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Power flow analysis for DC voltage droop controlled DC microgrids

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Abstract—This paper proposes a new algorithm for power flow analysis in droop controlled DC microgrids. By considering the droop control in the power flow analysis for the DC microgrid, when compared with traditional methods, more accurate analysis results can be obtained. The algorithm verification is carried out by comparing the calculation results with detailed time domain simulation results. With the droop parameters as variables in the power flow analysis, their effects on power sharing and secondary voltage regulation can now be analytically studied, and specialized optimization in the upper level control can also be made accordingly. Case studies on power sharing and secondary voltage regulation are carried out using proposed power flow analysis.

Index Terms—DC microgrid, droop control, power flow, power sharing, secondary control.

I. INTRODUCTION

With the promising potential to provide means for the integration of distributed renewable energy, to facilitate the modernization of present power system, as well as to improve power quality for customer and to participant in demand respond, microgrid, with its definition as a local grid that comprises distributed generation, energy storage systems and local loads, has been increasingly viewed as the one of most desirable solutions for the realization of “smart grid”.

According to the source type, microgrids can be divided into AC microgrids and DC microgrids. To cope with inherent problems related to AC microgrids, such as the need for synchronization of the distributed generators, the inrush currents due to transformers, reactive-power flow, harmonic currents, and three-phase unbalances, as well as to incorporate increasing modern DC components with less conversion loss, such as photovoltaic panels, batteries, fuel cells, LEDs, and electronic loads, DC microgrids have been chosen over AC microgrids [1]-[3]. Nowadays DC microgrids are found in data centers, telecom systems, and some buildings and offices, and there is a trend toward adopting more DC distribution network.

To manage the power flow of the DC microgrid, various control strategies, e.g. Master-slave control [4], average current control method [5], and droop control using virtual impedance [6], have been proposed. Among these strategies, due to its autonomous feature, communication-less, and simplicity, droop control is most frequently adopted in the control of paralleled DC converters, which is just the general form of DC microgrids. In this method, the main idea behind the droop

control is that, similar to the frequency in the AC bulk grid, the DC voltage in the DC microgrid can be treated as the control signal for the real power.

Although transmission line losses might not be the largest proportion for the system losses in the microgrid (e.g. PV system [7]), the power flow analysis is essential for DC microgrids due to the following reasons. For one thing, due to the inherent defects of droop control in DC microgrids based on local voltage which render the voltage regulation and power sharing not accurate, a precise control strategy might be proposed for DC power system based on power flow analysis results [8]. For another, the power sharing and voltage profile of the network are indispensable for the planning and operational stages of the DC microgrid, in term of systematic analysis, protection coordination design, network optimization and optimal operation, etc. Therefore, power flow analysis which is suitable for the DC microgrid based on droop control is highly needed, while unfortunately not enough research work exists in literature besides some work on HVDC [8]-[10]. Even some researches have been done for the high voltage DC power network, similar to the traditional AC power flow, they use slack DC bus in the model with the capability of balancing the active power in the network with constant DC voltage [9],[10]. It is not, however, the case in reality. In order to fully analyze the steady state feature of the DC microgrid, droop control of the DC microgrid should be taken into consideration into the power flow analysis algorithm.

In this paper, a power flow analysis algorithm is proposed for DC microgrids. The structure of this paper is as follows. In the second section, the mathematical model of proposed power analysis is formulated by modifying the traditional method. The verification of the proposed algorithm is presented in the third section based on a four-bus ring topology DC microgrid, and it shows effectiveness of the algorithm. In order to show the additional features compared with traditional methods, two case studies concerning power sharing and secondary regulation of the system is demonstrated with simulation results. Finally, conclusions are drawn in the last section.

II. MATHEMATICAL MODEL OF POWER FLOW CALCULATION FOR DROOP CONTROLLED DC MICROGRIDS

In this section the traditional method is reviewed and its limitation for DC microgrids is discussed firstly. Then, steady characteristic of droop controlled DC sources in DC microgrids

is presented as the foundation for the proposed algorithm. The mathematical model of the proposed algorithm is presented in the end of this section.

A. Traditional power flow method

Similar to the power flow analysis in AC power system, the standard way has been set up for power flow analysis of DC system. In the standard way of modeling, all the generators and loads are connected with the nodes defined as buses and, between the buses are the transmission lines which are modeled as impedance or impedance network. In the steady state analysis, the overall power dispatch of the network is determined by the line resistance and the difference of bus voltage magnitude between DC buses. Therefore, in the DC power system, at every bus, two variables need to be determined. They are the bus voltage and real injection power. The objective of the power flow is to calculate the power and voltage profile of each bus. In traditional method, it assumes that there is a bus working as voltage regulator and keeping the voltage constant while others control their active power injection. So the slack bus has bus voltage magnitude as known variable while others have bus injection real power as known variable. According to the nodal power balance of matching bus power injection, load power injection and generation power injection, the left unknown values will be solved by the power flow algorithm through a certain iteration method.

For DC microgrids, however, due to the limited volume of the disturbed DC sources, it is impractical to take any of them as slack bus which can compensate whatever amount of real power. Moreover, the traditional way of modeling of the power flow analysis does not take the droop control parameters into consideration which has decisive effects on the steady state characteristic of the system. The principle of the droop control in the context of hierarchical control architecture for DC microgrids will be discussed in the following part.

B. Steady characteristic of droop controlled DC sources in DC microgrids

In DC microgrids, it is equivalent that many DC sources are connected in parallel. To avoid the circulating current and to achieve the proper power sharing for the load autonomously, the DC source should not work as stiff voltage source. Taking the idea from speed droop regulated governors in the bulk grid, DC sources in DC microgrids are adopting a droop by subtracting part of the converter output current, which can also be done by multiplication a value reciprocal to deviation of measured voltage to reference voltage [11]. The first method is illustrated by the following equation [1].

$$V_G^* = V_0 - R_D i_G \quad (1)$$

Where V_G^* is the voltage reference to DC source which should be equal to the measured voltage value in a stable system in the steady state, V_0 is the output reference at no load condition which is usually modified from secondary control to

achieve voltage regulation, is the virtual impedance of the droop controller, and R_D is the output current of the DC source.

According to (1), the steady state characteristic of the DC microgrid is influenced by the droop control parameters, i.e., V_0 and R_D .

C. Modified power flow analysis for DC microgrids

With taking the droop control of the DC source into consideration, all the DC sources are modeled as Droop-buses and they are obeying the droop control principle illustrated as (1) in the last section. For simplicity, we assume loads in the system are only constant power loads, whose power is independent of the bus voltage, and considering more load types will be in the future work. There are two kinds of buses in the system, one is droop bus, and the other is constant power bus.

In the steady state model of the DC microgrid, it is possible to assume that the network is purely resistive with pure resistance as line impedance [11]. Assuming there are totally n buses in the network, according to the Kirchhoff's current law, that current injected at the bus i equals to the sum of current flowing to other $n-1$ buses, the network equation can be written as follows

$$I_{dc,i} = \sum_{\substack{j=1 \\ j \neq i}}^n Y_{dc,ij} (V_{dc,i} - V_{dc,j}) \quad (2)$$

Where $I_{dc,i}$ is the DC injection current in bus i , $Y_{dc,ij}$ is the admittance between the bus i and bus j , and $V_{dc,i}$ is the voltage magnitude in bus i ;

In a unipolar DC microgrid, for any bus, the injection power has the following relationship with injection current

$$P_{dc,i} = V_{dc,i} I_{dc,i} \quad (3)$$

Thus, network equation (2) can also be written as

$$\frac{P_{dc,i}}{V_{dc,i}} = \sum_{\substack{j=1 \\ j \neq i}}^n Y_{dc,ij} (V_{dc,i} - V_{dc,j}) \quad (4)$$

Additionally, for the Droop-buses, there is one more constraint they have to follow

$$V_{Gi} = V_{0i} - R_{Di} i_{Gi} \quad (5)$$

Where i_{Gi} can be written as,

$$i_{Gi} = \frac{P_{Gi}}{V_{Gi}} \quad (6)$$

According to the real power balance of the system, the power balance equation is as follows:

$$P_{Gi} - P_{Di} - P_{dc,i} = 0 \quad (7)$$

The overall mathematical model of power flow analysis is as follows:

$$\begin{cases} \frac{P_{dc,i}}{V_{dc,i}} = \sum_{\substack{j=1 \\ j \neq i}}^n Y_{dc,ij} (V_{dc,i} - V_{dc,j}) \end{cases} \quad (8)$$

$$\begin{cases} V_{Gi} = V_{0i} - R_{Di} \frac{P_{Gi}}{V_{Gi}} \end{cases} \quad (9)$$

$$\begin{cases} P_{Gi} - P_{Di} - P_{dc,i} = 0 \end{cases} \quad (10)$$

III. VERIFICATION OF THE PROPOSED POWER FLOW ALGORITHM

In order to verify the effectiveness of the algorithm, the calculated results by using it are compared with the results obtained from a detailed time domain simulation based on Matlab Simulink. To make the power supply more reliable, ring topology is often adopted, thus here four-bus system using the ring topology is taken as test system. The system topology is shown in Fig. 1. In this system, two DC sources are controlled by P-V droop controller through virtual impedance in bus 1 and bus 2. Two load buses are modeled as constant power load, with definite power demand. All the line resistances are 0.05Ω , and the rest of the parameters of the system is listed in Table I. To compare with the calculated results, the same system is set up in Simulink of Matlab with the same parameters. The comparison between results obtained from time domain simulation with results from calculation using proposed algorithm is shown in Table 2. It can be seen that the maximum voltage amplitude deviation to the simulation is less than 0.36%, and the maximum bus injection power deviation to the simulation is less than 0.6%. The good agreement between these results indicates the accuracy of the proposed algorithm for DC microgrids.

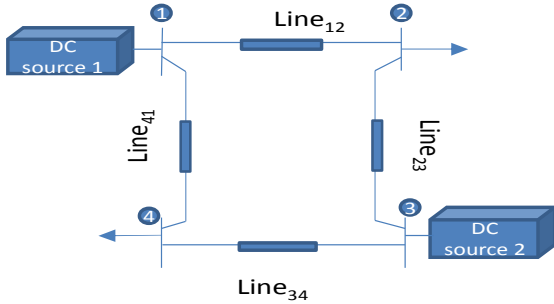


Fig. 1 Topology of test four-bus system

Many limitations are related to the traditional power flow algorithm for the DC microgrid. In order to show them, 4 more experiments have been carried out based on traditional algorithm with bus 1 as the slack bus while bus 3 set as the constant P bus. Since in the traditional method, power sharing cannot be known beforehand, two different load conditions in bus 3 are assumed as 10% of total demand and 70% of total demand respectively. To show that calculation results are also affected by the choice of initial voltage of the slack bus using traditional method, two different flat voltage values are compared as well. From the Fig. 2, it can be seen that, in all

these voltage profiles, the results calculated from the proposed algorithm are the closest to the results from the time domain simulation, i.e., with the consideration of droop control in the proposed algorithm, more accurate results can be obtained compared with traditional algorithm using slack bus.

TABLE I. PARAMETERS OF THE FOUR BUS TEST SYSTEM

DC source droop parameters			
parameters	symbol	value	units
Reference voltage in bus 1	V_{ref1}	48	V
Reference voltage in bus 2	V_{ref2}	48	V
Virtual resistance for DC source 1	R_{d1}	0.2	Ω
Virtual resistance for DC source 2	R_{d2}	0.5	Ω
Load parameters			
bus number	power(W)		
2	466.25		
4	697.5		

TABLE II. PARAMETERS OF THE FOUR BUS TEST SYSTEM

No	SimPowerSystem results		Power Flow Results	
	Mag.(p.u.)	Power(W)	Mag.(p.u.)	Power(W)
1	0.979167	822.5	0.975766	817.23
2	0.971354	466.25*	0.973167	466.25*
3	0.973958	350.625	0.974035	349.62
4	0.968750	697.5*	0.972306	697.5*

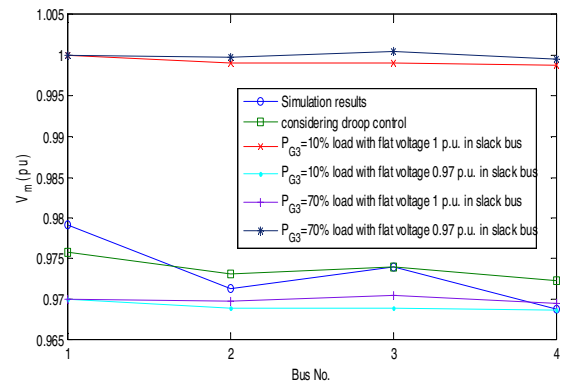


Fig. 2 Comparison of Voltage profiles of the four-bus test system using different algorithms

IV. CASE STUDIES

In this part, to show the additional features which are desirable for the Energy Management System of the DC microgrid but unfortunately cannot be provided by the traditional algorithms, two case studies have been carried out based the four-bus ring topology DC microgrid.

A. Power sharing control by modifying the virtual resistance

As is known, the main purpose of the droop control is to achieve autonomous power sharing between different DC sources, and the droop gain, i.e., the virtual resistance is often chosen according to the rated power of each DC source. That is to say, to change the value of the virtual resistance, the power flow of the system will be change, which can be modified according to the need or the optimization of the system. Without any representation of this important control variable in the power flow analysis, traditional methods cannot show

the power sharing changes according to the different control parameters adopted in the DC microgrid system, thus cannot be used to analyze droop controlled DC microgrid in the planning or operation stages. To represent the feature that the proposed method can be used to analyze power sharing based on changing the droop gain, a comparison of the power sharing results based on two different droop gain values is shown in Fig. 2. The R1 is chosen as 0.5Ω and R2 is 0.2Ω in Case 1; the R1 is 0.2Ω and R2 is 0.5Ω in case 2. Although power can be roughly reversely linear with the virtual resistance, due to the voltage being the local value and the existence of the line impedance, there will be some deviation from this rough approximation. The proposed algorithm can get the accurate power sharing results in advance.

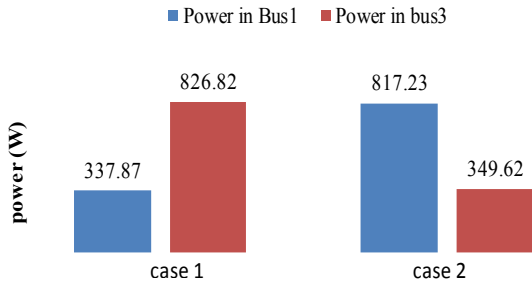


Fig. 3 Power sharing difference comparison with different virtual impedance

B. Secondary regulation analysis

To tackle the problem of voltage deviation, the secondary control in a hierarchical control architecture are proposed in [1] to restore the nominal value of the voltage inside the DC microgrid. In this secondary layer, after the error between the nominal bus voltage and measured bus voltage passing a PI controller, this value obtained is added to the V_{ref} of the primary control to restore the voltage. That is to say, the choice of the V_{ref} relates to the voltage regulation of the system, and thus to modify this value, the voltage profile of the DC microgrid can be regulated. To show that the proposed algorithm can analyze this important characteristic in advance, voltage profiles in per unit before and after secondary control are shown in Fig.4, which shows that the secondary control levels voltage in all the buses in the system to close to the nominal value. This additional feature of the proposed algorithm makes it possible for the upper level control layer of the Energy Management System to set the optimal reference value of V_{ref} according to the need of the operation based on the analysis results of it.

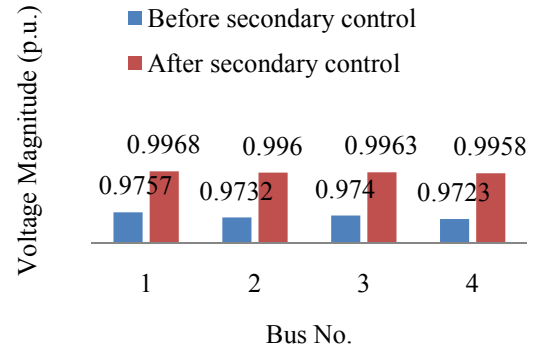


Fig. 4 Voltage profile comparison before and after secondary control

V. CONCLUSION

In this paper, a new algorithm of power flow analysis for droop controlled DC microgrid is proposed. Voltage droop control in the primary layer of the system has been taken into consideration in the power flow analysis for the DC microgrid. The algorithm verification is carried out by comparing the calculation results with detailed time domain simulation results. Compared with traditional methods, more accurate analysis results can be obtained, using the proposed algorithm. The proposed algorithm also makes it possible to analyze power sharing and secondary voltage regulation. Case studies on power sharing and secondary voltage regulation show that with the droop gain (virtual resistance) as a variable in the power flow analysis, effects of it on power sharing and secondary voltage regulation can now be analyzed, and the new analysis algorithm provides means for the upper level control layer to optimize the droop parameters beforehand.

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