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A Novel Power Scheduling Mechanism for Islanded DC Microgrid Cluster

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Abstract: Extension of the main grid to remote areas is economically not feasible. To electrify remote areas, one of the best choices is to install Renewable Energy Sources (RES) as a distributed generation (DG) and thus form a microgrid (MG) in islanded (Stand-alone) mode. In islanded mode, the MG has no support from the national grid. Thus, the overloading of islanded DC MG can collapse DC bus voltage and cause fluctuation in the load. Therefore, the power sharing and the interconnection among the microgrid (MG) cluster are necessary for reliable operation. Many methods for power sharing also aim at minimizing circulating currents which cannot be avoided when every MG feeds their load locally. Therefore, the proper power balancing among generation, loads, and in between MG cluster is challenging in islanded topology. This paper presents an intelligent controller for power sharing among PV-based MG clusters with load management of connected load during power deficiency. The priority is given to the local critical load of each MG. The second priority is given to the remaining load of the respective MG. The least priority is given to the loads connected to the neighboring MGs. The results show that the power continuation to the power-deficient load has been maintained when another MG has surplus power. The circulating current losses between the MG cluster has been fully avoided during no power sharing.

Keywords: power-sharing algorithm; DC microgrid; power sharing; power management

1. Introduction

Nowadays, distributed generation (DG) through renewables is a trend to meet the growing electricity demand and to tackle challenges like losses in the long transmission networks, depleting fossil fuel resources, dependency on fossil fuels, and environmental concerns. The extension of the main grid to the remote area is also economically and technically infeasible. To address these issues and to electrify remote areas, renewable energy sources (RES) are the best choice for power production as a DG. In RES, a photovoltaic (PV) panels-based power generation system has gained popularity in recent years. For the efficient use of DG, the concept of microgrid (MG) is getting a lot of attention. Recently, the MG concept has gained interest due to the easy integration of RES as well as regulatory policies for decreasing tendency in the use of fossil fuel resources [1].

The MGs are mainly categorized as AC MG and DC MG. Today, the AC MG is the main type and mostly used as an electric power transportation system. The first DC MG architecture was proposed by Thomas Edison in the 19th century. The generalized structure of the DC MG consists of DG sources (such as wind turbines, microturbine, fuel cell, PV array, etc.), energy storage, and DC loads, as shown in Figure 1a [2]. The DG in the DC MG is usually connected to the common DC bus using DC–DC converters and supplying power to the DC loads. In some cases, the conventional generator is used as an AC power source and available for power supply during the unavailability of DC power sources. The RES is unpredictable in nature and energy storage is used for power balance during the unavailability of RES. This is because DC MGs are mainly powered with RES [3,4]. Therefore, the energy storage may not be sufficient for power continuation to the load during the shortage of generation power [5]. Therefore, islanded MG situated in close vicinity to each other may need to be interconnected for the continuation of power to the loads during power shortage and reliability as depicted in Figure 1b.

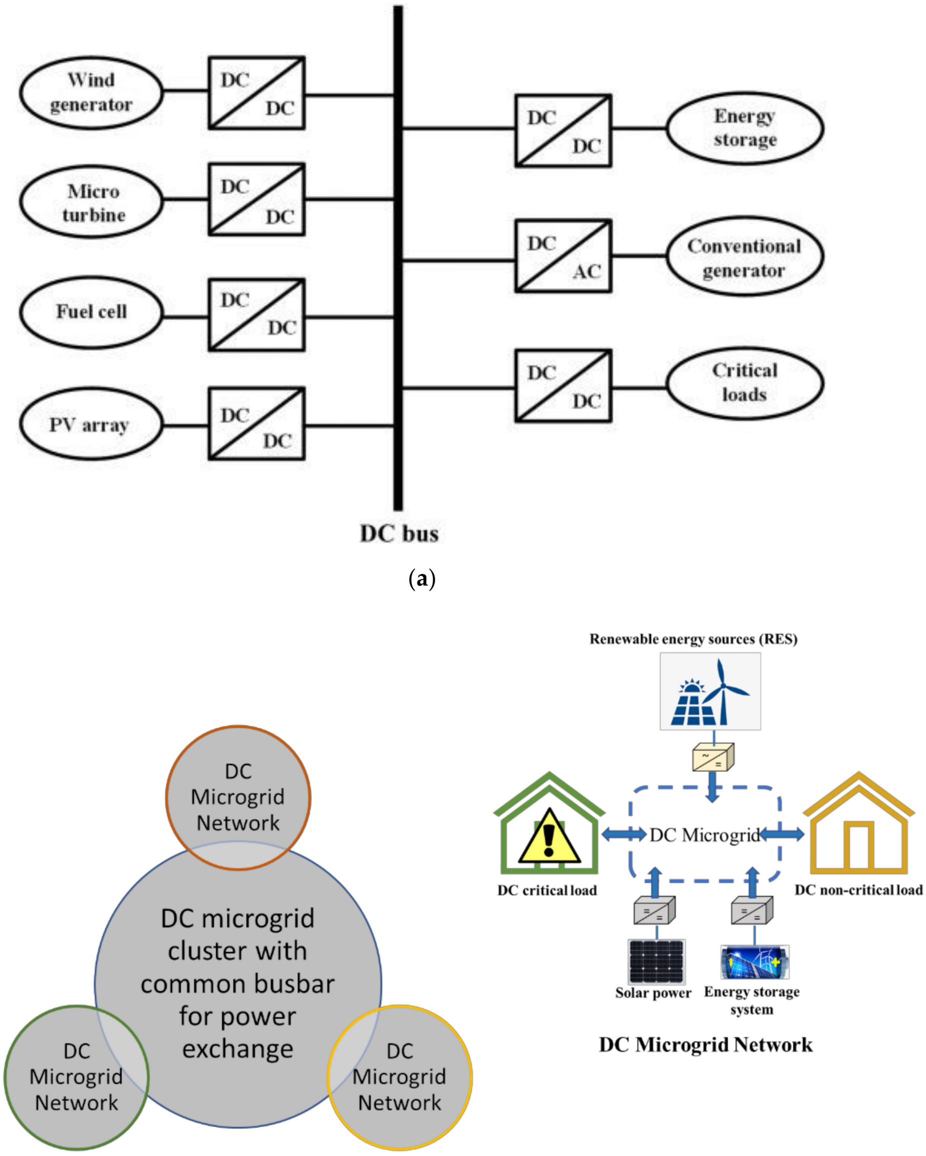

Figure 1. A generalized structure of DC MG; (**a**) Various components of a DC microgrid; (**b**) DC microgrid cluster.

Recently, the DC power is gaining popularity due to efficient solutions for power transmission and also the development of semiconductor materials which allow changing the voltage level. Additionally, many studies [6–9] have indicated that DC MGs are gaining interest due to but not limited to advantages such as having high energy efficiency, much easier integration with DG, no reactive power, no need for synchronization of phase and frequency, and no harmonics. Additionally, DC MG with DC load skips the DC–AC or AC–DC power conversion stages needed in AC micro-grids for the coupling of RES and loads. As a result, conversion losses are reduced and the system becomes economical. This study mainly focuses on PV panel-based DC MG providing power to the DC load.

There are two modes of operation of the DC MG with DG, i.e., Islanded mode and grid-connected mode [10]. In grid-connected mode, the power is balanced from the main grid during the deficiency of indigenous power generation in MG. However, in Islanded mode, the MG has one or more DG and a dedicated load. The Islanded mode is more preferable, especially for remote areas, due to the reduction of transmission losses in the transmission line [11]. According to the National Electric Power Regulatory Authority (NEPRA) report, the total losses in the Pakistan transmission and distribution systems were 18.32% in the financial year 2017–2018 [12]. The islanded mode has some challenges such as the balance between the power generation and load, stabilization of DC bus voltage, circulating current losses during no-load sharing, and the need for costly storage for power balance. The power management is necessary for Islanded DC MG with PV generation due to its intermittent nature. Overloading of the islanded DC MG can collapse the DC bus voltage [13].

In the islanded mode, even the PV systems-based MGs located nearby do not communicate or share electrical power. These MGs can be connected to meet the instantaneous demand of the varying load and form an MGs cluster [14]. The parallel interconnection however can cause the circulating current losses due to the parallel operation of different voltage sources during no power sharing.

Circulating current losses is gaining the attention of researchers nowadays, which arise due to a mismatch between the output voltages of MGs or between converters of different MGs. Many researchers proposed different methods to minimize circulating current losses. The decentralized control is designed in Anand and Fernandes [15], where a modified droop control method is presented. An adaptive droop control method is presented in Augustine et al. [16], which calculates off-line minimal droop value and apply it in real time. These centralized methods are proposed to decrease the circulation current loss as compared to droop control. A centralized controller is proposed in Qamar et al. [17], that could mitigate circulating currents in either identical or different power-rating situations. A modular multilevel converters control method is presented in Yang et al. [18] and a dynamically interacting control is proposed in Nawaz et al. [19], where circulating current losses are minimized. All these methods can only minimize current but cannot avoid it during no power sharing.

The power balancing methods are categorized as centralized, decentralized, and distributed. In centralized control, the controller performs control action by using different parameters of the data from all interconnected systems [20,21]. The centralized control has the disadvantage of single-point failure [22]. The decentralized control operates on local quantity measurement [23]. The decentralized control has the disadvantage of missing communication links and a lack of information on other systems, which is not a proper candidate for tertiary or system-level control [14]. In distributed control, the communication between neighbor systems is limited and can be considered as a proper candidate for power sharing in the DC MGs cluster [14]. In these methods, the DC sources are connected in parallel even when there is no need for power sharing. A little mismatch in output voltage will cause circulating current, especially when there is a need for power sharing.

Many methods in the literature are presented for power sharing and load scheduling. A selected few are summarized in Table 1, and qualitative analysis is performed with respect to the proposed work. A cooperative power management method is presented in Moayedi et al. [24]. This method is a tuning voltage setpoint for enabling power sharing. It requires sparse communication links to communicate between clusters of MG. Additionally, the mismatch between terminal voltages causes circulating current even when no power sharing is required. A bidirectional flyback converter is used to share surplus power with other MG is presented in Lagudu et al. [25]. This technique required more communication medium to communicate between the MGs. It uses centralized control which has a single point of failure problem. A bidirectional flyback converter is discussed in Konar and Ghosh [26] to share surplus power with other MG. This study does not consider the scenario that when an MG cannot be supported by other MG, then how it will behave. LFC (Load flow converter) is presented in Vuyyuru et al. [27], which performs power flow between MG of different voltage levels. Power control and management strategy based on bus signaling are presented in Sanjeev et al. [28]. The main drawback of this method is an unusual change in bus voltage may cause the alternate operating mode. Concentrated proportional power control is presented in Babazadeh-Dizaji et al. [29]. This technique requires a high bandwidth communication link. Additionally, all MGs have to share power in parallel, so circulating current will flow even when no power sharing is required. Furthermore, all the aforementioned studies do not consider prioritizing the critical load over non-critical load during power shortfall in MG cluster. Additionally, these do not consider the case when the imported generation power cannot support the critical load and can support the non-critical load during power deficiency in MG. The critical load should be shut down in that case and the non-critical load should be fed.

Table 1. Qualitative analysis of the proposed technique with state-or-the-art.

Methods	Description	Power Sharing Control	$I_{circulating}$ during No Power Sharing	Critical Load Priority ($D_{critical}$)	Power Import (P_i) to Non-Critical Load if $D_{non\text{-}critical} < P_i < D_{critical}$
Cooperative power management [24]	Tune voltage setpoint for power sharing in MG cluster	Decentralized	✗	✗	✗
SST (Solid-state transformer) based technique [25]	Use dual active bridge converter to share surplus power with other MG	Centralized	✓	✗	✗
Islanded DC MGs interconnection [26]	A bidirectional flyback converter is used to share surplus power with other MG	Centralized	✓	✓	✗
LFC (Load flow converter) [27]	Perform power flow between MG of different voltage levels	Decentralized	✓	✗	✗
PCMS (Power control and management strategy) [28]	Power control and management strategy based on bus signaling	Decentralized	✗	✓	✗
A concentrated control is presented for multiple Dc MGs cluster [29]	Concentrated proportional power control	Centralized	✗	✓	✗
CBB based power management and control (Proposed)	Power sharing for different load priorities	Decentralized	✓	✓	✓

Due to economic issues in remote areas, limited power generation units are installed in an MG which are generally based on the peak or average connected load profile of that area. The total load of an MG can be divided into the critical load and non-critical load. The previous studies do not consider maximizing power continuation to the partial critical load during generation shortfall.

This paper presents a distributed novel controller for Power sharing and load management for the PV powered standalone DC MG with varying loads. The controller performs need-based power sharing between the MG cluster during the mismatch of generation and load. Thus, parallel connection and circulating current between power generation units will be avoided during no-load sharing. Additionally, this controller will give power to the critical load, non-critical load, and then to other MG loads on a priority basis to increase the reliable supply of electricity to the critical loads. Additionally, the continuously increasing load demand of one MG will not disturb the electricity supply to neighboring MG load as it happens in a parallel interconnection.

The paper is organized as follows: Section 2 explains the system modeling while Section 3 discusses the power-sharing profile of the proposed controller. Section 4 contains results and discussion. In Section 5, the conclusion is presented.

2. System Model

Figure 2 depicts a DC microgrid cluster consisting of three MGs, i.e., microgrid 1 (MG1), microgrid 2 (MG2), and microgrid 3 (MG3). Each MG consists of a Solar PV array, local controller, and local variable resistive load. The local variable resistive load is further divided into critical and non-critical loads. The battery storages have been neglected so the electricity shortfall in any respective MG is compensated by importing power from neighboring MGs.

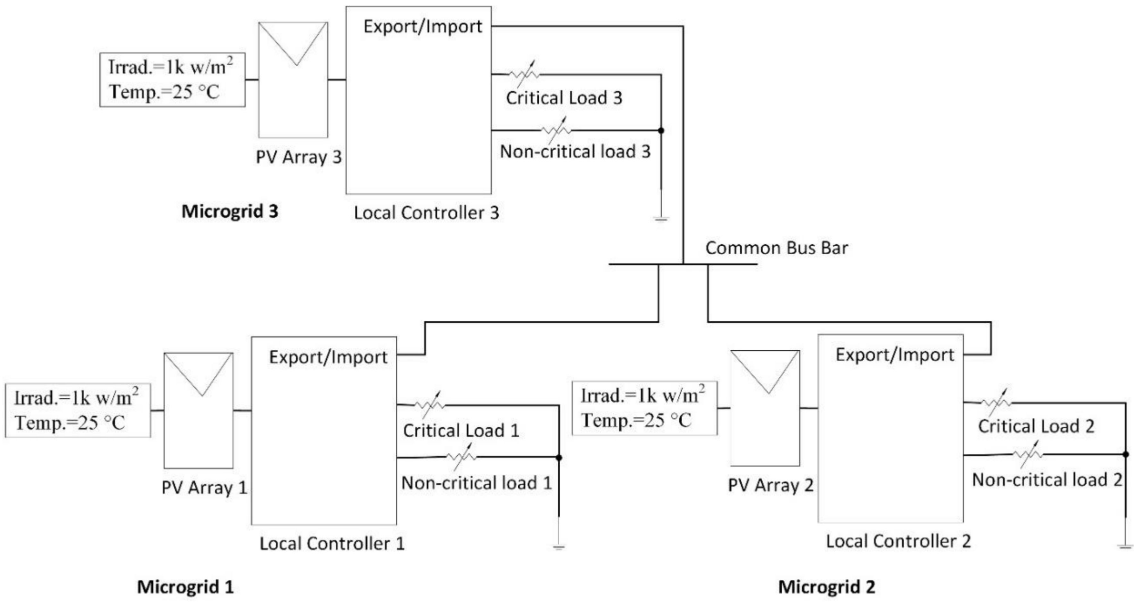

Figure 2. Proposed three MGs systems.

The mismatch between electricity generation and demand can occur either at the generation side, demand side, or both. For simplicity, the solar PV array is considered under constant standard condition (irradiance = 1 kw/m^2 and temperature = 25 °C) and load is made variable. The local controller takes power from PV and provides it to load by prioritizing the local critical then to the local non-critical load. After fulfilling the local demand, if there is any surplus power, this can be transferred to the other MGs through a common bus bar (CBB) provided the neighboring MGs initiated the request. The control unit of the local controller will decide the power flow based on the proposed power sharing and load management scheme. The CBB is a common point coupling, where every MG can export surplus power and can import power to its load during power deficiency in the MG. The import/export link can be used at a time for either power export or import.

The internal structure of the local controller is shown in Figure 3. It consists of a control unit, signal-controlled circuit breakers, control signals, and connection lines. The input to the control unit is the values of critical load ($D_{critical}$), non-critical load ($D_{non\text{-}critical}$), export power (P_{s_export}), and the irradiance. It decides based on the proposed power-sharing and load management algorithm. The control unit controls the flow of power to the critical load, non-critical load, and CBB. The PV power is connected to the CBB by using a signal-controlled circuit breaker for exporting power to the CBB. When the control unit decides power export to the CBB, it enables the circuit breaker and the respective MG can export power to the CBB. The signal-controlled circuit breakers are used to connect critical and non-critical loads to the local PV generation and CBB for local feeding when local power generation is sufficient for local demand. Similarly, signal-controlled circuit breakers are used to connect critical and non-critical loads to the CBB importing power from other MGs during power deficiency in the MG.

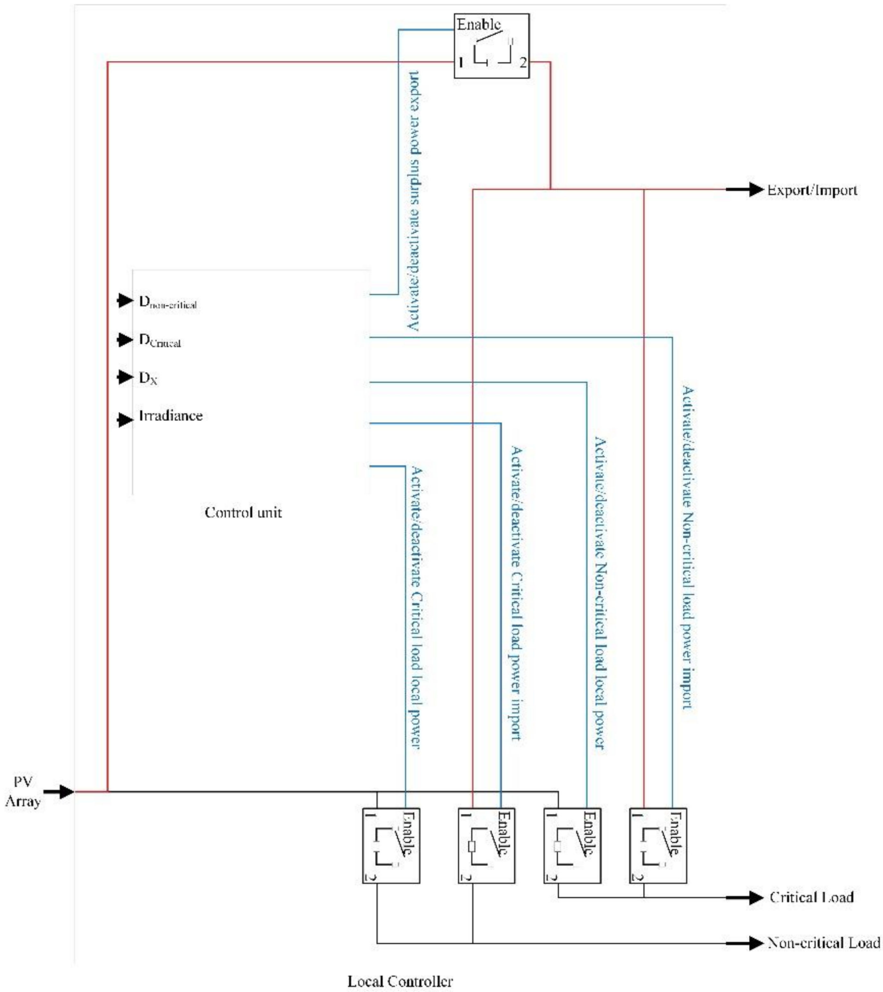

Figure 3. The internal structure of the local controller.

3. Power Sharing and Load Management Controller

The power demand of critical load ($D_{critical}$) and non-critical load ($D_{non\text{-}critical}$) are updated in a timely way as mentioned in the flowchart shown in Figure 4. The D represents the total power demand of the locally connected load to any MG and expressed as follows (Equation (1)):

$$D = D_{critical} + D_{non-critical} \quad (1)$$

D_x is the total power demand of MG which consists of the power demand of the local load (D) and the power exported/shared to other MG load (P_{s_export}) and expressed as follows (Equation (2)):

$$D_x = D + P_{s_{export}} \quad (2)$$

P_{s_export} is the surplus power of MG exported or shared to the bus bar and is expressed as follows (Equation (3)):

$$P_{s_{export}} = G - D \quad (3)$$

where G represents the maximum power generation capacity of the solar PV array at any instant. By assuming the temperature of the solar PV module constant at 25 °C, the G can be modeled using the following equation (Equation (4)) [30]:

$$G = \eta.IR.SA \quad (4)$$

where

η = Solar PV efficiency at 25 °C;
IR = incident irradiance on the surface of solar PV array PV in Watt/m^2;
SA = Surface area of Solar PV array PV in mm^2.

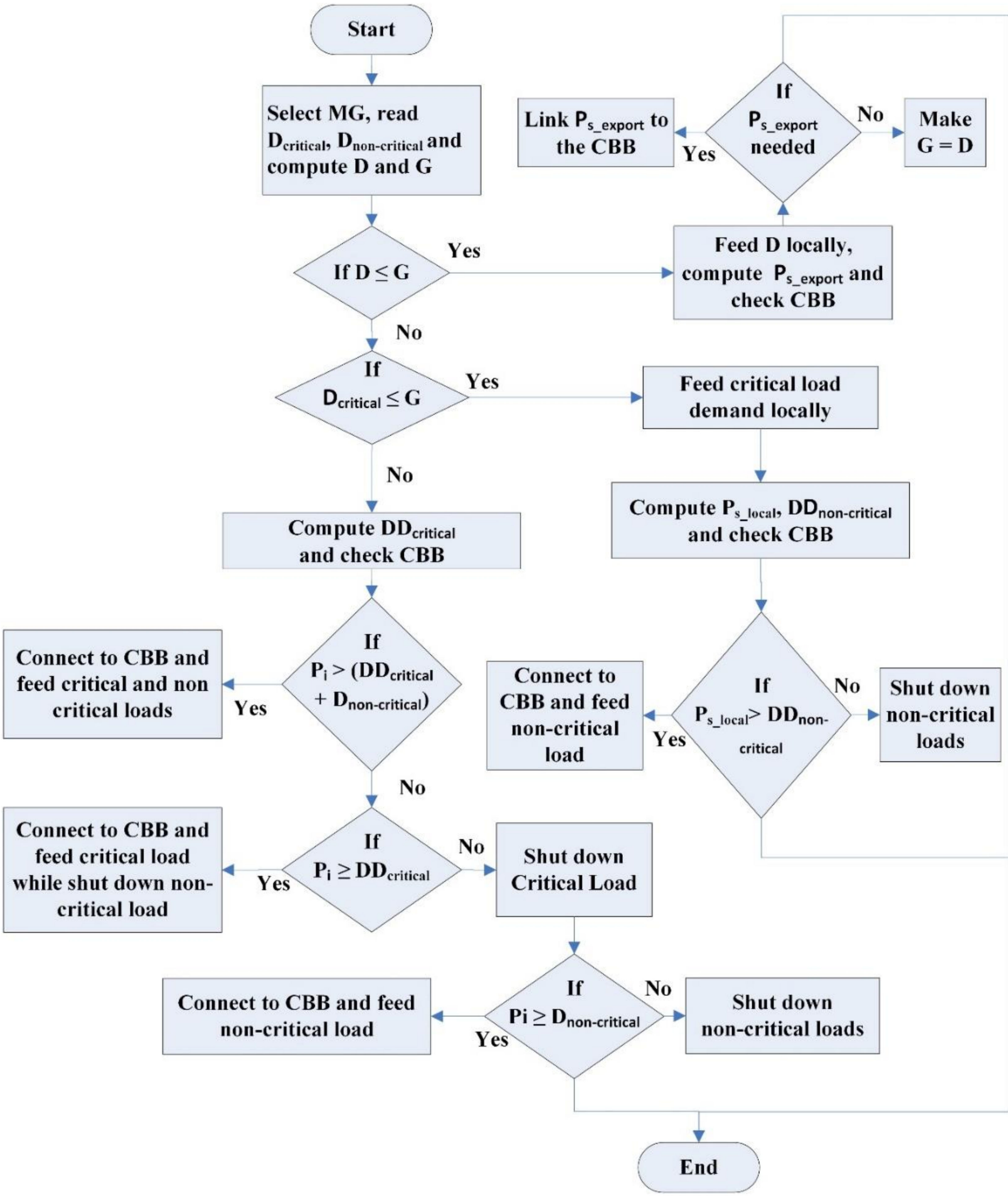

Figure 4. Flowchart of the proposed power-sharing and load management algorithm.

P_{s_local} is the local surplus power calculated when local generation is sufficient for critical load but not sufficient for non-critical load and equal to local PV generation minus $D_{critical}$. $DD_{critical}$ is the demand deficit of critical load and calculated when local generation is not sufficient for critical load and equal to $D_{critical}$ minus G. $DD_{non\text{-}critical}$ is the demand deficit of non-critical load and calculated when local generation is sufficient for critical load but not sufficient for non-critical load and equal to $D_{non\text{-}critical}$ minus P_{s_local}. P_{s_local} $DD_{non\text{-}critical}$ and $DD_{critical}$ can be expressed mathematically as follows (Equations (5)–(7)):

$$P_{s_{local}} = G - D_{critical} \quad (5)$$

$$DD_{non-critical} = D_{non-critical} - P_{s_{local}} \quad (6)$$

$$DD_{critical} = D_{critical} - G \quad (7)$$

In this algorithm, the flowchart will select any MG, i.e., MG1, MG2, or MG3. At the start, the values of P_{s_export}, $D_{critical}$, and $D_{non\text{-}critical}$ will be read. By comparing the solar PV array power generation capacity G with load consumption power, the flow chart flow will be decided any flow using five decision blocks, i.e., decision blocks 1, 2, 3, 4, and 5.

First, the value of D, $D_{x,}$ and G will be calculated using Equations (1)–(3), respectively. In the first decision block, the values of D and G will be compared. If D is less than or equal to G, the flowchart will remain in the yes condition. The local load of MG will be connected to the local generation and will be disconnected from CBB. Further, after the yes condition of the first block, if there is a sufficient amount of surplus power for export (P_{s_export}) and other MG needed it then MG will export it to the nearby-connected MG; otherwise, it will equalize the local generation and load demand. If the local generation is not sufficient for local demand in the first decision block, the flowchart will continue to the second decision block.

In the second decision block, the values of $D_{citical}$ and G will be compared. If $D_{critical}$ is less than or equal to G, the flowchart will remain in the yes condition. The critical load will be connected to local PV generation and will be disconnected from CBB. Since the local generation is sufficient for the local critical load but not for the non-critical load. Therefore, the values of local surplus power (P_{s_local}) and demand deficit of non-critical load ($DD_{non\text{-}critical}$) will be calculated by using Equations (4) and (5). Further, the CBB will be checked if there is surplus power for export (P_{S_export}) with other MG and greater than $DD_{non\text{-}critical}$, then it will be imported as a Pi and feed non-critical load by making a connection with CBB. Otherwise, the non-critical load will be shut down. The MG will not share the power with the CBB. If the local generation is not sufficient for critical demand in the second decision block, then the flowchart will continue to the third decision block.

In the third decision block, the demand deficit of critical load ($DD_{critical}$) will be calculated by using Equation (6). The CBB will be checked if there is surplus power for export (P_{S_export}) with other MG and greater than $DD_{critical}$ plus $D_{non\text{-}critical}$, then it will be imported as a Pi and feed the non-critical load plus deficiency of critical load by making a connection with CBB. If the power import (Pi) is not sufficient for $DD_{critical}$ plus $D_{non\text{-}critical}$ in the third decision block, then the flowchart will continue to the fourth decision block.

In the fourth decision block, the values of P_i and $D_{citical}$ will be compared. If P_i is greater than $DD_{critical}$, the flowchart will remain in the yes condition. The critical load will be fed by making a connection with CBB and shutdown down the non-critical load. Otherwise, if the P_i is not greater than $DD_{critical}$, the critical load will be shut down and the flowchart will continue to the fifth decision block. In the fifth decision block, the values of P_i and $D_{non\text{-}citical}$ will be compared. If P_i is greater than or equal to $D_{non\text{-}critical}$, the flowchart will remain in the yes condition. The non-critical load will be fed by making a connection with CBB. Otherwise, the non-critical load is shut down.

4. Results and Discussion

The mismatch between solar PV array power and connected load power can occur by either varying PV power or load power or both. For simplicity, we assume the maximum PV array power capacity constant (constant irradiance and temperature) and varying load power. The P_{import} is the imported power of an MG to its lad. For checking the functionality of the controller, the results for the following cases are discussed here:

- Case 1: All MG have sufficient power as compared to the locally connected load.
- Case 2: One MG has a power deficiency as compared to the locally connected load.
- Case 3: Two MG have power deficiency as compared to the locally connected load.
- Case 4: All MG have power deficiency as compared to the locally connected load.

4.1. Case 1. All MG Have Sufficient Power as Compared to the Connected Load

In this case, each MG load power is less than available PV power. The controllers will operate every MG as a separate entity and each MG will serve their local connected load. There will be no circulating current losses as compared to parallel interconnected MGs.

As shown in Figure 5a, $D_{critical1}$ and $D_{non\text{-}critical1}$ are increasing in specified times. Since there is no deficiency in other MGs so the export power of MG1 will be zero ($P_{s\_export} = 0$). The D_{x1} is less than the available PV maximum capacity. The same case is happening in MG2 and MG3, as shown in Figure 5b,c, respectively.

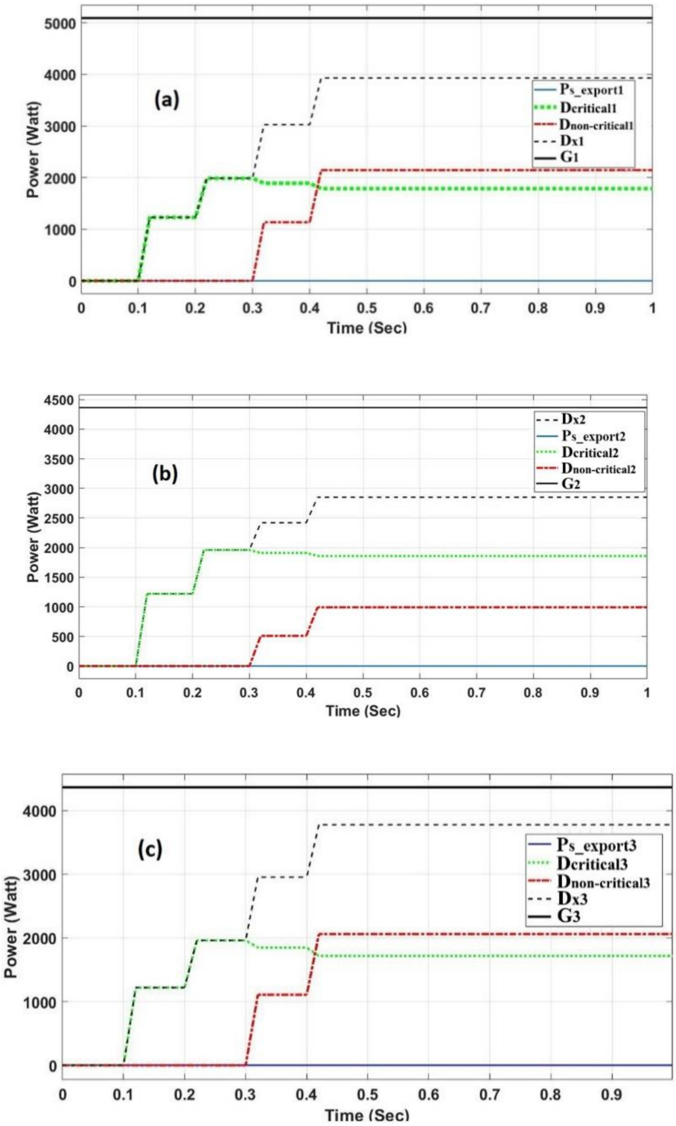

Figure 5. (Case 1) Power curves of PV and load for (**a**) MG1 (**b**) MG2 and (**c**) MG3.

4.2. Case 2. One MG Has Power Deficiency Compared to the Locally Connected Load

In this case, MG1 has power deficiency w.r.t connected load after 0.4 s, as shown in Figure 6a, the Load1 is increasing in nature and after 0.4 s the total load demand power of MG1 (D_{x1}) crosses the maximum capacity of G1. Therefore, according to the proposed algorithm, the power deficiency of non-critical load1 will be calculated. At the same time, the MG3 starts to share power with MG1 and power deficiency of the non-critical load1 but its limit is reached very quickly and no readier to support it and keep supporting its load, as shown in Figure 6c. At the same time, the MG2 has surplus power and can support the power deficiency of non-critical load1, as shown in Figure 6b. Therefore, the power deficiency of non-critical load1 will be fed from MG2.

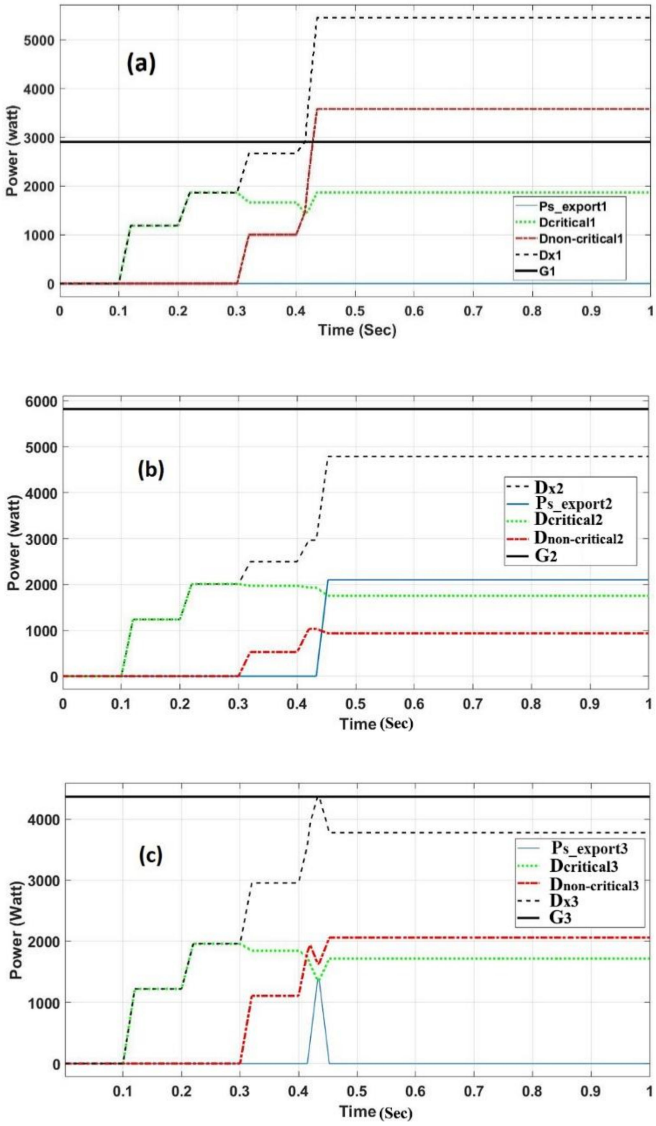

Figure 6. (Case 2) Power curves of PV and loads for (**a**) MG1 (**b**) MG2 and (**c**) MG3.

4.3. Case 3. Two MG Has a Power Deficiency as Compared to the Locally Connected Load

In this case, the MG1 and Mg3 have power deficiency w.r.t connected load at the specified time. The MG1 has power deficiency after 0.4 s, as shown in Figure 7a. $D_{critical1}$ and $D_{non\text{-}critical1}$ are continuously increasing and after 0.4 s the MG1 load crossing the G1 capacity. Therefore, according to the proposed algorithm, the power deficiency of non-critical load1 will be calculated. The MG3 starts to support non-critical load1 but $D_{non\text{-}critical1}$ is also crossing the G3 capacity in a very short time. Therefore, MG3 is no more able to support non-critical load1, as shown in Figure 7b. Since the MG2 has extra power at the same time, so it starts power to non-critical load1.

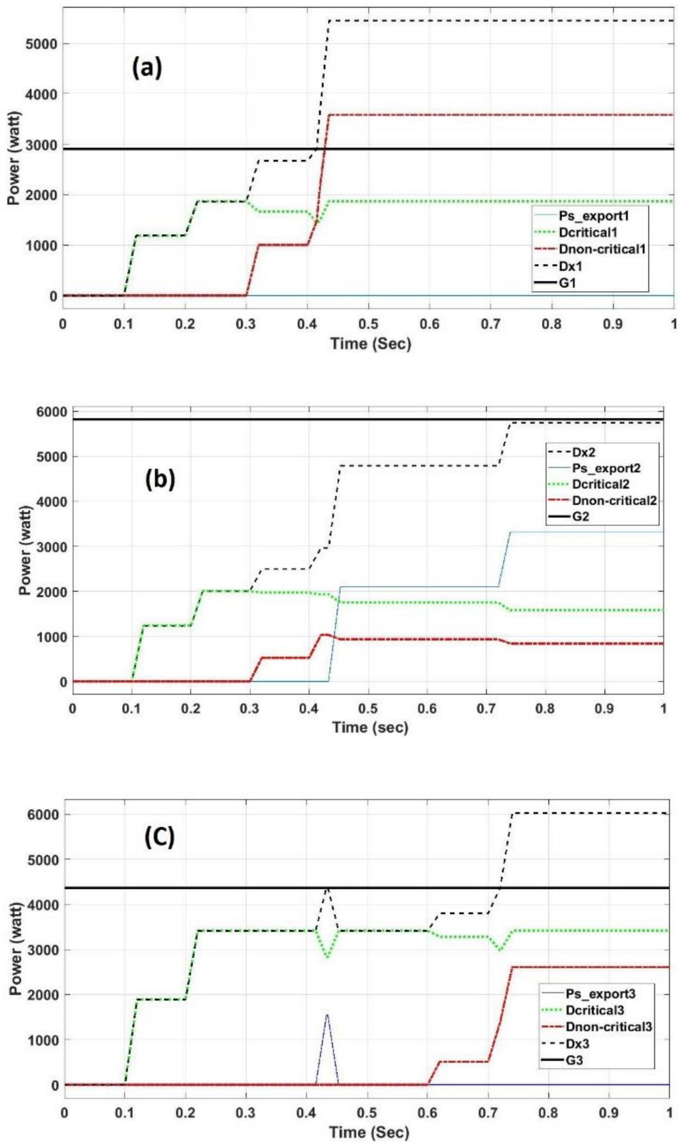

Figure 7. (Case 3) Power curves of PV and loads for (**a**) MG1 (**b**) MG2 and (**c**) MG3.

The MG3 has power deficiency after 0.7 s and it's connected load exceeding the G3 limit, as shown in Figure 7c. Therefore, according to the proposed algorithm, the power deficiency of non-critical load3 will be calculated. At the same time, the MG2 has extra power and non-critical load3 will start to take surplus power from PV2 for feeding its deficiency.

4.4. Case 4. All MGs Have Power Deficiency as Compared to the Locally Connected Load

In this case, all MGs (MG1, MG2, and MG3) have deficiencies after 0.4 s where there locally connected load exceeds the PV capacity. In all MGs, the non-critical loads will be disconnected and can only support the critical load. In MG3, the power of critical load3 is increasing in nature. After 0.7 s, the $D_{critical3}$ crossing PV3 limit and MG3 cannot support it anymore. Therefore, after 0.7 s, the MG3 controller will disconnect critical load3 and start power to non- critical load3, as shown in Figure 8.

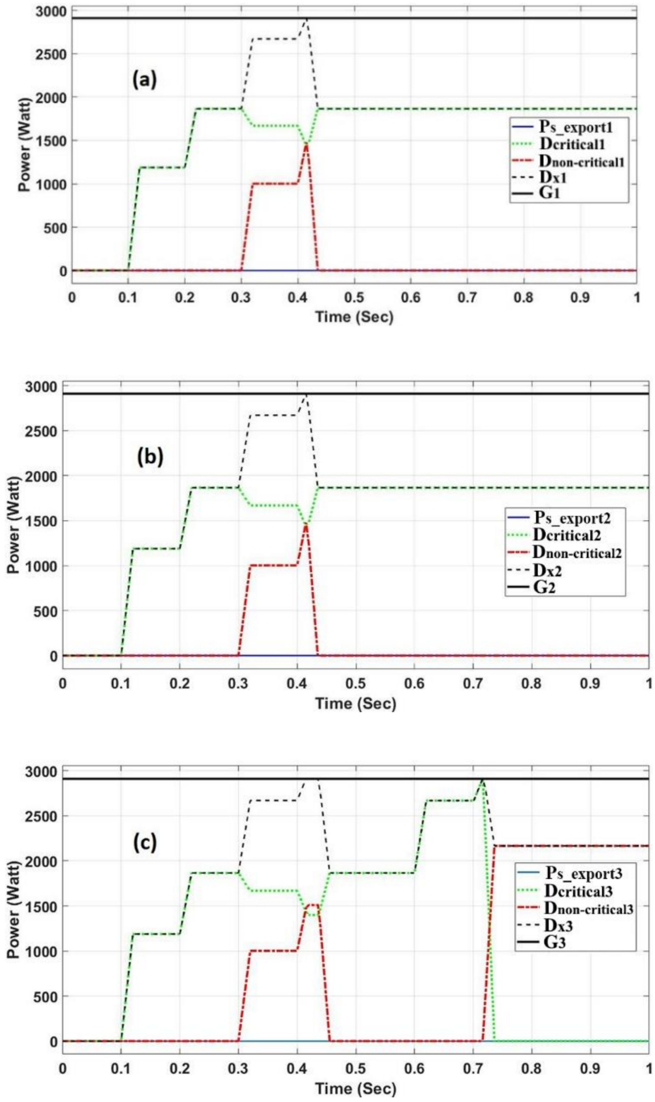

Figure 8. (Case 4) Power curves of PV and loads for (**a**) MG1 (**b**) MG2 and (**c**) MG3.

5. Conclusions

This paper proposed a novel algorithm for load management and power sharing in an MGs cluster installed close to each so that to avoid circulating current losses during no power sharing. The convention power-sharing methods can only minimize circulating current but cannot avoid it. This paper provides load management during power deficiency in MG. The MG connected load is divided into two loads: one is the critical load and the other is the non-critical load. The load management is based on giving priority to the critical local connected load, second priority to the non-critical load, and third priority to the other MG loads. Results show that the power continuation to the power-deficient load has been maintained when another MG has surplus power.

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