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Coordinated Control and Energy Management of Distributed Generation Inverters in a AC/ DC Microgrid

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Abstract
This paper presents a microgrid consisting of different distributed generation (DG) units that are connected to the distribution grid. An energy-management algorithm is implemented to coordinate the operations of the different DG units in the microgrid for grid-connected and islanded operations. The proposed microgrid consists of a photovoltaic (PV) array which functions as the primary generation unit of the microgrid and a proton-exchange membrane fuel cell to supplement the variability in the power generated by the PV array. A lithium-ion storage battery is incorporated into the microgrid to mitigate peak demands during grid-connected operation and to compensate for any shortage in the generated power during islanded operation. The control design for the DG inverters employs a new model predictive control algorithm which enables faster computational time for large power systems by optimizing the steady-state and the transient control problems separately. The design concept is verified through various test scenarios to demonstrate the operational capability of the proposed microgrid, and the obtained results are discussed.

I. INTRODUCTION

DUE TO increasing deployment of DGs in power systems,managing the power of different DGs and the grid hasraised a major concern [1]–[3]. In this field, microgrids havebecome a widely accepted concept for the superior connectionof DGs in power networks. Corresponding to the conventionalpower systems, ac microgrids have been established foremostand a variety of surveys have been reported particularly on thesubject of power sharing of parallel-connected sources [4]–[6].Since the majority of renewable energy sources, generate dcpower or need a dc link for grid connection and as a result of increasingmodern dc loads, dc microgrids have recently emergedfor their benefits in terms of efficiency, cost and system that caneliminate the dc-ac or ac-dc power conversion stages and Their accompanied energy losses [7]–[10]. However, since The majorityof the power grids are presently ac type, ac microgridsare still dominant and purely dc microgrids are not expected toemerge exclusively in power grids. Therefore, dcmicrogrids areprone to be developed in ac types even though in subordinate.Consequently, linking acmicrogridswith dc microgrids and employingthe profits of the both microgrids, has become interestingin recent studies [11]–[14].

Over the last decade, efficient and reliable communication and control technologies, coupled with an increase in smarter electrical facilities, such as electric vehicles and smart meters, have resulted in an increasing number of consumers participating in demand response management (DRM) [1]–[5]. The current research is also focused on achieving a smarter grid through demand-side management (DSM), increasing energy reserves and improving the power quality of the distribution system, such as harmonic compensation for nonlinear loads [5]–[8]. These new trends enable higher levels of penetration of renewable generation, such as wind and solar power into the grid. The integration of renewable sources can supplement the generation from the distribution grid. However, these renewable sources are intermittent in their generation and might compromise the reliability and stability of the distribution network. As a result, energy-storage devices, such as batteries and ultra-capacitors, are required to compensate for the variability in the renewable sources. The incorporation of energy-storage devices is also critical for managing peak demands and variations in the load demand. In this paper, a microgrid consisting of a photovoltaic (PV) array, a proton-exchange membrane fuel cell (PEMFC), and a lithium-ion storage battery (SB) is proposed. The PEMFC is used as a backup generator unit to compensate for the power generated by the intermittent nature of the PV array. The SB is implemented for peak shaving during grid-connected operation, and to supply power for any shortage in generated power during islanded operation and to maintain the stability of the distribution network. An energy-management algorithm is designed for the microgrid to coordinate the sharing of power among different DG units. The proposed controller for the inverters of DG units is based on a newly developed model predictive control (MPC) algorithm, which optimizes the steady-state and the transient control problems separately. In this way, the computation time is greatly reduced.

In what follows, this paper provides a comprehensive solution for the operation of a microgrid which will simultaneously dispatch real and reactive power during both grid-connected and islanded operations, compensate for harmonics in the load currents, and perform peak shaving and load shedding under different operating conditions.

The idea is to merge the ac and dc microgrids through a bidirectional ac/dc converter and establishinga hybrid ac/dc microgrid in which ac or dc type energysources and loads can flexibly integrate into the microgrids andpower can smoothly flow between the two microgrids. Reference[11] proposes a hybrid ac/dc microgrid in which the renewableenergy sources and storages are connected in a dc grid andsupplying power to the main ac grid and local ac loads. A hybriddc/ac microgrid configuration is proposed in [12], in which a dcpower line along with an energy conversion station are addedto the conventional three-phase power distribution system forthe integration of distributed domestic renewable sources. Themain idea is to use the locally generated energy and reducing thepower draw from the grid. Reference [13] proposes to combinea smart dc grid with the ac grid in order to suppress the dc busvoltage fluctuation using controllable loads and achieving thestabilization control of the ac grid using the grid-side converterinterlinking the dc and ac microgrids. A hybrid microgrid composedof various kinds of renewable energy sources is consideredin [14]. A coordinate control scheme is developed in orderto manage the whole system in different operating conditions.

II. SYSTEM STRUCTURE AND OPERATION MODES

A simple hybrid ac/dc microgrid is shown in Fig. 1. It consistsof an ac microgrid with conventional DG sources, a dc microgridwith two dc type sources and an IC links the two microgridstogether. Each of these microgrids also includes their

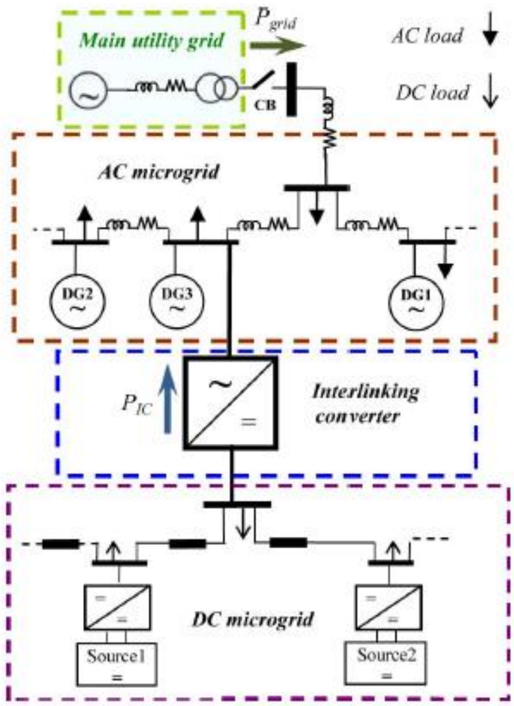

Fig.1.A typical hybrid ac/dc microgrid.

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Individual loads. Besides, during normal grid operation the hybridMicrogrid is connected to the main utility grid through theac microgrid. Basically, the microgrids are thought to operatein grid-connected or islanding modes [1]. In the grid-connectedoperation mode of the hybrid microgrid, the ac microgrid dynamicsare governed directly by the main utility grid and theIC primarily regulates the dc microgrid voltage and controlsthe power balance, as well. In this operating condition the dcsources can generate a constant power or can operate in maximumpower point for the renewable energy sources. In the islandingmode of operation, and during light loading of the dcpart, the demanded power is shared among the dc sources usingthe*P-Vdc* droop characteristics. When over-loading happensin the dc microgrid, the interlinking converter will also participatein load sharing using the proposed ac-dc droop control. Inthe following, the performance of the hybrid ac/dc microgrid isdescribed in either of these two modes.

A. Grid-Connected Mode

While the hybrid ac/dc microgrid is connected to the mainutility grid, DG sources in the ac microgrid are expected to eithergenerate a specified real/reactive power, or act as terminalvoltage regulator with a specified amount of active power andvariable reactive power [5]. On the other hand, the utility gridoperates as slack bus to support the difference in the active/reactivepower demand and to sustain the microgrid frequency.Similarly, in dc microgrid, DG sources would be controlled togenerate a specified active power. However, the utility grid isstill responsible for voltage support and power balance throughthe IC. According to Fig. 1 and neglecting the power losses, thismode can be described,

$$\text{dc microgrid}: P^*_{IC} = \sum_i P^{load}_{dc,i} + P^{loss}_{dc} - \sum_i P_{dc,i} \quad (1)$$

$$\text{ac microgrid}: P^*_{grid} = \sum_i P^{load}_{ac,i} + P^{loss}_{ac} + P^*_{IC} - \sum_i P_{ac,i}. \quad (2)$$

In this mode the renewable energy sources in the microgridcan operate in maximum power point, energy storages cancharge and non-renewable sources can be managed, e.g., forpeak shaving purposes, loss reduction or economical goals[4]. In the ac microgrid, DGs could also generate a specifiedreactive power, regulate terminal voltage or may be used forpower quality aims [21]. These power management studieshave been studied in dc microgrids [7], [8] and it is not intendedto be followed in this paper.

B. Islanding Mode

The more challenging situation is the islanding operation ofthe hybrid ac/dc microgrid. In the islanding mode, the total loaddemand should be shared and managed autonomously by theexisting DGs in the both microgrids, which involves rapid andflexible active/reactive power control strategies to minimize themicrogrid dynamics. A proper load shedding strategy is also requiredin case of deficiency in local generated power in orderto maintain the system stability [7]. This paper adopts decentralizedcontrol strategies based on droop control to manage thepower sharing among ac sources as well as dc sources, and betweenthe ac and dc microgrid. Different operating states mayoccur during islanding operation of the hybrid microgrid. Forthe sake of appropriate performance of the hybrid ac/dc microgridunder different grid conditions, four main operating statesare considered in the islanding mode, as follows:

Islanding state I: This operation state corresponds to the islandingoperation of hybrid ac/dcmicrogrid during which powergeneration in ac microgrid and dc microgrid suffices their individualloads (light load condition). The generation units ineach microgrid will regulate its power to meet the load. In thisstate, the IC halts transferring power and can just supply reactivepower for the ac microgrid. This state is expressed by,

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$$P^*_{IC} = P^*_{grid} = 0 \quad (3)$$

$$\text{dc microgrid}: \sum_i P^{load}_{dc,i} \leq \sum_i P_{dc,i} \quad (4)$$

$$\text{ac microgrid}: \sum_i P^{load}_{ac,i} \leq \sum_i P_{ac,i}. \quad (5)$$

Islanding state II: This state represents the case where thegenerated power in ac microgrid is deficient for the ac load demandbut there is surplus power in the dc microgrid. Therefore,the required power should be supplied by the dc sources throughthe IC. In this state we have,

$$\text{dc microgrid}: \sum_i P^{load}_{dc,i} < \sum_i P_{dc,i} \quad (6)$$

$$\text{ac microgrid}: \sum_i P^{load}_{ac,i} > \sum_i P_{ac,i} \quad (7)$$

$$P^*_{grid} = 0, P^*_{IC} = \sum_i P_{ac,i} - \sum_i P^{load}_{ac,i} - P^{loss}_{ac}. \quad (8)$$

Islanding state III: This state is similar to state II, except thatthe power deficit occurs in the dcmicrogrid and the ac microgridis in light load condition. Therefore, the ac microgrid suppliesthe required power for dc microgrid. In this case,

$$\text{dc microgrid}: \sum_i P^{load}_{dc,i} > \sum_i P_{dc,i} \quad (9)$$

$$\text{ac microgrid}: \sum_i P^{load}_{ac,i} < \sum_i P_{ac,i} \quad (10)$$

$$P^*_{grid} = 0, P^*_{IC} = \sum_i P_{dc,i} - \sum_i P^{load}_{dc,i} - P^{loss}_{dc}. \quad (11)$$

Islanding state IV: This operation state relates to the caseduring which the load demand in both ac microgrid and dcmicrogrid are greater than the maximum available sources capacity(overload condition). In this state, the IC halts transferringpower and a proper load shedding strategy must be run tostabilize the grids. This state is described by,

$$P^*_{IC} = P^*_{grid} = 0 \quad (12)$$

$$\text{dc microgrid}: \sum_i P^{load}_{dc,i} \geq \sum_i P_{dc,i} \quad (13)$$

$$\text{ac microgrid}: \sum_i P^{load}_{ac,i} \geq \sum_i P_{ac,i}. \quad (14)$$

III. DROOP CONTROL STRATEGY FOR INDIVIDUAL MICROGRIDS

A. Control of DGS in the AC Microgrid

Power management based on droop control is currently wellrecognized in ac microgrids. Real power generation of a DGis specified based on frequency-droop (ω-P) characteristic[4]. Since there is no dominant source to enforce the base frequencyin the islanded microgrid, the frequency of the microgridvaries by means of demanded power variations. The mainidea of this control is to increase the active power generationof DGs when the system frequency decreases. Similarly, for reactivepower management voltage-droop(V - P) is exploited.Reactive power generation of a DG is determined based on deviationsin the bus voltage. Therefore, the DG source acts in responseto themeasured local voltage deviations caused by eitherthe system or the local load.ω-Pand$V$ - Pcharacteristicscould be described mathematically by

$$P^{ref} = -\frac{1}{k_{ac}}(\omega^0 - \omega) + P^0 \quad (15)$$

$$Q^{ref} = -\frac{1}{k_q}(V^0 - V) + Q^0 \quad (16)$$

$$k_{p,ac} = -\frac{\omega^{\max} - \omega^{\min}}{P^{\max}} \quad (17)$$

$$k_{q,ac} = -\frac{V^{\max} - V^{\min}}{Q^{\max}}. \quad (18)$$

By this power control method, during the grid-connectedmode where the frequency of the system is fixed, real powergeneration of the DG is controlled by$P°$.

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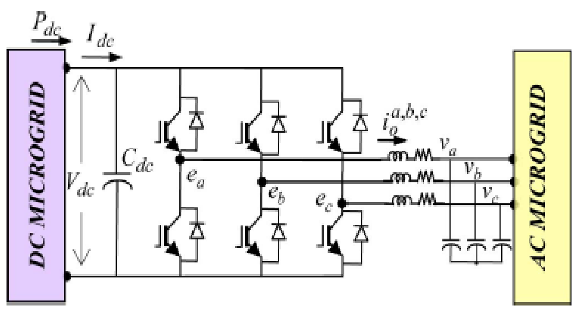


Fig.2. Configuration of the IC interfacing ac and dc microgrids.

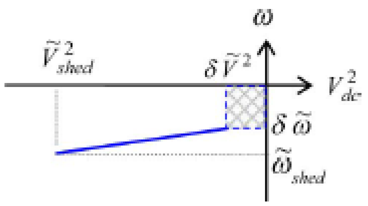


Fig.3. Proposed ac-dc droop characteristic.

B. Control of DGs in DC Microgrid

Alternatively, for the dc microgrid the dc voltage-droop (*Vdc- P*) control method is used for power sharing betweenDG sources in the microgrid. Typical*Vdc- P* droop characteristicscan be expressed by

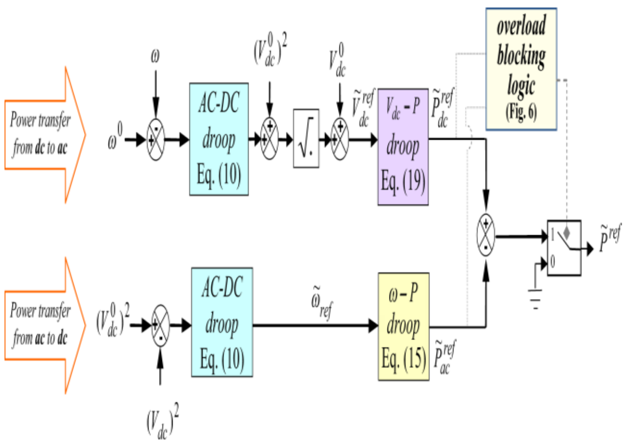
$$P_{dc}^{ref} = -\frac{1}{k_{dc}}(V_{dc}^{0} - V_{dc}) + P_{dc}^{0} \quad (19)$$

$$k_{p,dc} = -\frac{V_{dc}^{max} - V_{dc}^{min}}{P^{max}}. \quad (20)$$

IV. PROPOSED IC CONTROL FOR ISLANDING OPERATION

In addition to the power sharing strategies adopted for thestandalone dc or ac microgrids, it is required to develop a propercontrol strategy for the IC to share the demanded power between these two microgrids. However, the power management for the IC control is different from the proposed strategies currentlyused for the energy sources in the standalone ac or dc microgrids.In contrast to the ac or dc microgrids, the IC is expectedto manage a bidirectional flow of power between the ac and dcMicrogrids. In addition the IC should cooperate in power sharingbetween the energy sources in both microgrids with dissimilardroop characteristics. This is due to the fact that at any instantthe IC takes the role of supplier to onemicrogrid and at the sametime acts as a load for the other microgrid. These challengingissues can be handled by exploiting a proper control strategyfor the IC to transfer the required power between the microgrids.In order to eliminate fast communication links, a modifieddroop based control strategy is proposed to attain desirable performance. As discussed in the previous sections, during theislanding operation of the hybrid ac/dc micro grid different operatingstates might arise and the IC should recognize these statesand manage the whole hybrid microgrid. The following decentralizedcontrol strategy is adopted for this purpose.

The power management should determine the amount of active power that the IC must transfer from one microgrid to the other. In order to provide the power reference command, the dc bus voltage of the IC and the frequency of the ac microgrid are utilized as input to the power management system. Considering Fig. 2, the electrical energy stored in the dc capacitor is,



$$W_{dc} = \frac{1}{2} C_{dc} V_{dc}^{2}. \quad (21)$$

Neglecting the switching losses in the converter Pdc=Pac,the dynamics in the dc capacitor energy is the

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difference of power transfer between ac and dc microgrids. Therefore,

$$\frac{d}{dt}W_{dc} = \frac{1}{2}C_{dc}\frac{d}{dt}(V_{dc}^2) = P_{dc} - P_{ac} = \Delta P. \qquad (22)$$

On the other side, considering the w-P characteristic in the ac microgrid,

$$\Delta\omega = \omega^0 - \omega = k_\omega \Delta P. \qquad (23)$$

According to (22) and (23), using the forward Euler approximation with sampling period (Tc) [22] and assuming that the microgrid frequency is constant in this interval, a new droopcharacteristic for the IC called "ac-dc droop" is defined as,

$$(\omega_0 - \omega) = \bar{k}_\omega\left((V_{dc}^0)^2 - (V_{dc})^2\right), \bar{k}_\omega = k_\omega.\left(\frac{1}{2}\frac{C_{dc}}{T_s}\right). \quad (24)$$

The "ac-dc droop" characteristic is shown in Fig. 3.δώ Andδ*V*are the dead zone bands for the allowable variation of angular frequency and dc voltage, respectively. Dead zone is utilized in the proposed "ac-dc droop" in order to prevent any power transfer during light load operation of individual micro grids. During such operation condition the generating units in each microgrid will regulate the generated power to supply the corresponding micro grid load using the relevant*Vdc- P* or ω-Pdroop characteristics. *V*²*shed*andώ*shed*arerespectivelythe minimum dc voltage and ac microgrid frequency drop in dc and ac micro grids that the system is supposed to undergo load shedding.

Furthermore, since the IC is not the mere frequency or dcvoltage controller in the hybrid ac/dc microgrid, it is necessaryto participate in power sharing between ac and dc sources. Toimplement this scheme, the output of the ac-dc droop is fed tothe*Vdc- P* andω-P droops of the IC. It is necessary to mentionthat since positive sign for power transfer in the IC is consideredto be from dc to ac, the power for*Vdc- P* droop shouldbe regarded with negative sign. Finally, according to $\bar{V}_{dc}^{ref}$ and $\bar{\omega}^{ref}$ the amount of power to be transferred via the IC is determinedby the two reference power calculated through these twoloops. A schematic block diagram of the proposed power managementstrategy for the IC is depicted in Fig. 4. The impact ofthe proposed droop control for the IC on the power sharing ofsources in each microgrid is illustrated within two load increasescenarios in each microgrid,

1) In the first scenario it is assumed that the dc microgridis near overloading and there is excess power in the acmicrogrid. Upon increasing the load in the dc microgrid,the dc voltage will accordingly decrease. If the voltagedrop is beyondδ*V*, referring to the proposed ac-dc droop(Fig. 3) this voltage deviation produces a new referenceangular frequency $\bar{\omega}^{ref}$. This $\bar{\omega}^{ref}$ will then determinesthe reference power for the IC power controller using theconventional ω-Pdroop. This is the amount of power tobe transferred from ac to dc microgrid. Therefore, the ICtreats as a source for the dc microgrid and partly restoresthe voltage of the dc microgrid. On the other hand, the ICtakes the roll of a load for the ac microgrid and increasesthe power generation of the ac sources.

2) The other scenario happens when the ac microgrid is nearoverloading. When the ac load increases again, causes thefrequency to decrease below δώ. Referring to the proposedac-dc droop a new reference voltage $(\bar{V}_{dc}^{ref}$ is presented.Finally, by using the droop the required powerto be transferred to the*Vdc- P* dc microgrid is determined. Therefore,according to these two scenarios whenever the loadincreases in one of the microgrids, the "ac-dc droop" characteristicrelates the ac and dc microgrids using the dc linkperformance and the equivalent frequency droop characteristicof the ac microgrid which is determined by,

$$\Delta P = k_\omega \Delta\omega, k_\omega = \left(\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}\right) + D \quad (25)$$

WhereR1, ….. Rn are droop coefficient of ac sources *D*andis the load-damping constant of the ac microgrid. Usingthis droop characteristic it is possible to relate the differentdroops of ac and dc microgrid and consequently share thepower in the whole microgrid.

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By this power management strategy the response of IC indifferent islanding states is as follows:

Islanding state I: Throughout this state, Δω < δω andΔVdc² <δV² therefore the output of "ac-dc droop" is

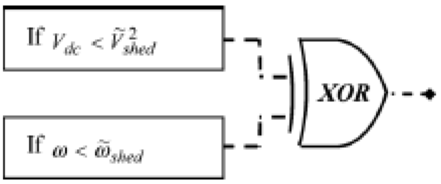

Fig.5. Overload blocking logic for real power controller of the IC.

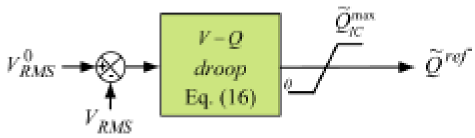

Fig.6. Reactive power controller for the IC.

$\tilde{V}^{ref}_{dc} = V^0_{dc}$ For dc micro grid and $\tilde{\omega}^{ref} = \omega_0$ for ac microgrid.Consequently, $\tilde{P}^{ref} = 0$ and IC transfers no power.

Islanding state II: In this state $\Delta V^2_{dc} < \delta \tilde{V}^2$ butΔω< δωTherefore, $\tilde{P}^{ref} = -\tilde{P}^{ref}_{dc}$ and IC supplies power to the acmicrogrid.

Islanding state III: In this stateΔω < δω butΔVdc² < δV² therefore, and IC supplies power to the dc microgrid.

Islanding state IV: During this state, $\omega < \tilde{\omega}_{shed}$ andΔVdc² <δV²*shed*. In order to block the IC for any power transfer, an overloadblocking logic shown in Fig. 5, is added at the output theproposed droop control in which by using an "EXCLUSIVE OR(XOR)" logic, whenever both microgrids enter overloading theIC is blocked and no power will transfer.

The reactive power control of the IC is more straightforwardsince there is no reactive power in dc microgrid and the IC isdesignated to play as a voltage support in droop-control modeto share the reactive power with other DGs in ac microgrid.The reactive power sharing is based on the conventional droopshown in Fig. 6, the local RMS voltage is measured and usingthe droop, the*V-Q* reactive power reference is determined.Since the active power transfer is the prime task of the IC, adynamic reactive power limit is added to the control block toconsider the capacity limit of the IC. The reactive limit is definedas,

$$\tilde{Q}^{max}_{IC} = \sqrt{\left(S^{max}_{IC}\right)^2 - P^2_{IC}}. \qquad (26)$$

Finally, a current control scheme [23] is utilized in IC controlfor tracking the reference active/reactive power calculated bythe power management system.

V. MODELING AND SMALL SIGNAL STABILITY ANALYSIS

Section IV describes the proposed droop method for the IC inthe hybrid AC/DC microgrid. This section investigates a smallsignalanalysis for the hybrid microgrid to analyze the stabilityof the system. In order to reduce system equations and for thebetter analysis of the proposed droop controller, the dc sourcesand their individual droops are aggregated to form one combineddc source. This is also done for ac sources, dc and ac loadsas well. Therefore the hybrid microgrid shown in Fig. 1 is simplifiedfrom the perspective of IC, as shown in Fig. 7. Furthermore,as discussed in Section II, different scenarios can be consideredfor the operation of the hybrid microgrid, but for the stabilityanalysis only the worst case condition is considered whichis the islanding states II and III defined in Section II.

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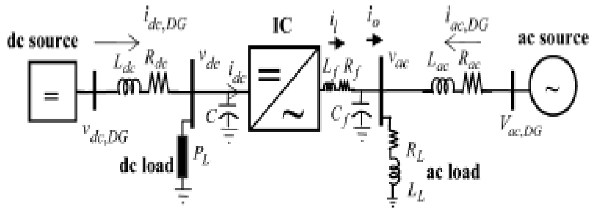

Fig.7. Simplified equivalent model of the hybrid microgrid.

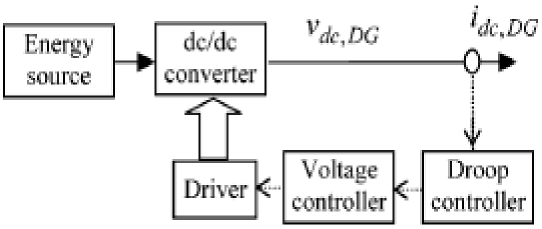

Fig.8.Block diagram of the dc source.

A. DC Micro grid Modeling

The dc microgrid comprised of sources, loads and the dc network.Componentsmodeling are discussed in the following subsections.

1) DC Source Modeling:

The block diagram of a dc sourceis shown in Fig. 8. By measuring the output current of the dcsource and using the droop controller, the reference voltagevalue for the voltage controller of the dc/dc converter is determined.Since the voltage controller are much faster than thedroop controller [25] and in order to reduce the system equations,the fast dynamics are neglected and the dc/dc converteris assumed to be a controllable voltage source. This means thatthe voltage controller can exactly follow the reference voltageand consequently the output voltage is equal to its referencevalue. The droop equation for the dc source is,

$$v_{dc,DG} = \frac{1}{R_{dc}} i_{dc,DG} + v^{0}_{dc,DG}. \qquad (27)$$

Linearizing (26) by using small-signal approximation leadsto,

The represents the small-signal perturbation of the correspondingparameter.

2) DC Load Model:

The majority of loads in the dc microgridsutilize power electronic converters for grid connection since these converters are generally tightly regulated; theseloads behave as a constant power load (CPL) [26]. Therefore,the CPL load model is considered for stability analysis. Asshown in [26], the small signal model of CPL can be expressedby a negative resistance, as given by

$$\hat{i}_{L,dc} = g_L \cdot \hat{v}_{L,dc}$$
$$g_L = -\frac{P_L}{V^2_{L,dc}}. \qquad (29)$$

3) DC Network Model:

The dc network is equivalentlymodeled as a series combination of resistance and reactance asshown in Fig. 7 The network equation can be represented asfollows,

$$\hat{v}_{dc} = L_{dc}\frac{d\hat{i}_{dc,DG}}{dt} + R_{dc}\,\hat{i}_{dc,DG}. \qquad (30)$$

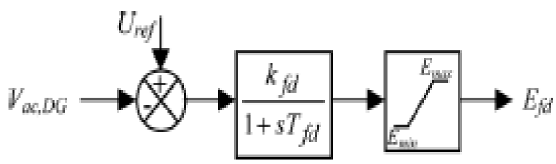

Fig.9. Excitation system model of synchronous generator.

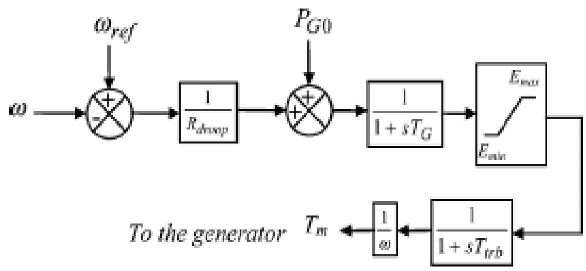

Fig.10. Governor and turbine model of synchronous generator.

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B. Ac Micro grid Modeling

Similar to dc micro grid, the ac micro grid is also consists of acsources, ac loads and the ac network, as shown in Fig. 7. The aggregatedac source is a two-pole, three-phase synchronous machine,equipped with excitation and governor systems. Detailedsmall signal modeling of the synchronous machine is fully consideredin [27] and for the sake of brevity this is not presentedhere. A first-order excitation system is used for terminal voltagecontrol, as shown in Fig. 9. The equation of this system is,

$$\dot{\hat{E}}_{fd} = \frac{k_{fd}}{T_{fd}}(U_{ref} - E_t) - E_{fd}. \qquad (31)$$

Two first-order governor and turbine are adapted to controlthe frequency, as shown in Fig. 10.

The small signal state space model of the load and the acnetwork are,

$$\frac{d\hat{i}^d_{L,ac}}{dt} = -\frac{R_L}{L_L}\hat{i}^d_{L,ac} + \omega\,\hat{i}^q_{L,ac} + \frac{1}{L_L}\hat{v}^d_{ac} \qquad (32)$$

$$\frac{d\hat{i}^q_{L,ac}}{dt} = -\frac{R_L}{L_L}\hat{i}^q_{L,ac} - \omega\,\hat{i}^d_{L,ac} + \frac{1}{L_L}\hat{v}^q_{ac} \qquad (33)$$

$$\frac{d\hat{i}^d_{ac,DG}}{dt} = -\frac{R_{ac}}{L_{ac}}\hat{i}^d_{ac,DG} + \omega\,\hat{i}^q_{ac,DG} + \frac{1}{L_{ac}}(\hat{v}^d_{ac} - \hat{v}^d_{ac,DG}) \qquad (34)$$

$$\frac{d\hat{i}^q_{ac,DG}}{dt} = -\frac{R_{ac}}{L_{ac}}\hat{i}^q_{ac,DG} - \omega\,\hat{i}_{ac,DG} + \frac{1}{L_{ac}}(\hat{v}^d_{ac} - \hat{v}^d_{ac,DG}). \qquad (35)$$

C. IC Modeling

Fig. 11 shows the control block diagram of the IC in *d-q*referenceframe. The real power reference is determined accordingto the proposed droop shown in Fig. 4. The active power controlloop generates the reference current*i*d* using PI controller. Thecurrent control loop measures the output currents and controlsthe converter to follow the reference value using PI controller.

The droop characteristics for active power shown in Fig. 4can be expressed by,

$$(\omega_0 - \omega) = \bar{k}_\omega\left(\left(V^0_{dc,DG}\right)^2 - \left(v_{dc,DG}\right)^2\right) \qquad (36)$$

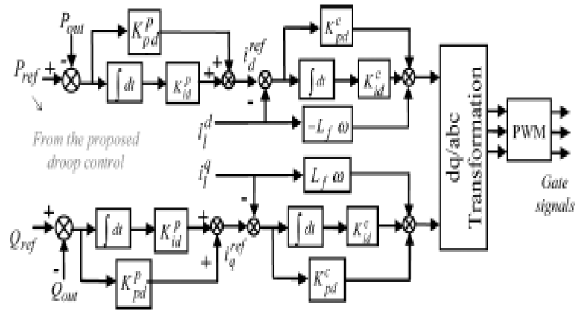

Fig.11. Control block diagram of the IC.

$$P^{ref}_{ac} = k_{ac}(\omega_{ref} - \omega) \qquad (37)$$

$$P^{ref}_{dc} = k_{dc}(V^{ref}_{dc,DG} - v_{dc,DG}). \qquad (38)$$

Combining (35) and (36), the reference power for the ac microgridis,

$$P^{ref}_{ac} = k_{ac}\left[\left(\frac{1}{\bar{k}_\omega}\left(v^2_{dc,DG} - {V^0_{dc,DG}}^2\right) + \omega_0\right) - \omega\right]. \qquad (39)$$

The linearized model of the proposed droop for the ac microgridcan be obtained as,

$$\hat{P}^{ref}_{ac} = \alpha_{ac}\,\hat{v}_{dc,DG} - k_{ac}\,\hat{\omega}$$
$$\alpha_{ac} = 2\frac{k_{ac}}{\bar{k}_\omega}V_{dc,DG} \qquad (40)$$

Where*Vdc* is the dc-bus voltage at the operating point.Similarly, the linearized reference power for the dc microgridcan be expressed by,

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$$\hat{P}_{dc}^{ref} = \alpha_{dc}\,\hat{v}_{dc,DG} - k_{dc}\hat{\omega}$$
$$\alpha_{dc} = -\frac{k_{dc}\bar{k}_{\omega}}{2\sqrt{\omega_0}}V_{dc,DG}. \quad (41)$$

A conventional PLL [28] is used for estimating the systemangular frequency, ω. The linearized model of the PLL is representedby,

$$\dot{\hat{\omega}} = -K_{pll}\,K_{p\omega}\hat{\omega} - K_{pll}\,K_{i\omega}\,m_q\hat{v}_{ac}^q - K_{pll}K_{i\omega}m_d\,\hat{v}_{ac}^d. \quad (42)$$

The parameters are defined in [28].
The linearized model of real power controller derived fromFig. 11 is [4]

$$\dot{\hat{\phi}}_{id} = \hat{P}_{ref} - \hat{P}_{out} \quad (43)$$
$$\hat{i}_d^{ref} = K_{id}^p\hat{\phi}_{id} + K_{pd}^p(\hat{P}_{ref} - \hat{P}_{out}). \quad (44)$$

$\hat{P}_{out}$ Is represented by the linearized equation of the instantaneousreal power in the *d-q*frame as,

Finally, the reference voltage for the PWM switching is followedby the current controller according to the reference current.The corresponding small-signal state space equation of thecurrent controller is,

$$\dot{\hat{\phi}}_{vd} = \hat{i}_d^{ref} - \hat{i}_l^d \quad (46)$$
$$\hat{v}_d^{ref} = K_{pd}^c(\hat{i}_d^{ref} - \hat{i}_l^d) + K_{id}^c\hat{\phi} - \hat{\omega}\,L_f\,\hat{i}_l^d. \quad (47)$$

Since the dc bus voltage in the IC is not fixed, the switchingprocess should also be considered for stability analysis. There

TABLE I
POWER FLOW IN EACH OPERATING CASE

	Case I	Case II
Ac source generation (kW)	645	624
Dc source generation (kW)	440	461
IC power transfer (kW)	-55 (ac to dc)	-33 (ac to dc)
Dc load (kW)	490	490
Ac load (kW)	580	580
k_ω ((rad/s)/kW)	12	20

TABLE II
TWO DOMINATING OPERATING MODES

	Case I	Case II
Mode 1	-0.074 ± *j*8.75	-0.054 ± *j*8.68
Mode 2	-1.36 ± *j* 3.2	-1.43 ± *j* 3.1

Fore, the converter and its output filter small signal model canbe represented by [29],

$$\frac{d\hat{i}_o^d}{dt} = -\frac{R_f}{L_f}\hat{i}_o^d + \omega\,\hat{i}_o^q + \frac{1}{L_f}\hat{v}_{ac}^d - V_{dc}\,\hat{d}_d - \hat{v}_{dc}\,D_d \quad (48)$$

$$\frac{d\hat{i}_o^q}{dt} = -\frac{R_f}{L_f}\hat{i}_o^q - \omega\,\hat{i}_o^d + \frac{1}{L_f}\hat{v}_{ac}^q - V_{dc}\,\hat{d}_q - \hat{v}_{dc}\,D_q \quad (49)$$

$$C\frac{d\hat{v}_{dc}}{dt} = \frac{3}{2}(\hat{d}_d I_l^d + \hat{d}_q I_l^q + D_d\,\hat{i}_l^d + D_q\,\hat{i}_l^q) - \hat{i}_{dc} \quad (50)$$
$$\frac{d\hat{v}_{ac}^d}{dt} = \omega\,\hat{v}_{ac}^q + \frac{1}{C_f}\hat{i}_l^d - \frac{1}{C_f}\hat{i}_o^d \quad (51)$$
$$\frac{d\hat{v}_{ac}^q}{dt} = -\omega\,\hat{v}_{ac}^d + \frac{1}{C_f}\hat{i}_l^q - \frac{1}{C_f}\hat{i}_o^q. \quad (52)$$

The small signal model of the hybrid ac/dc microgrid is developedby combining the state-space representation of eachac subsystem transferred to a global reference frame and thestate-space model of the dc microgrid.

D. Small Signal Analysis

The linearized model of the hybrid microgrid is used tostudy the small signal dynamics of the microgrid during autonomousmode of operation. Based on the system model andcorresponding parameters, the two dominating modes are:

Mode 1: Electromechanical mode of ac source which is selectedas a gas-fired turbine-generator

Mode 2: Related to the droop gain of the IC which is thefunction of k_{dc}, k_{ac}, k_{ω} .

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The dominant modes are identified for two operating casesshown in Table I. The first case corresponds to the powertransfer from the ac to dc microgrid with $k_\omega = 12$ (thiscorresponds to the value for the proportional power sharingbetween the sources [4]) and the second relates to the powertransfer with $k_\omega = 20$. The corresponding modes are shownin Table II. It is found that by increasing the ac-dc droop gain,the amount of power participation for the ac source decreaseswhich increases the ac source damping (dominating mode).The same result can be deduced for the power transfer fromdc to ac, in which increasing the ac-dc droop gain results inthe greater participation of dc sources in the power sharing andincreases the dominating mode damping.

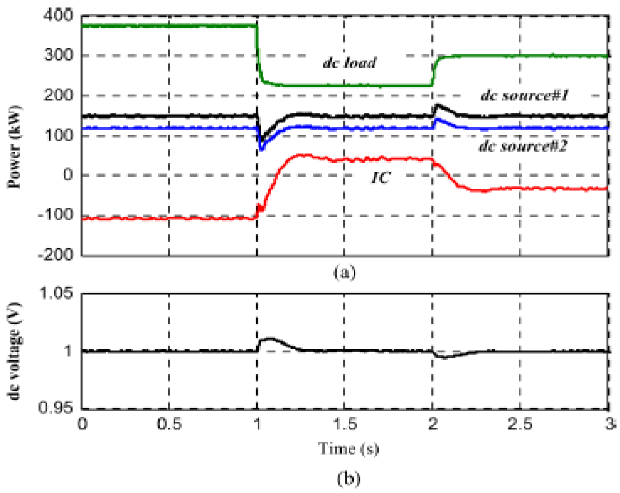

Fig.12. Simulation results for Case 1.

VI. CASE STUDIES AND SIMULATION RESULTS

In order to validate the proposed power management control,a hybrid ac/dc microgrid is simulated in PSCAD/EMTDC using detailed switching model for the converters. Consideringthe schematic diagram of Fig. 1, the ac microgrid includes twogas-fired DG units with synchronous generators, excitation andgovernor control systems. Furthermore, the dc microgrid containstwo dispatch able dc sources. System parameters are presentedin Appendix. Different operating scenarios, configurationof loads and generation are considered in the simulations inorder to validate the performance of the proposed power managementmethod in controlling the IC in the hybrid ac/dc microgridand sharing the power between the ac and dc microgrids.

A. Case 1

In this case, the hybrid ac/dc microgrid is supposed to beconnected to the main utility grid. At first, dc sources generatea fixed power, a portion of the demanded load is supplied bythe local sources in dc microgrid and the insufficient power isprovided through the IC. At*t=1*s, a large portion of the dcload switches off and the dc power generation is more than theload demand. The IC moves to the inverting mode and feedsthe surplus power to the ac grid. Similarly, at *t=2*sdc loadincreases and approximately matches the generated dc power.The IC power, dc load and the generated power of the dc sourcesalong with dc-bus voltage are shown in Fig. 12. It can be concludedthat the IC can smoothly balance the power inside the dcmicrogrid during grid-connected mode. Throughout this controlstrategy, the dc sources are allowed to follow the energy managementstrategies and considering the economic facts straightforwardly[30].

B. Case 2

This case simulates the hybrid ac/dc microgrid operation intransition from grid-connected mode to islanding mode. Beforeislanding occurs, the dc microgrid is in light load condition andfeeds the surplus power to the ac grid. At*t=1*s the microgridis disconnected from the main grid, and the islandingevent is detected by the IC at*t*=1.06s . A 60 ms delay is assumedfor typical islanding detection methods [31]. The IC controlstrategy is changed from the grid-connected to the proposedcontrol strategy for islanding control of the hybrid ac/dc microgrid.The demanded ac load is greater than the generated powerin the ac microgrid and causes the frequency drop. In order tobalance the power, the IC controller shares the surplus power inthe dc microgrid with the ac sources in the ac microgrid. Duringthe islanding

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operation at$t$=2 s the ac load is increased furtherand this causes the IC to transfer more power from the dc to acmicrogrid. Simulation results are shown in Fig. 13. The increasein the ac load leads to frequency drop in the ac microgrid. TheIC as well as the ac sources detects the frequency drop and byusing the proposed droop characteristic the amount of power tobe transferred to the ac microgrid is determined and shared betweenthe dc sources. Simulation results are also summarizedin Table III for the steady state generation conditions. It can beseen that the load is proportionally shared between the ac anddc sources. A small sharing error in the power sharing is due tothe different voltage level that is sensed by the sources in the dcmicrogrid. Results show that this control strategy can maintainthe power balance by sharing the total load demand between theexisting ac and dc sources and prevents any frequency drift andneed for load shedding during the time that the demanded poweris less than the sum of the ac and dc sources rating.

C. Case 3

Similar to case 2, this case also deals with the situation oftransition from the grid-connected into the islanding mode but,despite case 2 in this case the ac microgrid is operated in lightload condition and the dc microgrid is over loaded. At$t=1$sthe microgrid is disconnected from the main grid, and since thedc load power is greater than the rated power of the dc sources,causes dc voltage-drop. In order to balance the power, the ICcontroller shares the surplus power in the ac microgrid with thedc sources in the dc microgrid. During the islanding operationat$t=2$s the dc load is increased further and this causes the ICto transfer more power from the ac to the dc microgrid. Simulationresults are shown in Fig. 14. The increase in the dc loadis detected by the dc sources first and results in voltage drop.The IC also perceives this voltage drop and by using the proposeddroop characteristic the amount of power to be transferredto the dc microgrid is determined and shared between the acsources. Simulation results are also summarized in Table IV forthe steady state generation conditions. It can be seen that theload is proportionally shared between the ac and dc sources. Small sharing error in the power sharing is due to the differentvoltage level that is sensed by the sources in the dc microgrid. Itcan be realized that the proposed control strategy can accuratelymanage the power imbalance by sharing the demanded powerbetween the sources in both ac and dc microgrids and avoidsany instability in ac and dc microgrids.

D. Case 4

In order to evaluate the performance of the proposed controlstrategy in different load profiles during the islanding operation,the islanded hybrid ac/dc microgrid is simulated in case 4. Thetwo microgrids are initially operating in light load condition;

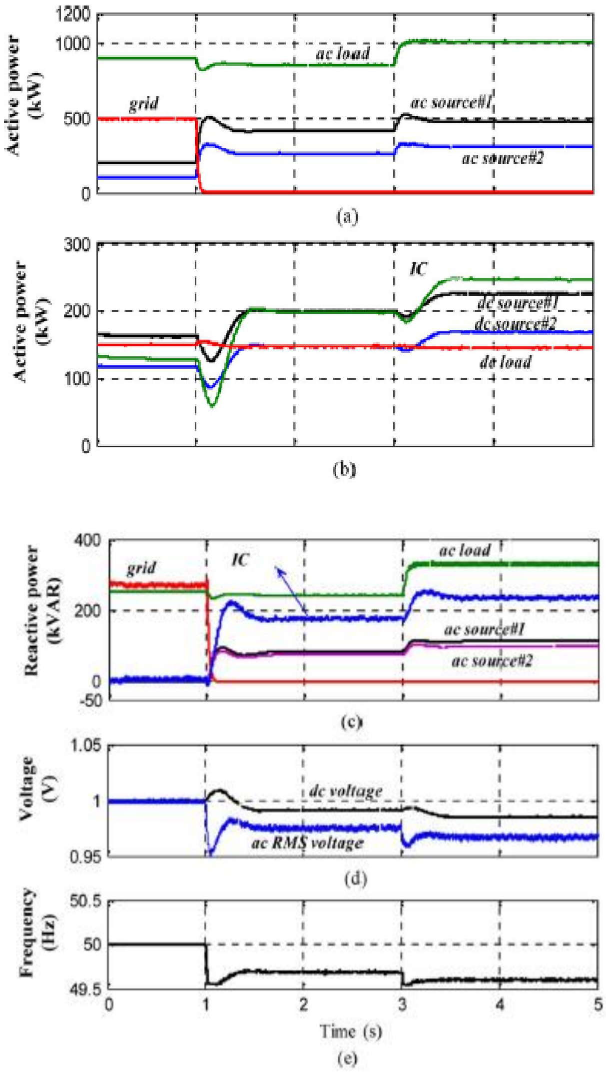

Fig.13. Simulation results for Case 2.

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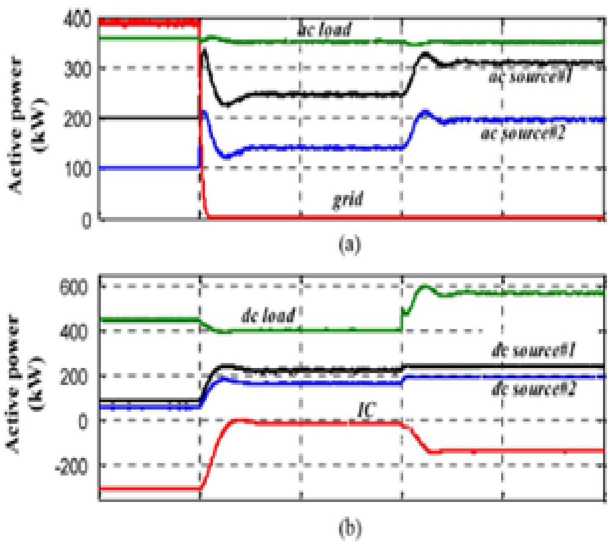
TABLE III
STEADY-STATE OPERATING CONDITIONS OF SOURCES IN CASE 2

	t= 1-3 sec	t= 3-5 sec
Total load (kW)	1000	1150
ac source #1 (kW)	390	450
ac source #2 (kW)	250	280
dc source #1 (kW)	210	255
dc source #2 (kW)	170	185

this means that the load power in both ac microgrid and dc microgridare less than the total rating of individual sources. Accordingto the control strategy,when themicrogrids are operatedin light load condition the IC transfers no power. Att=1 s aload increase happens in the acmicrogrid in which the power demandis greater than available ac generation, the IC detects thefrequency drop and calculates the required power to be transferredfrom dc to ac microgrid (P_{dc}^{ref}) and shares this power demandbetween sources. Then at$t$=2 s again the load decreasesand the ac microgrid enters the light load condition. After thatat$t$=3 s dc load is increased and the IC detects the voltagedrop and calculates the required power to be fed to dc microgrid $(P_{dc}^{ref})$and shares this power demand between sources. Simulationresults are shown in Fig. 15.And the steady state results are



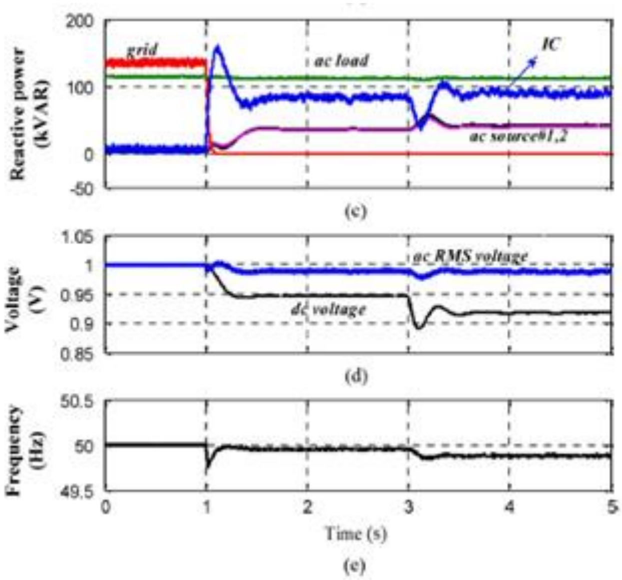


Fig.14. Simulation results for Case 3.

TABLE IV
STEADY-STATE OPERATING CONDITIONS OF SOURCES IN CASE 3

	t= 1-3 sec	t= 3-5 sec
Total load (kW)	750	920
ac source #1 (kW)	230	320
ac source #2 (kW)	140	200
dc source #1 (kW)	215	220
dc source #2 (kW)	170	200

Summarized in Table V. It can be realized that the IC can reasonablymanage the power sharing and avoids any instabilityduring the autonomous operation of the hybrid microgrid.

E. Case 5

Case 5 simulates the performance of the IC facing over loadcondition on both ac and dc microgrids. Both microgrids areprimarily operating in light load condition. Att=1 s the loadpower is increased in the dc microgrid and causes overloadingof the microgrid in which the IC feeds the required power. Att=2 sthe ac load is also increased and makes the ac microgridover loaded. While both microgrids are over loaded, theIC transfers no power and each microgrid is responsible

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for thepower management. Due to power deficiency in bothmicro-

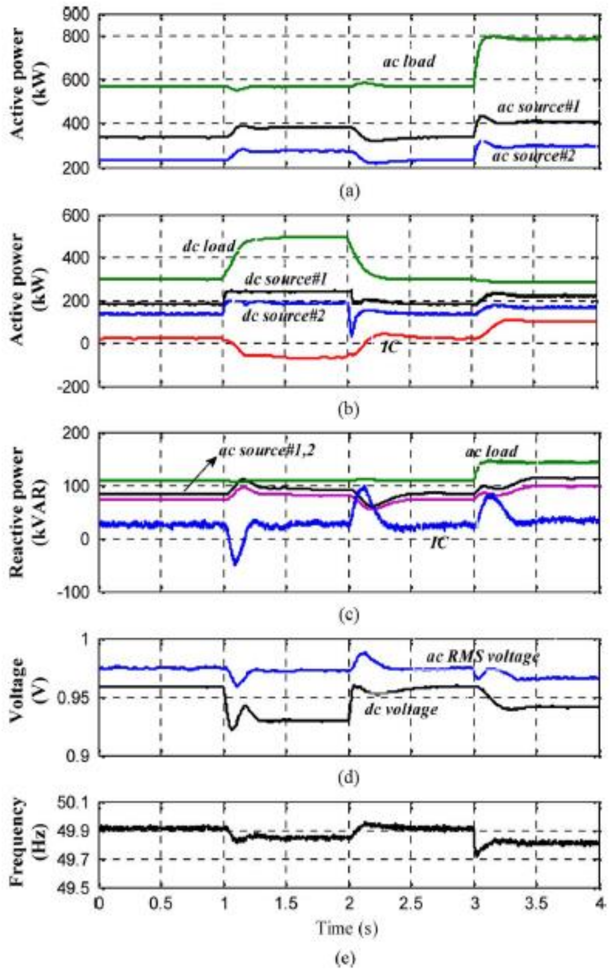

Fig.15. Simulation results for Case 4.

TABLE V
STEADY-STATE OPERATING CONDITIONS OF SOURCES IN CASE 4

	t=0-1 sec	t= 1-2 sec	t= 2-3 sec	t= 3-4 sec
Total load (kW)	865	1060	865	1070
ac source #1 (kW)	330	390	340	400
ac source #2 (kW)	215	265	215	280
dc source #1 (kW)	190	245	185	230
dc source #2 (kW)	150	190	145	175

Grids, dc voltage drops below allowable voltage range (0.9 p.u)and activates the dc load shedding system. On the other hand,the ac frequency also drops and a portion of ac load is shed tostabilize the ac microgrid. Fig. 16 shows the performance of thehybridmicrogrid and over load blocking logic in this study case.It is necessary to mentioned that if the overload blocking is notused, it makes the interconnection of the power managementcontrol between the ac and dc microgrids, which causes powerswing between ac and dc.

F. Case 6

In this case the participation of the DC microgrid on thesystem frequency is studied by varying droop gain of the IC

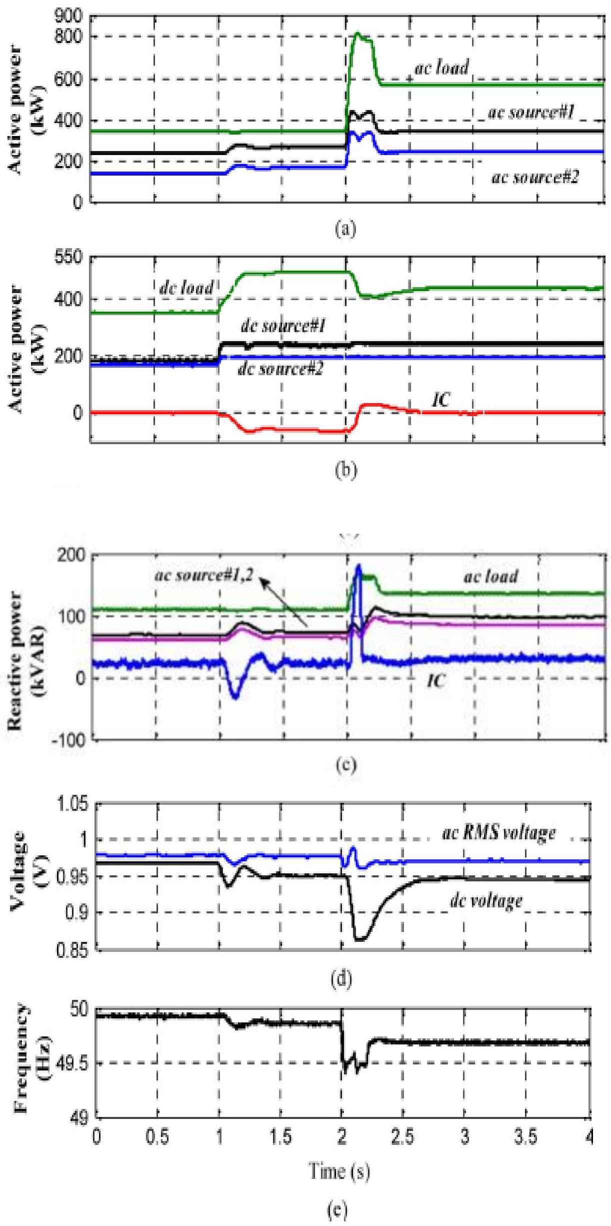

Fig.16. Simulation results for Case 5.

TABLE VI
PARTICIPATION OF THE DC MICROGRID ON THE SYSTEM FREQUENCY

k_ω	8	12	20
Steady-state frequency (Hz)	49.05	49.42	49.73

(k_ω)For a similar load change in the ac microgrid. Simulationresults are shown in Table VI. When k_ω increases the participationof dc microgrid on the ac microgrid increases whichresults in smaller steady-state frequency deviation.

VII. CONCLUSION

This paper proposes a decentralized control strategy based onthe two-stage modified droop method for the control of the ICinterfacing dc and ac microgrids. This hybrid microgrid architectureprepares an infrastructure for flexible connection of differentac or dc loads and sources to the grid. By measuring theac microgrid frequency and the dc microgrid voltage and usingproposed droop characteristic, the power management strategyprovides the power reference for the IC control to share thepower demand between the existing power sources in both acand dc microgrids. Using the proposed droop method, the ICis able to perform power sharing between the two microgridsin the transition from grid-connected to islanding mode as wellas during the islanding operation. This makes it possible to decreasethe required power conversions stages and hence thesystem cost and efficiency. The performance of the proposedcontrol strategy considering different operating states is demonstratedthrough time-domain simulation of a hybrid ac/dc microgridin the PSCAD/EMTDC software. A more sophisticatedcontrol strategy for power sharing control of several interconnectedac and dc microgrids can be extended from the result ofthis work, which is under investigation by the authors for thefuture study.

TABLE VIII
DC SOURCES PARAMETERS

	dc source 1	dc source 2
Rating (nominal)	300 (kW)	250 (kW)
R_{dc}	0.0013 (A/V)	0.0011 (A/V)

TABLE IX
IC PARAMETERS.

	dc source 1
Rating (nominal)	300 (kVA)
DC voltage	1500 (V)
DC capacitance	5000 (μF)
Filter capacitance	2500 (μF)
Filter inductance	100 (μH)
K_{dc}	2 (kW/V)
K_{ac}	11.9 (kW/(rad/s))
K_ω	11.45 (kW/(rad/s))

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