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MANAGEMENT OF POWER IN INTERLINKED AC-DC MICRO-GRIDS

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Abstract: The current power the executives plans for interlinked AC-DC microgrids have a few operational disadvantages. A portion of the current control plans are planned with the primary target of sharing force among the interlinked microgrids dependent on their stacking conditions, while different plans manage the voltage of the interlinked microgrids without considering the particular stacking conditions. In any case, the current plans can't accomplish the two goals effectively. To address these issues, a self-ruling force the executives plan is proposed, which unequivocally considers the particular stacking state of the DC microgrid before bringing in power from the interlinked AC microgrid. This system empowers voltage guideline in the DC microgrid, and furthermore diminishes the quantity of converters in activity. The proposed plan is completely self-sufficient while it holds the fitting nplay highlights for generators and tie-converters. The presentation of the proposed control plan has been approved under various working situations. The outcomes show the adequacy of the proposed plan in dealing with the power shortage in the DC microgrid proficiently and self-sufficiently while keeping up the better voltage guideline in the DC microgrid.

Index Terms: Autonomous control, distributed control, droop control, hybrid microgrids, interlinked microgrids, power management.

I. INTRODUCTION

THE specialized headway in power gadgets is assuming a significant job in the arrangement of renewables and elective vitality advances [1]–[3] which have so far been broadly acknowledged in various types of system topologies and setups [4], [5]. Likewise, they have been controlled and overseen utilizing different control procedures and designs [6], [7]. Their system topologies and control techniques are for the most part resolved to augment the advantages while meeting the heap prerequisites. At present, sustainable and elective vitality innovations are broadly conveyed in microgrids. The sending of these new innovations as a microgrid is favored because of a few advantages,such as ideal use of assets, improved power quality and upgraded supply unwavering quality [8]–[10]. As of late, further developed matrix structures have risen including the zonebased lattice designs, multi-microgrids, interlinked AC-AC microgrids and interlinked AC-DC microgrids. The primary target of these propelled system structures is to abuse most extreme advantages from renewables and elective vitality assets. For instance, by interconnecting at least two microgrids, it will empower save sharing, bolster voltage and recurrence, and at last upgrade the general dependability and flexibility of interlinked microgrids. The interlinking course of action between at least two microgrids or with utility networks principally relies upon the general goals, just as the control and the executives plan utilized in individual microgrids. The microgrids can be interlinked straightforwardly or through orchestrating tie-converters. The fitting tie-converters are principally utilized when at least two microgrids have distinctive working voltages or potentially frequencies. The tieconverters are additionally fundamental if the microgrids to be interlinked have diverse control techniques and the power stream among them should be controlled. So also, the interlinking of the DC microgrid with the utility network or another AC microgrid additionally requires attach converters to direct the power stream among different functionalities, and that has been researched under different situations in the distributed writing . In the interest hang control has been proposed for the interlinking or tie-converters of the AC-DC microgrids. The power stream activity is resolved dependent on the standardized terminal voltage and recurrence of the hang controlled interlinked AC-DC microgrids. This plan empowers self-governing force move between two interlinked microgrids dependent on their relative stacking condition. The power stream choice dependent on the relative stacking may make the interlinking converter work consistently, and along these lines it might bring about superfluous operational misfortunes. A similar power sharing plan has been reached out to interlinked microgrids with a capacity framework . This plan is additionally improved with the dynamic auto-tuning tominimize the vitality move through interlinking converters. The proposed auto-tuning empowers the power move just when one microgrid is vigorously stacked, and another microgrid is delicately stacked. The hang-based power sharing idea has been additionally researched for various working states of the interlinked AC and DC microgrids. The power the executives procedure is displayed for a threeport framework including AC, DC and a capacity organize. The choice about the power sharing depends on the stacking state of the interlinked systems which is essentially equivalent to exhibited. Moreover, a correspondence based staggered supervisory control is proposed to decrease the activity of interlinking converters. Another power the board plan displayed in for the interlinked AC-DC microgrid has a target to control the voltage of the DC microgrid without thinking about the particular stacking level of the generators. This plan can be executed uniquely at a solitary tie-converter, henceforth restrains the fitting n-play include. Moreover, a couple of incorporated power the executive's plans have been examined for interlinked AC-DC microgrids. The key worry with the brought together plans is the unwavering quality related with the quick correspondence joins. In this manner, the decentralized plans are normally liked. So far the distributed decentralized power sharing plans for interlinked AC-DC microgrids are either totally dependent on hang rule or voltage guideline. The hang based power sharing plans move power dependent on relative stacking of the interlinked microgrids. The power move during a possibility or uneven stacking condition bolsters the voltage and recurrence however does not control the voltage as well as recurrence ofthe interconnected microgrids. Be that as it may, these plans empower plug-n-play highlight for the interlinking converters. With this element, in the event that there is more than one interlinking converter, all converters will work paying little mind to the general power move prerequisite. This may cause superfluous converter operational misfortunes. Oppositely, the voltage guideline plans control the voltage of the DC microgrid without considering explicit stacking states of the generators, and does not have the attachment n-play include for tie-converters. These weaknesses can be explicitly tended to utilizing the proposed control plot in this paper. The proposed independent power the board conspire for interlinked AC-DC microgrids mulls over the particular stacking state of the generators, and moves control from AC to DC microgrid during its pinnacle burden request, and furthermore manages the voltage of the DC microgrid. The proposed plan empowers the fitting n-play include for tie converters and decreases the quantity of converters in activity to stay away from pointless misfortunes. In the thought about situation, the DC microgrid has insufficient age limit because of the high inconstancy of the heaps and inexhaustible age. The AC microgrid is considered to have managed voltage and recurrence just as the surplus capacity to move to the DC microgrid during its pinnacle request or possibility condition. To accomplish the highlights talked about over, a half and half hang and voltage guideline mode control has been proposed for the tie-converters in interlinked AC-DC microgrids. The proposed control plan depends on the tie-converter terminal voltage data to decide the general stacking state of the hang-controlled DC microgrid. In view of the set stacking limit, the tie-converter begins naturally and moves capacity to the DC microgrid during the pinnacle burden request or possibility condition in the DC microgrid. With the proposed cross breed control mode, the voltage of the DC microgrid is directed at a characterized ostensible level. Likewise, the proposed plan permits interfacing more than one tie-converters, yet instead of the current plan where all tie-converters work at the same time paying little heed to the power move request, the consequent tie-converter just initiates once the main converter control limit has been soaked. The proposed plan is completely independent with upgraded highlights.

II. CONTROL OF AC AND DC MICROGRIDS

The considered DC microgrid includes a non-dispatchable generator (solar-PV) and dispatchable generators (microturbine, fuel-cell) and loads, as shown in Fig. 1. The nondispatchable-solar PV system is set to operate in current control mode and thus extracts maximum power at all the times. The dispatchable generators are typically used for firming the renewable capacity and can be controlled either through a centralized or decentralized control scheme. The decentralized droop scheme is the most widely used and preferred, as it is simple and reliable. Therefore, the traditional droop (P-V) scheme has been used for the dispatchable generators of the DC microgrid (see Fig. 1), which is given by

$$\begin{aligned} V_{\mathrm{dc,ref},i} &= V_{\mathrm{dc,max}} - \partial_{\mathrm{dc},i} P_{\mathrm{dc},i} \\ \partial_{\mathrm{dc},i} &= \frac{V_{\mathrm{dc,max}} - V_{\mathrm{dc,min}}}{P_{\mathrm{dc,max},i}} = \frac{\Delta V_{\mathrm{dc}}}{P_{\mathrm{dc,max},i}} \end{aligned} \qquad (1)$$

where, iis the DC generator number (i= 1, 2, 3...); $V_{dc,ref,i}$is the reference voltage of i^{th}generator; $P_{dc,i}$is the output power of

i^{th}generator; $V_{dc,max}$ and ($V_{dc,min}$= V_{dc,nom,TC_1}) are the defined maximum and minimum voltage; $P_{dc,max,i}$ is the maximum or rated power of i^{th}generator; and $\partial_{dc,i}$ is the droop gain of i^{th}generator.

Based on (1), the voltage reference for the droop controlled generators 1 and 2 can be calculated by (2) and (3). As generators 1 and 2 share common DC bus voltage (i.e., $V_{dc,ref,1} = V_{dc,ref,2}$), (2) and (3) can be equated and rewritten by (4), which demonstrates that the droop controlled generator will share proportional power according to their rated power capacity.

$$V_{\mathrm{dc,ref},1} = V_{\mathrm{dc,max}} - \partial_{\mathrm{dc},1} P_{\mathrm{dc},1} \tag{2}$$

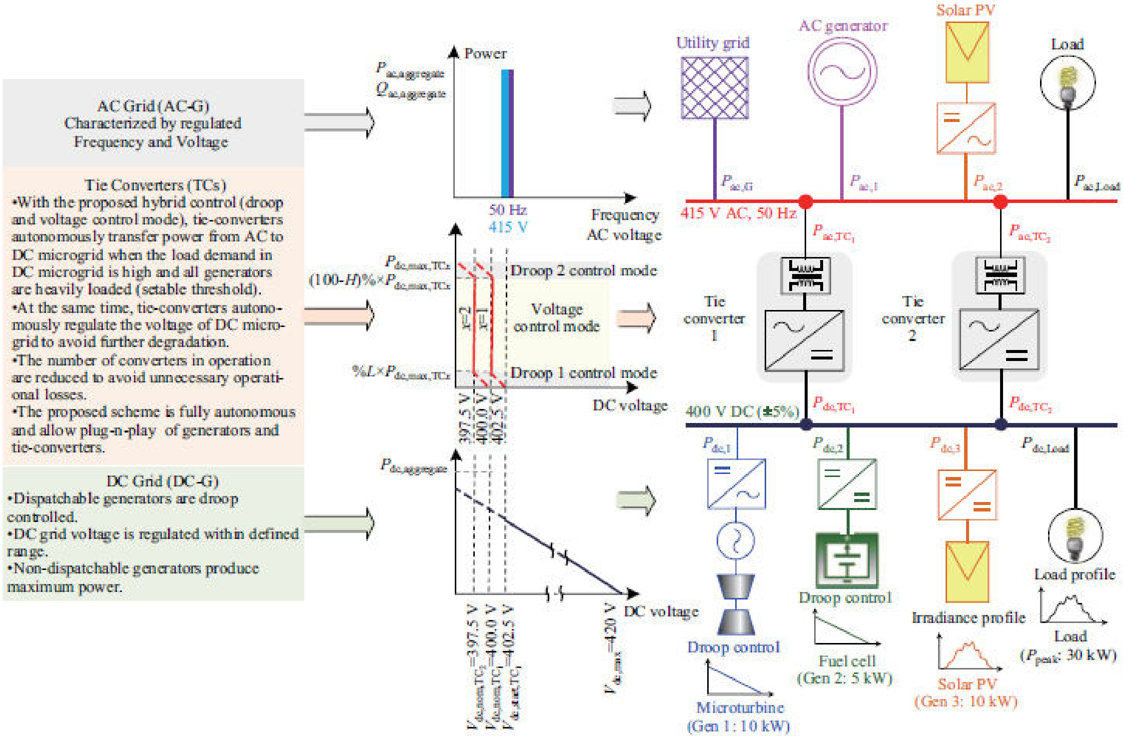
$$V_{\mathrm{dc,ref},2} = V_{\mathrm{dc,max}} - \partial_{\mathrm{dc},2} P_{\mathrm{dc},2} \tag{3}$$

$$\partial_{\mathrm{dc},1} P_{\mathrm{dc},1} = \partial_{\mathrm{dc},2} P_{\mathrm{dc},2} \rightarrow \frac{P_{\mathrm{dc},1}}{P_{\mathrm{dc,max},1}} = \frac{P_{\mathrm{dc},2}}{P_{\mathrm{dc,max},2}} = \frac{P_{\mathrm{dc},i}}{P_{\mathrm{dc,max},i}} \tag{4}$$

The equality in (4) is based on the fact that the voltage at the generator terminals is the same. Practically, the voltage at all the generator terminals is not the same due to the fact that they are connected through feeders/cables of different lengths. This voltage mismatch at the generator terminals affects the power sharing accuracy, which needs to be compensated by using any of the appropriate compensation methods . The droop equation with compensation of the feeder voltage drop can be rewritten by

$$V_{\mathrm{dc,ref},i} = V_{\mathrm{dc,max}} - \partial_{\mathrm{dc},i} P_{\mathrm{dc},i} + i_{\mathrm{dc},i} X_i. \tag{5}$$

The voltage of the droop controlled DC microgrid will vary with the changing load, but within the defined permissible range. For the considered DC microgrid, the voltage range with increased aggregated loading is shown in Fig. 1 (bottomleft). For the droop controlled generators, the voltage range is



- With the proposed hybrid control (droop and voltage control mode), tie-converters autonomously transfer power from AC to DC microgrid when the load demand in DC microgrid is high and all generators are heavily loaded (setable threshold).
- At the same time, tie-converters autonomously regulate the voltage of DC micro-grid to avoid further degradation.
- The number of converters in operation are reduced to avoid unnecessary operational losses.
- The proposed scheme is fully autonomous and allow plug-n-play of generators and tie-converters.

- Dispatchable generators are droop controlled.
- DC grid voltage is regulated within defined range.
- Non-dispatchable generators produce maximum power.

Fig. 1. Interlinked AC-DC microgrids and their control strategy.

set between 395 V and 420 V, indicating that the generators will deliver no-power at 420 V and 100% power at 395 V. Once the DC generators are heavily loaded (e.g., ≤ 402.5 V at 80% generators loading), the tie-converters will start to import power from the AC microgrid to meet the peak load demand, and also regulate the voltage of the DC microgrid.For the example of interlinked microgrids in Fig. 1, the voltage and frequency of the AC microgrid is considered stiff. The AC microgrid can be droop controlled with secondary voltage and frequency regulation, or operating in grid-connected mode. The characteristics of the AC microgrid are shown in Fig. 1, where the voltage and frequency are constant at nominal value (e.g., 50 Hz and 415 V). In addition, the AC microgrid has sufficient generation capacity to meet its local demand and export surplus power to the DC microgrid which has been demonstrated through the proposed autonomous control of the tie-converters. The details of the tie-converters control are given in Section III.

III. PROPOSED HYBRID CONTROL OF TIE-CONVERTERS

THE specialized headway in power gadgets is assuming a significant job in the arrangement of renewables and elective vitality advances [1]–[3] which have so far been broadly acknowledged in various types of system topologies and setups [4], [5]. Likewise, they have been controlled and overseen utilizing different control procedures and designs [6], [7]. Their system topologies and control techniques are for the most part resolved to augment the advantages while meeting the heap prerequisites. At present, sustainable and elective vitality innovations are broadly conveyed in microgrids. The sending of these new innovations as a microgrid is favored because of a few advantages, such as ideal use of assets, improved power quality and upgraded supply unwavering quality [8]–[10]. As of late, further developed matrix structures have risen including the zonebased lattice designs , multi-microgrids , interlinked AC-AC microgrids , and interlinked AC-DC microgrids . 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Likewise, the proposed plan permits interfacing more than one tie-converters, yet instead of the current plan where all tie-converters work at the same time paying little heed to the power move request, the consequent tie-converter just initiates once the main converter control limit has been soaked. The proposed plan is completely independent with upgraded highlights. the number of tie-converters in operation should be based on power transfer demand; 3) To regulate the voltage of the droop controlled DC microgrid; 4) To achieve fully autonomous control without depending on the communication network; 5) To enable the plug-n-play feature for tie-converters and generators.

Unlike the existing schemes for the interlinked AC-DCmicrogrids, a hybrid droop and voltage regulationmode control is proposed for the tie-converters and themathematical form of the proposed control scheme is given by:

$$V_{\mathrm{dc,ref,TC}x} = \begin{cases} \text{Off}; & V_{\mathrm{dc}} > V_{\mathrm{dc,start,TC}x} \\ V_{\mathrm{dc,start,TC}x} - \delta_{\mathrm{L,TC}x} \times P_{\mathrm{dc,TC}x}; & 0 \leq P_{\mathrm{dc,TC}x} \leq L\% \times P_{\mathrm{dc,max,TC}x} \\ V_{\mathrm{dc,nom,TC}x}; & L\% \times P_{\mathrm{dc,max,TC}x} < P_{\mathrm{dc,TC}x} < (100-H)\% \times P_{\mathrm{dc,max,TC}x} \\ V_{\mathrm{dc,nom,TC}x} - \delta_{\mathrm{H,TC}x}[P_{\mathrm{dc,TC}x} - (100-H)\% \times P_{\mathrm{dc,max,TC}x}]; & (100-H)\% \times P_{\mathrm{dc,max,TC}x} \leq P_{\mathrm{dc,TC}x} \leq P_{\mathrm{dc,max,TC}x} \end{cases} \tag{6}$$

where TCxrepresents the tie-converter number (x = 1, 2, 3..);V_{dc} is the DC microgrid voltage; $V_{dc,ref,TCx}$is the reference voltage of xthtie-converter; $V_{dc,start,TCx}$is the threshold voltage to start of xthtie-converter; $V_{dc,nom,TCx}$is the nominal voltage to be regulated by xthtie-converter; $P_{dc,TCx}$is the DC power output of xthtie-converter; $P_{dc,max,TCx}$is the maximum power limit of xthtie-converter; L% and H% are the percentage of tie-converer rated power allocated for droop1 and 2 mode, respectively; $V_{dc,nom,TCx+1}$ is the DC microgrid voltage when xthtie-converter transfers maximum power;$P_{dc,max,TCx}$) is the droop 1 gain (at low power) of xtie-converter;$P_{dc,max,TCx}$) is the droop 2 gain (at high power) of x tieconverter.As shown in Fig. 1, tie-converter 1 starts in droop 1 control mode when the voltage in the DC microgrid drops to the set threshold of $V_{dc,start,TCx}$. This voltage threshold implies that all the generators in the DC microgrid are heavily-loaded (e.g. over 80% loaded). The start of the tie-converter in the droop control mode enables a smooth transition to the voltage regulation mode at the set condition i.e., $P_{dc,TCx} > L\% \times P_{dc,max,TCx}$. During the voltage regulation mode, the tie-converter imports power from the AC microgrid to meet the DC microgrid peak power demand as well as regulate its voltage to be set to the nominal value of $V_{dc,nom,TCx}$.Furthermore, unlike the parallel operation of all tieconverters in the existing schemes, the converters operation has been prioritized. The first tie-converter only starts when all the generators in the DC microgrid are heavily-loaded. Once the first tie-converter power capacity is near to saturation at $P_{dc,TCx} = (100 - H)\% \times P_{dc,max,TCx}$, its control mode is changed from the voltage regulation to droop 2 control mode to allow minor voltage drop. This minor voltage drop caused by the droop 2 control mode will enable the next tie-converter to start its operation. In case of failure of the first tie-converter, the second tie-converter will automatically start its operation followed by the voltage drop due to high load demand. Therefore, the proposed control strategy ensures efficient operation during all operating conditions without compromising the inherited flexibility of the droop based scheme. The allocation of the tie-converter's power for droop 1 and droop 2 control mode depends on the chosen value of L% and H% which are user definable, and should be tuned to allow smooth transition between different modes while considering the voltage and power measurement tolerance/errors in the considered microgrid.

With the proposed voltage regulation mode, the overall voltage regulation performance of the DC microgrid can be improved. In particular during the peak load demand, the voltage of the DC microgrid is regulated at the nominal value, which is not the case with the existing power management schemes for interlinked microgrids. The performance of the proposed scheme has been validated for different load operating scenarios, as described in Section IV.

IV. PERFORMANCE VALIDATION

The performance of the proposed scheme has been validated for two different scenarios of the DC microgrid. In the first scenario, the microgrid comprises a dispatchable microturbine (Gen 1), fuel cell (Gen 2) and variable load. In the second scenario, a non-dispatchable solar PV generator (Gen 3) is added to scenario 1. The system parameters are summarized in Tables I–III.

TABLE I
CONTROL MODE OF DC AND AC MICROGRIDS

Entity	Control Mode	
AC microgrid	Islanded-microgrid with regulated voltage and frequency Grid-connected mode	
Tie-converter	Hybrid droop and voltage control mode	
DC microgrid	Dispatchable generators	Droop controlled
	Non-dispatchable generators	Current control mode with MPPT

Table Ii: Dc Micro grid Parameters

Description	Parameter	Value
Voltage	V_{dc} (V)	400 (+5%, –1.25%)
Micro-turbine	$P_{dc,max,1}$ (kW)	10
	$\vartheta_{dc,1}$ (V/kW)	2.5
Fuel cell	$P_{dc,max,2}$ (kW)	5
	$\vartheta_{dc,2}$ (V/kW)	5
Solar PV	$P_{dc,max,3}$ (kW)	10
Load	$P_{Load,peak}$ (kW)	25

Table Iii: Ac Microgrid And Tie Converter Parameters

Description	Parameter	Value
AC microgrid	V_{ac} (V)	415 $(l-l)$
	f (Hz)	50
Tie-converter	P_{dc,max,TC_1} (kW)	10
	$V_{dc,start,TC_1}$ (V)	402.5
	V_{dc,nom,TC_1} (V)	400.0
	V_{dc,nom,TC_2} (V)	397.5
	$L\% = H\%$	10%

The mode transition logic of the tie-converter is given in the logic flow diagram shown in Fig. 2, and the detailed control block diagram of the tie-converter is shown in Fig. 3. Both scenarios have been tested at different load operating conditions to demonstrate the robustness and effectiveness of the proposed scheme.

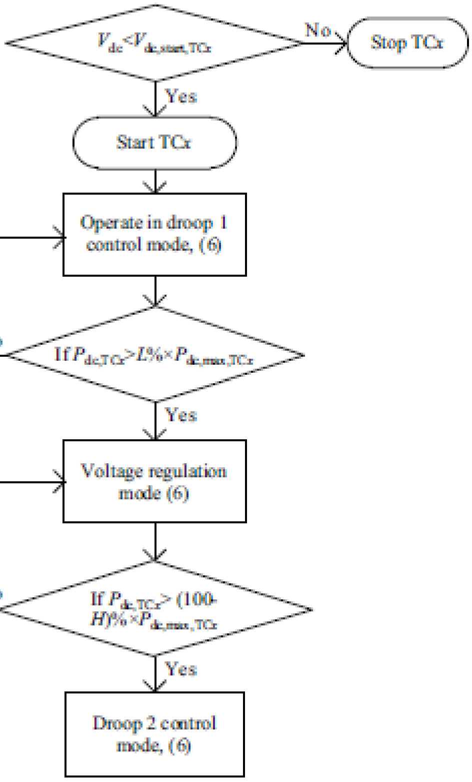

Fig. 2.Logic flow diagram showing mode transitions of tie-converter.

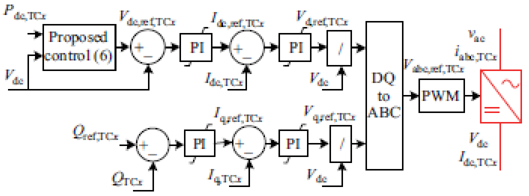

Fig. 3.Control block diagram of tie-converter.

A. Scenario 1: DC Microgrid with Variable Load

The DC microgrid comprises microturbine ($P_{dc,max,1}$ = 10 kW), fuel cell ($P_{dc,max,2}$ = 5 kW) and variable DC load ($P_{Load,peak}$= 20 kW) and it is interlinked with the AC microgrid through a tie-converter ($P_{dc,max,TC1}$ = 10 kW), as shown in Fig. 4.

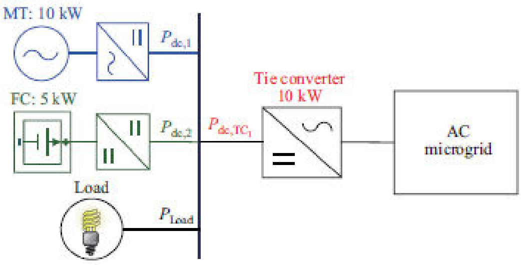

Fig. 4. Scenario 1: DC microgrid with microturbine, fuel cell and load.

The load in the DC microgrid is varied in steps from 5 kW to 20 kW (i.e. 5 kW → 10 kW → 15 kW → 20 kW →10 kW). At the 15 kW load demand, the expected loadingsof generator 1 and generator 2 are more than 80%, and thevoltage of the DC microgrid is below the set threshold ofVdc,start,TC1 = 402.5 V. This condition will enable the tieconverter1 to import power from the AC microgrid andregulate the voltage of the DC microgrid at the definednominal value of Vdc,nom,TC1 = 400.0 V. This expectedperformance can be witnessed from the results shown in Fig. 5.At the highlight point 1, at 8 s, the voltage of the DC microgriddecreases below 400 V followed by the step load change from

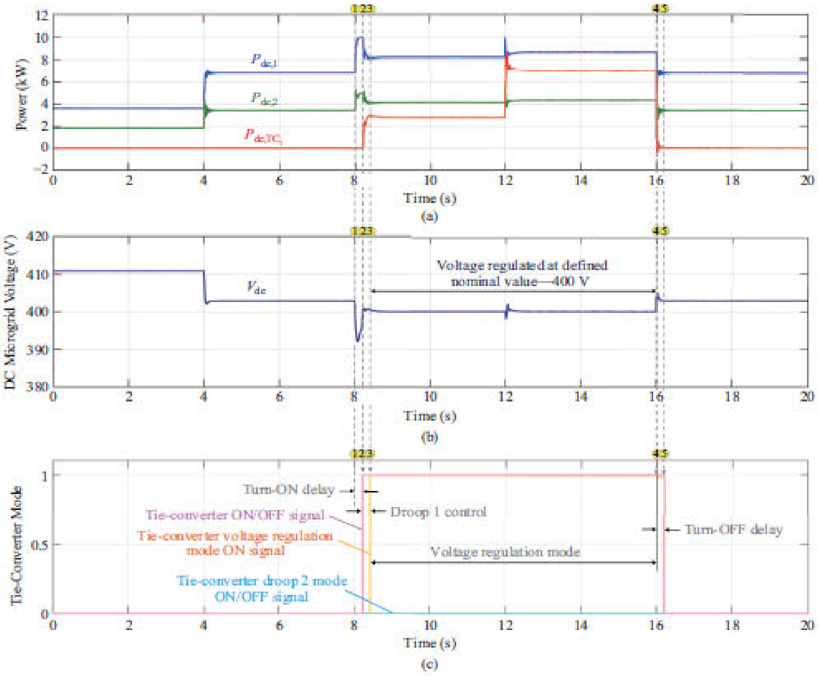

Fig. 5. Scenario 1: Results showing (a) generators and tie-converter power, (b) DC microgrid voltage and (c) tie-converter control signals for four different load operating conditions.

10 kW to 15 kW. This voltage drop triggers tie-converter 1to start in droop 1 control mode at point 2. After startingin droop 1 control mode, the tie-converter control mode isimmediately transitioned to the voltage regulation mode atpoint 3, since the set threshold (Pdc,TC1 > 10%×Pdc,max,TC1)is satisfied. At 12 s, the load in the DC microgrid is furtherincreased from 15 kW to 20 kW, and the power transferredfrom the AC microgrid is increased accordingly. Throughoutthe peak-load demand in the DC microgrid from 8 s to 12 s,tie-converter 1 remains operational and regulates the voltage ofthe DC microgrid. Once the load demand in the DC microgridis decreased at the highlighted point 4, at 16 s, the tie-converter turns off automatically after a short delay at point 5, as shownin Fig. 5. As demonstrated, tie-converter 1 only operates onceall the DC generators are heavily loaded. During its operation, the voltage in the DC microgrid is regulated to the definednominal value of 400 V. Therefore the proposed strategy hasbetter voltage regulation performance and ensures efficientoperation.

B. Scenario 2: DC Microgrid with Non-dispatchable Generatorand Load Profile

A non-dispatchable generator–sun based PV framework is addedto situation 1, as appeared in Fig. 6. The power yield ofthe sunlight based PV framework depends on a ceaselessly differing irradiance profile. The heap in situation 2 likewise has a changing profile with a pinnacle request of 25 kW. This test situation is created to further show the viability of the proposed procedure for different viable working states of inexhaustible age and burden request.

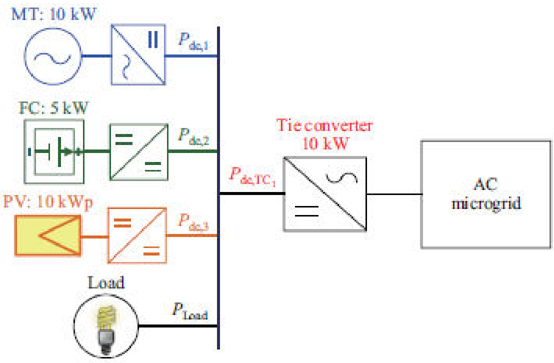

Fig. 6. Scenario 2: DC microgrid with microturbine, fuel cell, solar PV and load.The load in the DC microgrid increases gradually to the peak value 24.5 kW, and then decreases, as shown in Fig. 7(a).

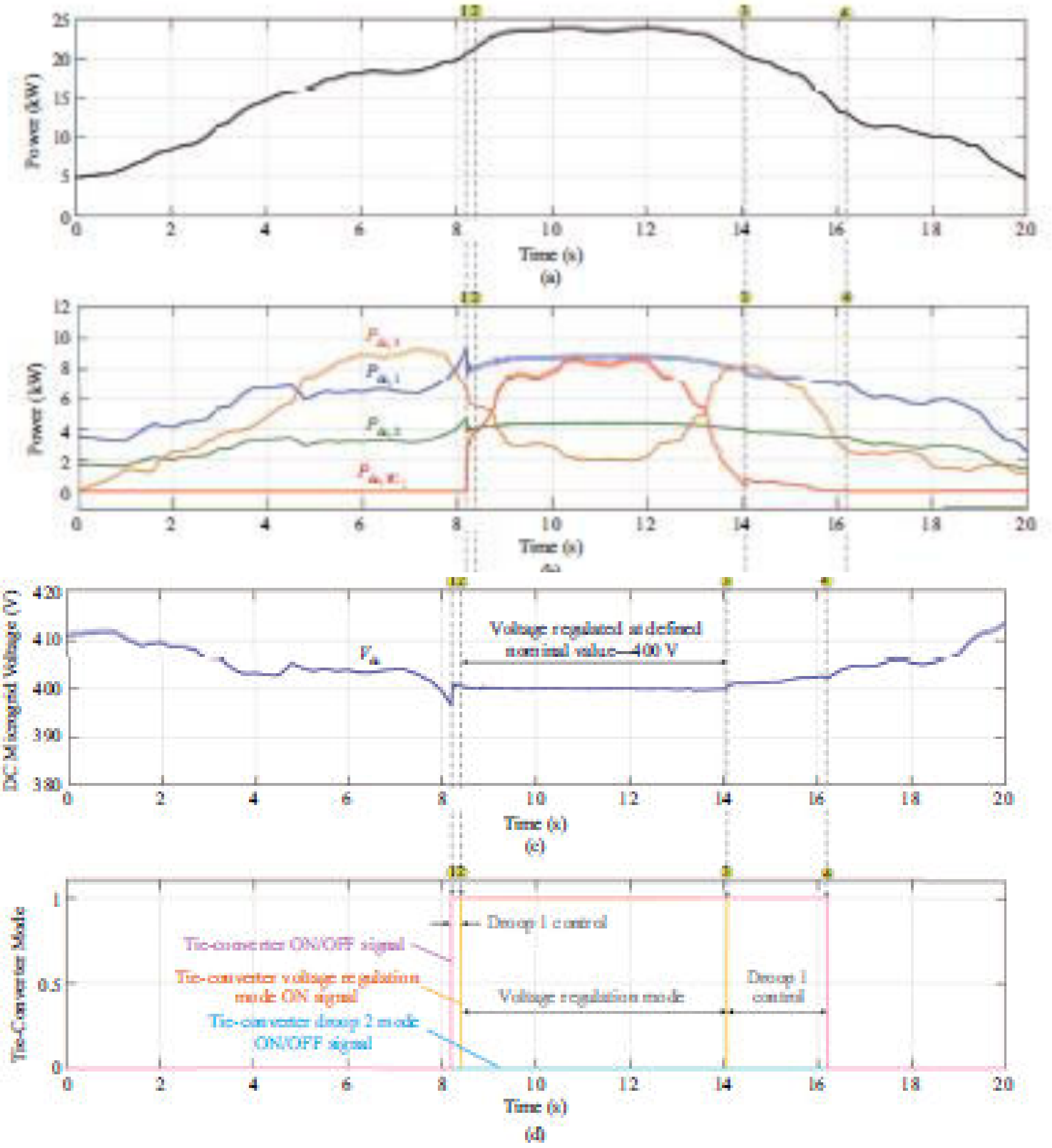

Fig. 7. Scenario 2: Results showing (a) DC microgrid load demand, (b) generators and tie-converter power, (c) DC microgrid voltage and (d) tie-convertercontrol signals at varying solar PV and load operating conditions.

The loading on the DC generators increases with the increasing load demand. At the highlight point 1, the loading on generator 1 and generator 2 exceeds 80% and the voltage of the DC microgrid drops below the set threshold of $V_{dc,start,TC1} = 402.5$ V when the load demand is very high and the solar PV output is less. In agreement with the proposed control, tie-converter 1 starts at highlighted point 1 and imports power from the AC microgrid to overcome the power deficit in the DC microgrid while regulating its voltage. Tie-converter 1 operates in the voltage regulating mode from point 2 at 8.5 s to point 3 at 14.2 s. From point 3 and onward, the load in the DC microgrid deceases such that the tie-converter power output is below $10\%\times P_{dc,max,TC1}$ and this condition requires the tie-converter to operate in the droop 1 control mode before it turns off at highlighted point 4 at 16.4 s. From point 4 and onward, the load demand in the DC microgrid is less than the generation, hence it can be met by the local generators. As expected, it has been demonstrated that the tie-converter only operates during the power deficit in the DC microgrid. In addition, the voltage of the DC microgrid is also regulated by importing power from the AC grid. This behavior depicts the grid-connected mode of the AC microgrid but through a tie-converter.

V. CONCLUSION

An independent power the board plan has been exhibited for interlinked AC-DC microgrids having various arrangements. The proposed plan deals with the power deficiency in the DC microgrid proficiently and self-governingly. The quantity of tie-converters in activity has been decreased with the proposed prioritization to dodge pointless operational misfortunes. The plan has exhibited better voltage guideline in the DC microgrid. The exhibition and power of the proposed plan have been approved for two distinct situations of the DC microgrid at variable burden conditions.

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