{dc,pu}$ = $\omega_{ac,pu} = -0.2$), resulting in proportional power sharing of the total load between the two microgrids.

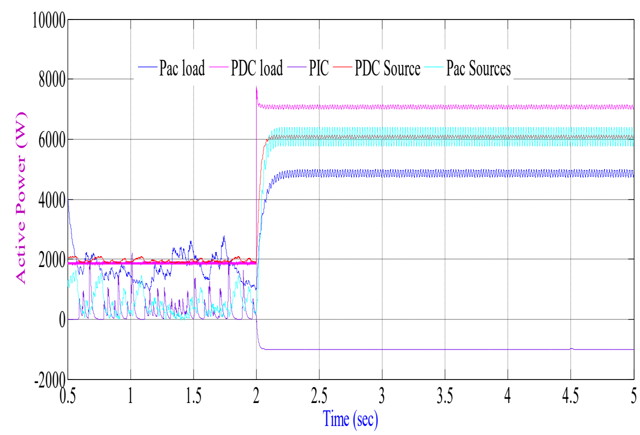

Fig.4.2 Power responses under case-I

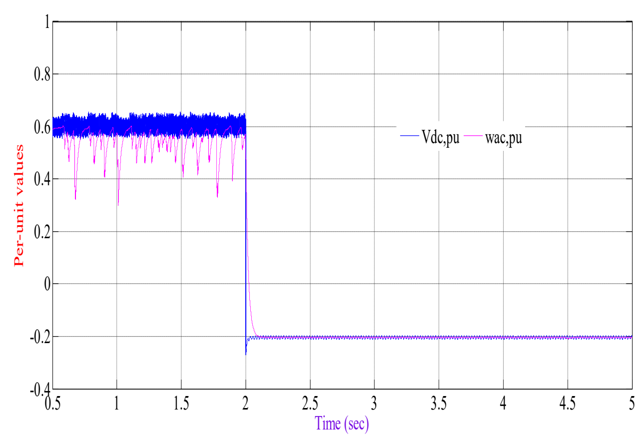

Fig.4.3 Per unit values under case-I

Case II:

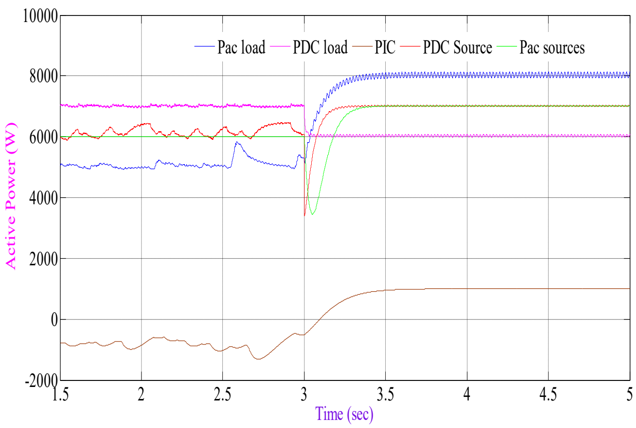

Fig.4.4 Power responses under case-II

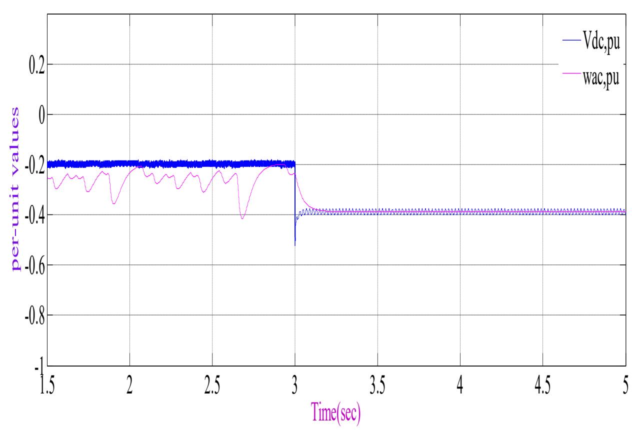

Fig.4.5 Per unit values under case-II

Similar to case I, in this case, the initial load conditions are set to 5 kW for the ac microgrid and 7 kW for the dc microgrid. The interlinking converter transfers 1 kW from the ac microgrid to the dc microgrid in the steady-state described in case 1 to achieve proportional power sharing. At t=3 s, the load demands of the ac and dc microgrids are changed to 8 kW and 6 kW, respectively. Then normalized values of the ac side frequency and dc side voltage are changed to -0.6 p. u and -0.2 p. u, respectively. Upon sensing the mismatch in normalized values, the amount of the active power to be transferred by the interlinking converter is updated to 1 kW resulting in the interlinking converter to reverse the power flow with 1 kW shifted from the dc to ac microgrid.

Thus the $\omega_{IC,pu} - P$ droop is selected and updated to control the frequency. The operation mode of the interlinking converter is changed from mode-1 to mode-2 now. Fig.4.3 shows the power responses and the normalized values of the ac side frequency and the dc side voltage. It can be seen that the total load is proportionally shared between the ac and dc microgrids. In the steady-state, the ac and dc source generations are noted to be the same at about 7 kW each. And the ac and dc microgrids have the same normalized value of -0.4 p. u. as shown in Fig.4.5.

Case III:

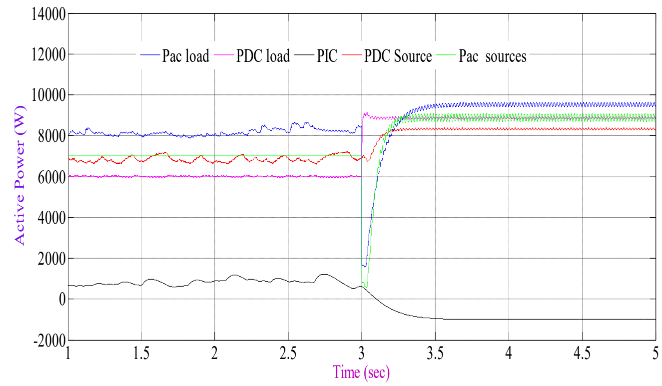

Fig.4.6 Power responses under case-III

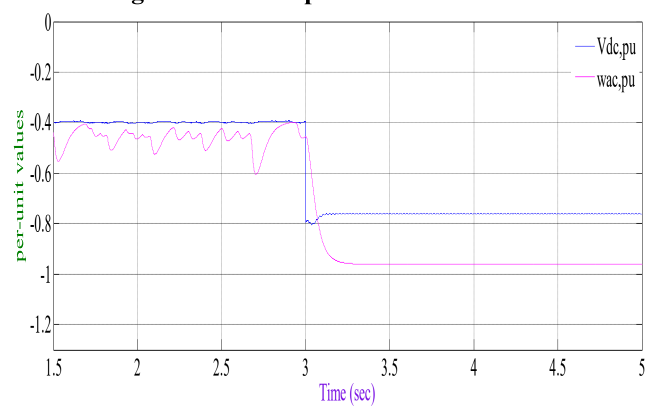

Fig.4.7 Per unit values under case-III

The over load condition of both the ac and dc microgrids is considered in this case. The initial conditions are set to 8 kW for the ac microgrid and 6 kW for the dc microgrid, respectively. That means the ac microgrid is initially operating in over load condition while the dc microgrid is operating in normal load condition. In the steady state, the interlinking converter transfers 1 kW from the dc microgrid to the ac microgrid, which is discussed in case 2 in detail. At t=3 s, the ac and dc microgrids are changed to 9.5 kW and 9 kW, respectively, which makes both the ac and dc microgrids over loaded. This can also be demonstrated by the measured normalized values (-0.9 p. u and -0.8 p. u). The active power to be transferred by the interlinking converter is updated to 0 kW, which means the interlinking converter, transfers nopower and each microgrid is responsible for the power sharing in this load condition. Fig. 4.6 and Fig.4.7 shows the power and the normalized values of the ac side frequency and the dc side voltage.

Case IV:

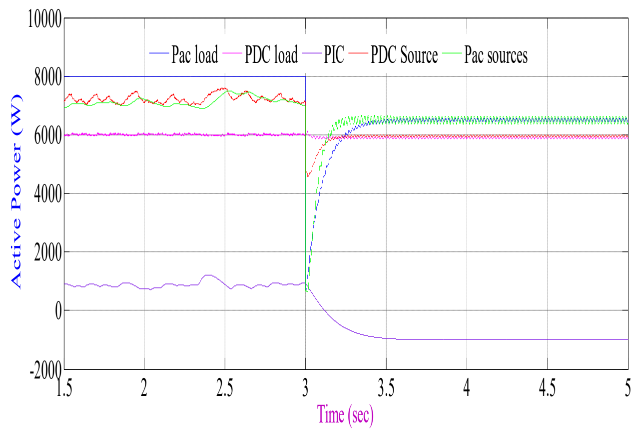

Fig.4.8 Power responses under case-IV

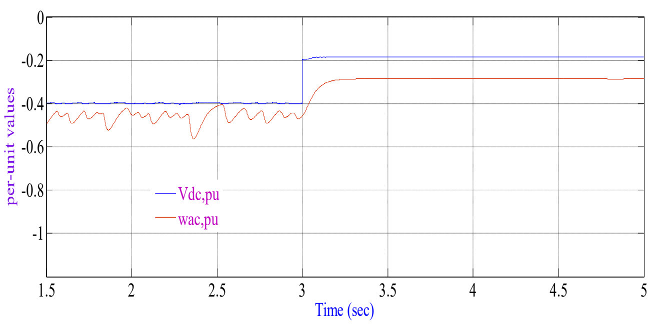

Fig.4.9 Per unit values under case-IV

In this case, the initial conditions are set to 8 kW for the ac microgrid and 6 kW for the dc microgrid, respectively. That means the ac and dc microgrids are initially operating in over load and normal load condition, respectively. In the steady state, the interlinking converter transfers 1 kW from the dc microgrid to the ac microgrid. At t=3s, the ac microgrid is changed to 6.5 kW and the dc microgrid remains 6 kW. Although the ac and dc microgrids are operating at normal load condition, the active power to be transferred by the interlinking converter is updated to 0 kW (PIC,tk =0 kW) since the deviation is less than the threshold (ηe < η), which means the interlinking converter transfers no power and each microgrid is responsible for the power sharing in this load condition. Fig.4.8 and Fig.4.9 shows the power and the normalized values of the ac side frequency and the dc side voltage.

Case V:

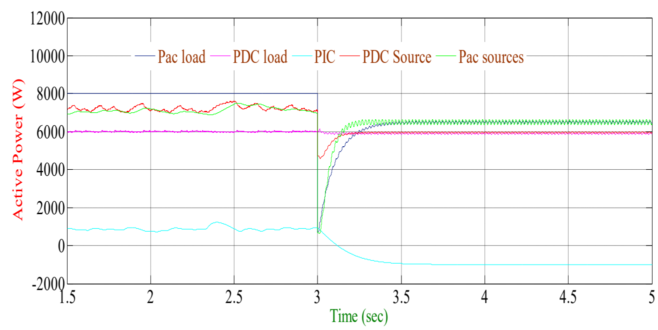

Fig.4.10 Power responses under case-V

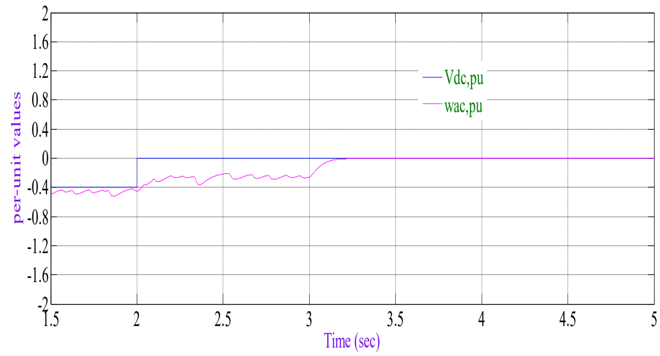

Fig.4.11 Per unit values under case-V

Based on case 4, the secondary control scheme is added in this case. The load conditions considered in this simulation is the same as that in case 4. Fig.4.11 shows the simulation results, from which it can be seen that the per unit values of the ac frequency and dc voltage are restored to zero corresponding to their nominal values with help of the secondary controllers. At t=3 s, the ac microgrid is changed to 6.5 kW and the dc microgrid remains 6 kW. In this load condition, no active power is transferred by the interlinking converter since the deviation is less than the threshold (ηe < η), which means each microgrid is responsible for the power sharing. Therefore, the secondary controller of the interlinking converter is stopped to work and the secondary controllers in each ac and dc microgrid remain working.

V. CONCLUSION

In this thesis, investigates on coordinated power sharing issues of interlinked ac and dc microgrids. To realize proportional power sharing between ac and dc microgrids, a novel primary controller including a dual-droop controller and a data-driven model-free adaptive voltage controller has been firstly proposed in this work. Following, a secondary control scheme has also been proposed to cooperate with each microgrid to restore the dc voltages and the ac frequency to their nominal values.

Using the proposed scheme, the interlinking converter, just like the hierarchical controlled DG units, will have the ability to regulate and restore the dc terminal voltages and the ac frequency while keeping proportional power sharing. Simulation results have been given to verify the proposed power sharing strategy. In the future, the proposed scheme can be possible to validate through experimental studies.

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