18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

Decentralized current sharing in dc microgrids considering normal and disturbed operation modes

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Abstract. The accurate ratio-based current sharing, which is one of the desired features of the droop controlled dc microgrid, might be affected by the system impedance. Several strategies have been presented in the literature to achieve precise current sharing. This paper proposes a new controller reconfiguration algorithm that is capable to achieve enhanced operation during normal conditions and after system disturbances. For this purpose, the proposed algorithm allows the converter to follow the set-points determined by a higher-level controller when there is no disturbance in the system. After a system disturbance, when the necessity for the current sharing arises, the proposed controller enables accurate ratio based current mismatch sharing between the droop controlled converters. The time-domain simulation conducted in Matlab/ Simulink environment demonstrates the effectiveness of the proposed approach.

Key words. dc microgrid, droop control, common voltage based droop.

1. Introduction

Compared to ac microgrids, the dc microgrids enable a reduced number of conversion stages when a large number of dc loads are present in the system. In this aspect, dc microgrids are becoming increasingly appealing as dc loads such as consumer electronics, variable-frequency drives, LED lighting systems, data centers, and electric cars are becoming a significant portion of the energy-consuming loads [1]. Furthermore, dc microgrids can overcome challenges associated with ac microgrids such as reactive power flow, frequency regulation, transformer inrush current and power quality issues.

Fig. 1 depicts a general structure of an isolated dc microgrid, which is formed by parallel connection of the power sources and the loads with the help of the power electronic converters. The converters interfacing the loads are usually adapting some form of power control to deliver the required power to the consumer. On the other hand, droop control is adapted for the converters connecting the power sources to the dc grid.

Being decentralized in nature, droop control aims to regulate dc voltage simultaneously by several converters and to share the system power mismatch between power sources based on the preselected ratios. The load sharing accuracy is however affected by the line impedances of

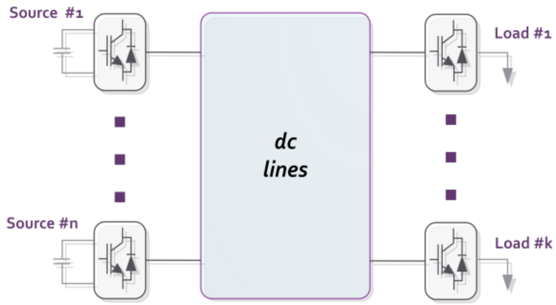

Fig. 1: The general structure of dc microgrid

the dc grid. Improper power-sharing can result in overloading of converters, which might, in turn, cause thermal stress on the switches [2].

The control approaches that have been presented in the literature to solve the aforementioned issue can be divided into three main groups: centralized, distributed and decentralized control strategies. The first two groups rely on a high-bandwidth communication infrastructure to exchange an information with the local controllers to adjust the reference signals [1], [3]–[13]. The cost and reliability related issues are the main drawbacks of the communication based approaches. Several decentralized strategies rely on the precise knowledge of the network topology and impedances during the whole operation period [14]–[16]. However, any change of this information such as system reconfiguration and load switching would result in sharing error with the latter strategies. The on-line estimation of this information is proposed in references [15], [16], which are however applicable to single bus dc microgrid only.

The last group of the papers relies on an intentional injection of ac signal into the dc grid [17]–[20]. References [17]– [19] superimpose a small ac signal in all droop controlled converters, after which the dc voltage is adjusted based on the small active [17] or reactive [18], [19] power flow resulted from the superimposed signal.

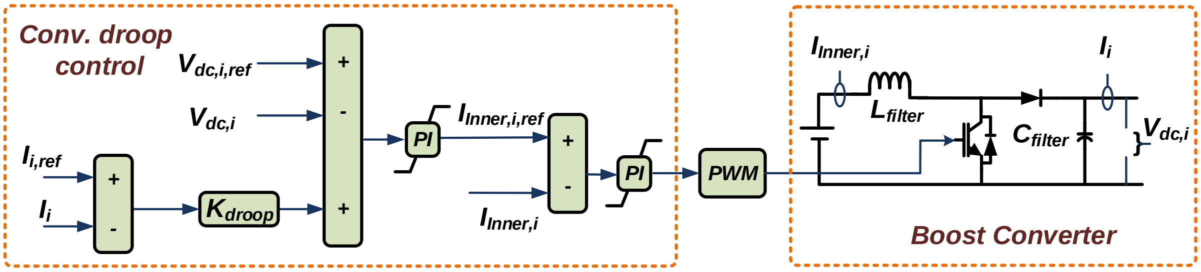

Fig. 2: Conventional control structure of the dc/dc converter

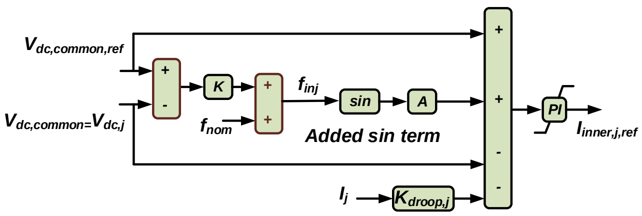

Fig. 3: Control of droop controlled converter injecting the ac signal

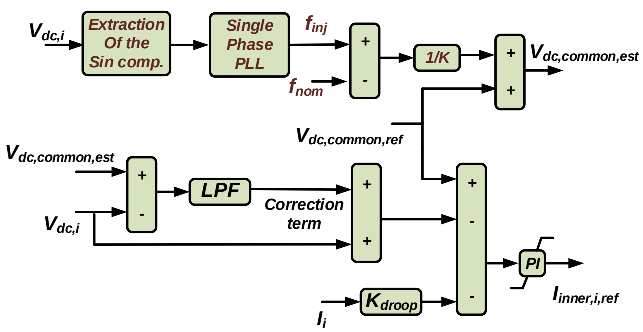

Fig. 4: Control of all droop controlled converters except the converter injecting the ac signal

The latter approaches, however, significantly modify the conventional droop-control structure and they strictly rely on the synchronization between the injected signals. If the latter is not achieved, then not only the proper current sharing but the overall system stability might be jeopardized. To overcome the issue of synchronization between the injected signals, reference [20] proposed a new control strategy that relies on a single converter for injecting the ac signal. The frequency of the injected ac signal contains information about the dc voltage magnitude at the injecting converter. As the frequency is a global variable, this magnitude information becomes available in the rest of the converters and is becoming locally available common voltage signal in all converters. By modifying the local voltage feedback to become equal to common voltage in a steady-state, an accurate current sharing is achieved. However, this approach also requires identical reference voltage for all droop controlled converters. Setting identical voltage reference might not be always preferred, especially considering the voltage and current setpoints are regularly updated by the secondary or tertiary level controllers.

This paper proposes a control strategy that can provide operator desired performance during normal conditions as well as can enable the converters to accurately share the disturbance power based on the prespecified gains. Therefore, a controller reconfiguration scheme is developed to switch between the conventional set-point based controller to the controller of [20] for ensuring accurate current sharing after the disturbance. The time-domain simulations demonstrate the existing issues and verifies the capability of the proposed controlled to provide enhanced performance during both modes of operation.

II. Existing Control Approaches

A. *Conventional control of the dc subgrid*

Fig. 2 demonstrates one of the implementations of the conventional control structure for the droop-controlled dc/dc converter. The innermost layer of the filter inductor current $I_{i,inner}$ is regulated to its reference value $I_{i,inner,ref}$ provided by the outer loop. This reference is generated in the voltage regulation loop and is equal to

$$I_{i,inner,ref} = (V_{dc,i,ref} - V_{dc,i} + (I_{i,ref} - I_i) * k_{droop,i}) * G_{PI}(s) \tag{1}$$

where $V_{dc,i,ref}$ and $V_{dc,i}$ are the reference and measured voltages of the i_{th} converter, respectively, $I_{i,ref}$ and I_i are the reference and measured outputs currents of that converter, respectively, $k_{droop,i}$ is the droop gain of the converter for determining its power mismatch sharing portion, and $G_{PI}(s)$ is the transfer function of the PI controller. Considering that an integral action allows the PI controller to regulate the dc error to zero in steady-state, (2) can be written for the steady-state current sharing

$$I_i - I_{i,ref} = \frac{V_{dc,i,ref} - V_{dc,i}}{k_{droop,i}} \tag{2}$$

The difference $V_{dc,i,ref} - V_{dc,i}$ might not be identical for all converters as the voltage changes with any change in the system power. Therefore, the current mismatch sharing after a system disturbance might not be possible to precisely determine based on the prespecified portion.

B. *Common voltage based communication-less structure*

One of the solutions to overcome the aforementioned issue is to always set equal voltage set-points in all droop-control converters and then acquire the voltage of a preselected bus in a continuous manner for using as voltage feedback. In that case, the current mismatch in any droop controlled converters would be given by (3) and would be solely determined based on the prespecified ratio for that converter.

$$I_i - I_{i,ref} = \frac{V_{dc,common,ref} - V_{dc,common}}{k_{droop,i}} \tag{3}$$

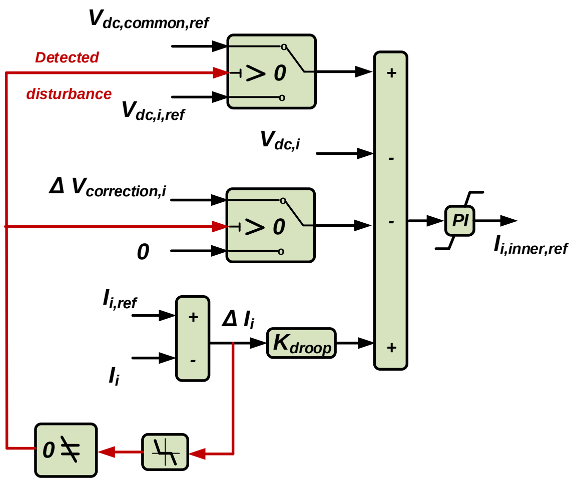

Fig. 5: The proposed control strategy for the i_{th} droop controlled converter

Several studies used approaches relying on the above logic both on the distribution [20] and the transmission levels [21], [22]. The decentralized controller proposed in [20] for dc microgrid is depicted in Fig. 3 and Fig. 4. As seen in Fig. 3, a preselected j_{th} converter is used to add a small ac signal to the dc voltage reference, therefore to generate an ac component on dc system voltage. The frequency of the ac signal is varied as a function of the measured voltage $V_{dc,j}$ at that specific converter as per

$$f_{inj} = (V_{dc,j,ref} - V_{dc,j}) * K_{norm} + f_{nom} \tag{4}$$

where K_{norm} is the normalization constant and f_{nom} is the nominal frequency around which the frequency will be varied. Depicted in Fig. 4, the frequency of the propagated voltage is estimated at the i_{th} converter from the locally measured voltage. As the frequency is not affected by the dc grid topology and parameters, it is used to locally estimate the common voltage $V_{dc,j,ref}$ at the i_{th} converter. The steady-state voltage feedback of all converters then becomes equal to the common signal. By having identical voltage references and feedback signals, ratio-based current sharing can be achieved.

III. The Proposed Control Strategy

The common voltage based strategy described in the previous section requires universal voltage references for all droop controlled converters. However, in some microgrids, the voltage and current references of an individual converter are periodically updated by the outer (tertiary) control layers to achieve the desired system operation. During the period when the references are updated by the system operator (e.g. by using the power flow results), the current sharing is automatically taken care of by the determined proper set-points. If after the disturbance common voltage feedback is used in combination with the previously determined reference set-points, unpredictable current mismatch sharing might happen.

This paper proposes an algorithm which can provide set-point based performance in normal operation and accurate current mismatch sharing during system disturbances. Fig. 5 demonstrates the implemented control philosophy for the i_{th} droop controlled converter. With the set-points determined by a higher-level controller, e.g based power flow results, the measured current I_i should be equal to its reference value $I_{i,ref}$. As far as the current difference ΔI_i lies in the prespecified deadband, no disturbance is detected and therefore the current sharing algorithm is not activated.

After the disturbance in the system, the converter current outputs will deviate from their reference value to accommodate the change of the system load/ generation. During small changes of the system load, as the current mismatch sharing error is not significant, ΔI_i does not exceed the prespecified current deadband and the output of the disturbance detection algorithm is 0. Therefore, both switches in Fig. 5 are in the lower position, and the converter control remains identical to the conventional droop control structure.

Once there is a relatively large load change in the system, ΔI_i exceeds the current threshold to serve as an indicator of a power unbalance in the system and necessity to activate the mechanism for ensuring proper current deviation sharing between droop controlled converters. The disturbance detection imposes activation of the common voltage based controller to avoid significant sharing errors. Therefore, both switches in Fig. 5 turn to their upper position and the voltage reference is switched from the power flow determined setpoint to a global voltage setpoint (e.g 1pu). Furthermore, the correction term, given by (5), is also activated.

$$\Delta V_{correction,i} = (V_{dc,common} - V_{dc,i}) * G_{s,LPF} \tag{5}$$

where the first order low pass filter $G_{s,LPF} = \frac{\omega_c}{\omega_c + s}$ is used to slow the effect of the dynamics associated with the estimation of the common voltage. As in steady state the LPF has no effect on dc quantities, the local voltage signal is determined as per

$$\begin{aligned} V_{dc,feedback,i} &= \Delta V_{correction,i} + V_{dc,i} \\ &= V_{dc,common} - V_{dc,i} + V_{dc,i} = V_{dc,common} \end{aligned} \tag{6}$$

Therefore, the activated correction term allows achieving identical voltage feedback, which, together with the activated universal voltage references, allows the converters to achieve a precise droop-operation. The current sharing during the normal and disturbed mode of operation with the proposed controller is summarized in (7).

$$\Delta I_i = \begin{cases} \dfrac{V_{dc,i,ref} - V_{dc,i}}{k_{droop,i}}; \Delta I_i \in [I_{min}, I_{max}] \\[2ex] \dfrac{V_{dc,common,ref} - V_{dc,i} + \Delta V_{correction,i}}{k_{droop,i}} \\[2ex] = \dfrac{V_{dc,common,ref} - V_{dc,common,ref}}{k_{droop,i}}; \Delta I_i \notin [I_{min}, I_{max}] \end{cases} \tag{7}$$

IV. Simulation Results

Fig. 6 demonstrates the test system used for validation of the proposed algorithm. The system is a multi-bus dc microgrid and comprises of three power sources and two loads connected at separate buses. The system voltage level is 400 V and

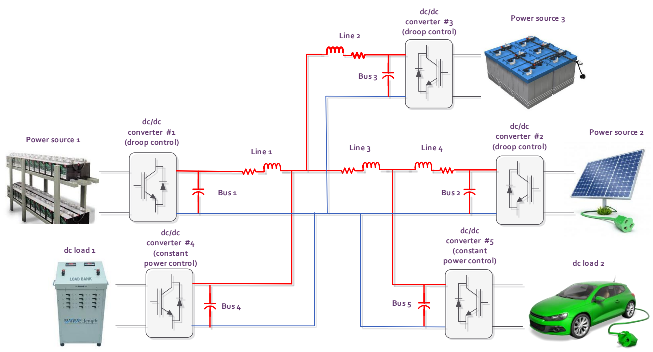

Fig. 6: The test system under study

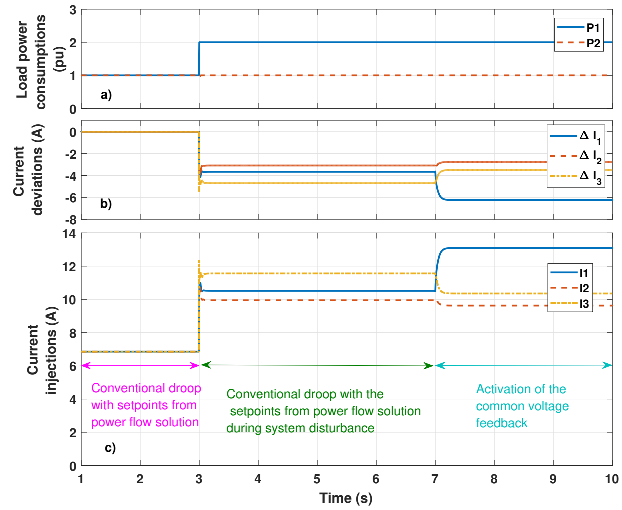

Fig. 7: The average currents of the droop controlled converters

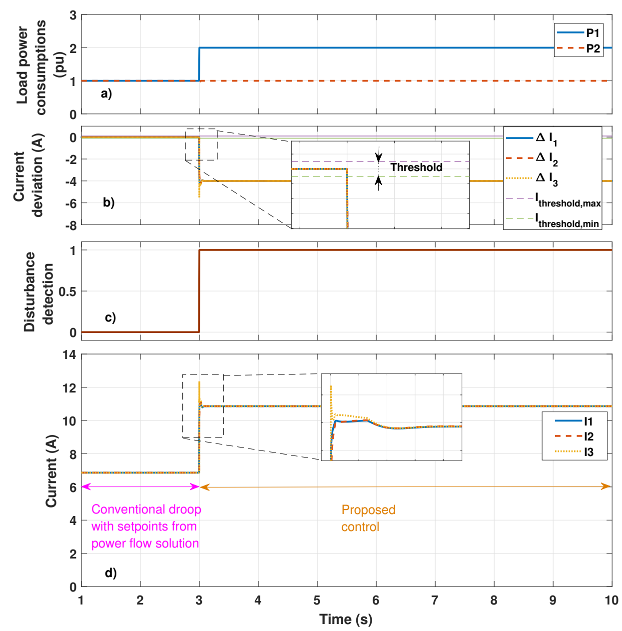

Fig. 8: The average currents of the droop controlled converters

the base power is 3kW. Cases with both equally rated and unequally rated converters are considered. The model of the system of Fig. 6 is developed in Matlab/ Simulink environment for conduction of time-domain simulations. Constant power control is applied for the converters connecting the loads to the dc microgrid. The rest of the system parameters can be found in Table I.

The system performance during the system load change when equally rated converters are considered is shown in Fig. 7 and Fig. 8. Please notice that the average values of voltages, currents and powers are shown for the clarity of the illustration, while the mentioned parameters contain an ac ripple during a disturbance mode of operation introduced for the current-sharing purpose. Initially, up to time t=3 s, both loads are consuming 1 pu power. The circuit is simulated considering the set-points predetermined by the power flow results: the reference voltages from the first to third converters are 1.01294 pu, 0.99125 pu and 0.9958 pu, respectively, and the reference currents for all droop controlled converters are set to 6.8565 A.

At time t=3 s, the power consumption of the load connected at Bus 4 is increased by 1 pu as shown in the subfigure Fig. 7a. This causes the change of the converter outputs currents. Subfigures b and c of Fig. 7 demonstrate the current deviations and the actual current injections of the droop controlled converters, respectively. As can be seen from both subfigures, the performance with the conventional controller causes an imprecise mismatch sharing and unequal loading between the dc/dc converters. At time t=7s, common voltage feedback is activated for all droop controlled converters. However, because of the difference in the voltage reference set-points, the sharing error is not mitigated.

Identical 1 pu load change is applied to the equally rated converters equipped with the proposed controller and the results are depicted in Fig. 8. Before the system disturbance, the proposed controller allows operation with the set-points determined by the higher-level control loops. As shown in subfigure b of Fig.8, the current deviation of the droop controlled converters ΔI experiences significant change during the load increase at 1s. As this deviation is greater than the pre-selected threshold of 0.1 A, the proposed algorithm detects the system disturbance. Afterword, for all droop-controlled converters, the proposed controller turns on identical voltage reference as well as the correction term to achieve identical voltage feedback. This results in a precise current sharing determined based on the droop gains only. As in this scenario the droop gains are equal, subfigure d of Fig.8 validates the accurate controller performance by achieving a uniform steady-state current sharing between all converters.

The system performance when unequal sharing is required between the converters is shown in Fig. 9. In this scenario, the droop gain of the first converter is twice lower than the gain of the third converter and twice higher than the identical parameter of the second converter, respectively. In the subfigure Fig. 9a at the time t=3 s the load increase causes current mismatches for all three converters to exceed the defined threshold, causing detection of the disturbance with the proposed controller. However, in this scenario, the proposed controller is activated only at time t=10 s to clearly visualize its advantage over its alternatives. As seen in Fig.

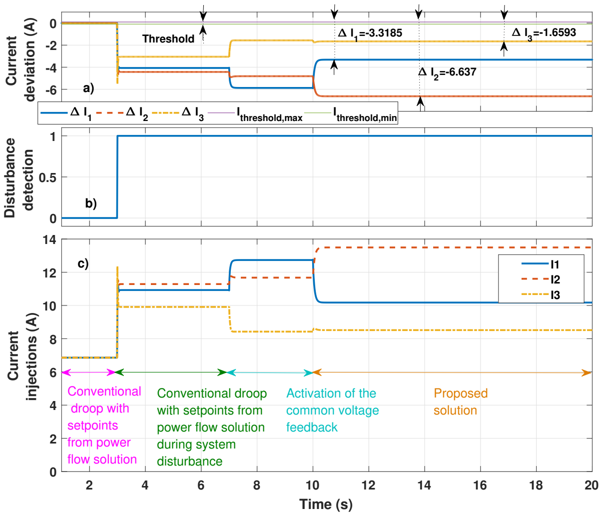

Fig. 9: The average currents of the droop controlled converters

9a, before the activation of the proposed controller the current mismatches are not sharing according to the predefined ratios. Once the controller of Fig. 5 is activated, the current deviations from the first to third converters become equal to 3.3185 A, 6.637 A and 1.6593 A, respectively. The achieved exact sharing verifies the validity of the proposed controller.

V. Conclusion

A controller reconfiguration strategy has been presented and analyzed in this paper. The proposed approach is capable of operating based on the predetermined set-points during normal conditions while ensuring an accurate ratio-based current sharing during the system disturbances. The performance of the proposed algorithm has been validated through time-domain simulations in Matlab/ Simulink environment.

VI. Appendix

The parameters of the considered DC system.

TABLE I: Microgrid parameters

$V_{DC,Grid}$	400 V	Line 1 and 6 Resistances	2 Ω
S_{base}	3 kW	Line 2 and 5 Resistances	1 Ω
Filter Inductance	0.2 mH	Line 3 and 4 Resistances	1.5 Ω
Filter capacitance	500 μF	Line 1 and 6 Inductances	15 mH
Filter Resistance	0.05 Ω	Line 3 and 4 Inductances	11.25 mH
Nom. Inj. Frequency	50 Hz	Line 2 and 5 Inductances	7.5 mH
$k_{p,DC}$	0.1 A/V	$k_{i,DC}$ (voltage reg.)	20 A/V
$k_{p,inner}$	0.02 pu/A	$k_{i,inner}$ (current reg.)	1 pu/A

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