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Stability analysis and dynamic energy management of PV-hybrid storage based DC microgrid

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Abstract. PV-hybrid storage based DC microgrid is an effective large-scale application of PV generation. In this paper, the stability of the PV-hybrid storage based DC microgrid is analyzed based on the source-load impedance model and the stability rule is presented. Furthermore, the dynamic energy management strategy of PV-hybrid storage based DC microgrid is developed to both ensure the stable operation of the DC microgrid and realize the full utilization of the PV generation energy. A downscaled DC microgrid experimental prototype is developed and the detailed experimental results validate the correctness and feasibility of theoretical analysis and energy management strategy.

1. Introduction

Regarded as the most effective route to solve the energy crisis and environmental disruption, the renewable energy, especially the PV generation technologies have attracted more and more attention in the world wide range[1-5]. Due to the feature of the PV panels, i.e., small generation power of a single unit and the generation power being sensitive to the solar intensity and environment temperature, it is still a challenge to realize the large scale application of the PV generation systems so far.

DC microgrid is an emerging multiple sources integration type. In a DC microgrid, it is allowed to connect the various kinds of renewable energy generators, including the PV generation system and wind generation system together to realize the power supply with a high performance. Based on the idea of the microgrid, it is easy to realize the integration of different generators and reduce the effect of the power variation of so many generators on the utility grid. For the DC microgrid, due to the DC character of the output voltage and current of the PV panel, the DC microgrid is very suitable for the large scale integration of the PV generation system to output a huge power[6-8]. As compared to the AC microgrid, the DC microgrid based large scale PV generation systems possesses the advantages of less cost, easy to implementation and so on[9].

There are mainly two types of DC microgrid for the PV generation systems integration. The first one is the grid-connected type, which is connected to the main power grid by an AC-DC converter. Another one is the standalone type, which is not connected to the main power grid. In the both types of DC microgrid, the energy storage systems, i.e., battery or supercapacitors (SC) based systems, are usually used to smooth the power ripple of the renewable energy generation systems. Because so many generators and energy storage systems and load are connected together in the DC microgrid, an energy management unit with a good energy management strategy is necessary for the DC microgrid to realize the stable operation[10-13]. In addition, the stability problem of the DC microgrid should also be considered carefully. Due to so many distributed devices connected together, all of them should be analyzed as a whole to obtain the global stability of the DC microgrid. The researchers have presented several management strategies related to DC microgrid in recent years[14-16]. In [14], a decentralized robust strategy for the hybrid AC-DC microgrid is presented to improve the stability and eliminate the effect of nonlinear unbalance loads. In [15], a decision-tree-based algorithm is used to control coordinately the electric vehicles, PV units and battery energy systems contained in the microgrid to increase the energy efficiency and reduce overall operational costs. In [16], a multi-level energy management and optimal control for the residential DC microgrid is proposed to ensure that the system is able to work at its optimal set points and increase the controllability.

In this paper, the stability issue of the standalone PV-hybrid energy storage DC microgrid is analyzed deeply and a dynamic energy management strategy is presented. The contribution of this paper is briefly described below. (1) The impedance model of the DC microgrid is built for the first time and the impedance constrained qualification between various sources and loads to realize the global stability is obtained based on the impedance analysis method. (2) A dynamic energy management strategy for the DC microgrid considering that the feature of the battery and SC is presented to realize the stable operation and high dynamic performance of the DC microgrid. An experimental platform with a small power is built to verify the theoretical analysis and the presented energy management strategy.

2. Structure and principle of PV-hybrid storage based DC microgrid

The schematic diagram of the PV-hybrid storage based DC microgrid is shown in Figure 1, which includes PV generation system, SC based energy storage systems, battery based energy storage systems and a power management system to coordinate the subsystems and loads together. The power management system adjusts the output power of various PV generation systems and various energy storage systems on-line according to the real-time power relationship between the sources and the loads, in order to realize the stable operation of the DC microgrid and the utilization of the PV systems with a high efficiency.

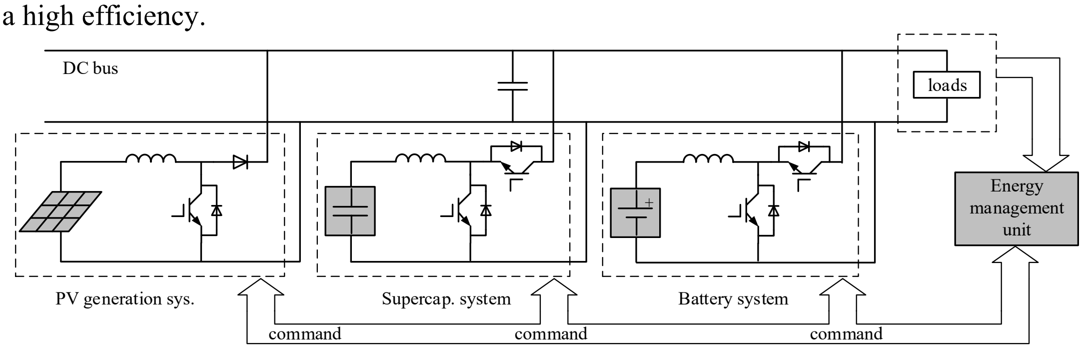


Figure 1. The schematic diagram of the PV-hybrid storage based DC microgrid.

As shown in Figure 1, due to so many distributed sources and loads contained in the DC microgrid, the stability of the entire DC microgrid should be considered carefully. The existing literature have pointed out that although each device can be stable independently, there is the possibility that the system becomes instable when so many devices operate in parallel. In this paper, the impedance analysis method is introduced to analyze the stability of the DC microgrid, and then the impedance constraints between the sources and loads are obtained to obtain the general stability conditions of the DC microgrid.

According to the impedance analysis method, loop impedance gain of DC microgrid T_Z is defined as

$$T_Z = \frac{Z_o}{Z_i} \tag{1}$$

where Z_o is the total output impedance of all the sources in DC microgrid, which can be described as

$$Z_o = Z_{o1} // Z_{o2} // \cdots // Z_{oM} \tag{2}$$

where $Z_{o1}, Z_{o2} \cdots Z_{oM}$ is the output impendence of each source. Z_i is the total input impedance of all the loads in DC microgrid,which can be described as

$$Z_i = Z_{i1} // Z_{i2} // \cdots // Z_{iN} \tag{3}$$

$Z_{i1}, Z_{i2} \cdots Z_{iN}$ is the input impendence of various sources. By combining all the sources and load together, the DC microgrid is equivalent to a single source and a single load, as shown in Figure 2. According to the classical control theory, the sufficient condition for system stability is T_Z does not encircling the (-1,j0) point on the complex plane, and the relative stability of the closed-loop system increases with the increase of the distance from (-1,j0) point to T_Z [13]. The gain margin and the phase margin are respectively expressed as

$$\begin{cases} GM = 20\lg K_g \\ PM = 180^\circ + \varphi(\omega_c) \end{cases} \tag{4}$$

where K_g is the non-logarithmic gain margin, which equal to the reciprocal of the open-loop amplitude-frequency characteristic $1/A(\omega_g)$ corresponding to the frequency ω_g at radian $-\pi$ of the phase-frequency characteristic, and $\varphi(\omega_c)$ is the phase angle of the shearing frequency ω_c .

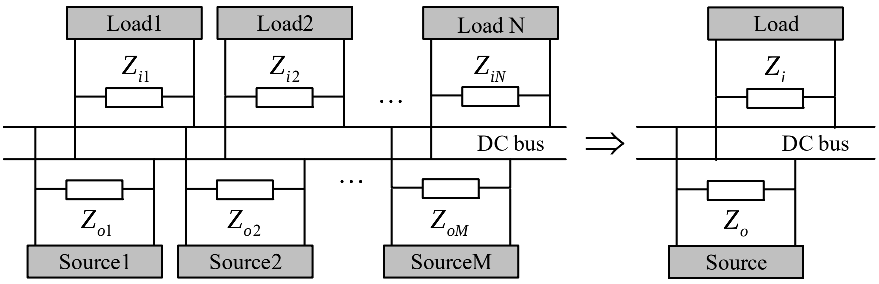


Figure 2. DC microgrid loop impendence equivalent diagram.

In this paper, $PM \geq 60^\circ$, $GM > 6\text{dB}$, are set as the forbidden region on the complex plane and they are defined as the phase margin and gain margin conditions[17, 18]. The system is unstable when T_Z is in forbidden region. Forbidden region can be described as:

$$\begin{cases} GM = 20\lg K_g < 6\text{dB} \\ PM = 180^\circ + \varphi(\omega_c) < 60^\circ \end{cases} \tag{5}$$

that is

$$\begin{cases} \dfrac{1}{K_g} > 0.5 \\ \varphi(\omega_c) \in [-180^\circ, -120^\circ] \cup [120^\circ, 180^\circ] \end{cases} \tag{6}$$

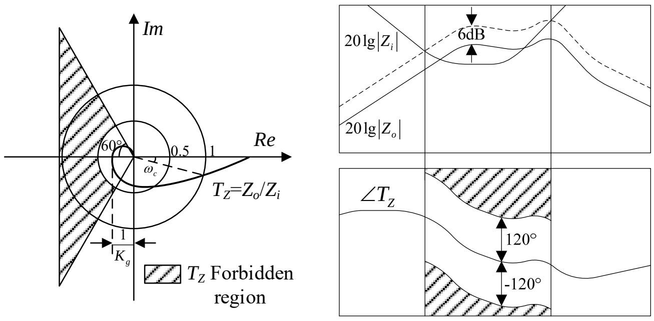
According to (6), the forbidden region is drawn on the complex plane and shown in the shadow of figure 3. And as long as the loop gain T_Z does not enter the forbidden region, the DC microgrid can operate stably. Impedance specifications can be obtained by setting the forbidden region:

(1) $|Z_o| < 0.5|Z_i|$, corresponding to the inner area of the circle in Figure 3(a) or the left and right regions in 3(b);

(2) $|Z_o| \geq 0.5|Z_i|$ and the phase angle difference of Z_o, Z_i at the cut-off frequency of loop gain T_Z does not exceed $\pm 120^\circ$, corresponding to the outer non forbidden region of the circle in Figure 3 (a), or the middle non cut-off region part of 3 (b).

If the total source and the total load of DC microgrid satisfy the above two impedance specifications, the DC microgrid is stable for small signal. Impedance specification (2) allows the output or input impendence to vary widely. In the design stage of DC microgrid with the design margin, the upper and lower limitations of the input and output impedances of the total source and total load can be deduced according to the power balance relationship, so as to satisfy the impedance specification condition, and then the absolute stability condition of DC microgrid can be obtained.

In addition, in the actual DC microgrid, the battery/capacitor based energy storage systems possess two operating modes, charging and discharging. When they are under charging mode, they are a ‘load’. However, when they are under discharging mode, they are a ‘source’. Limited by the page space, they are not analyzed separately and only the conclusion is described below.



(a) Nyquist curve (b) Pode curve

Figure 3. Nyquist forbidden region of loop gain T_Z.

The total source output impedance under charging mode of the energy storage systems is always greater than that under discharging mode of the energy storage systems. From the obtained impedance forbidden region that, if the relationship between the two source output impedance and total load input impedance under charging mode satisfies the above impedance constraint, the relationship of them under discharging mode must also satisfies this impedance constraint. From this point of view, the obtained impedance constraint should be used to guide the design of the DC microgrid under charging mode of the energy storage systems so that the DC microgrid is globally stable in various operating modes.

3. Dynamic energy management strategy for PV-hybrid storage based DC microgrid

In the PV-hybrid storage based DC microgrid, PV generation systems, the SC based systems and battery based systems can be operated as the power source of DC microgrid. Three sources cooperate with each other to maintain a stable operation of DC microgrid. According to the operating characteristics of these three sources, the dynamic operation process of DC microgrid can be classified into six modes and they are described as follows.

Mode1: When decreasing of light intensity or increasing of loads cause power shortage in a short time, the SC based systems supply the power difference between the sources and loads; when the light intensity returns to normal or loads decrease, the SC should be charged. The reason using SC but not battery is to avoid frequently charging or discharging of the battery thus the lift time of the battery can be prolonged.

Mode2: When decreasing of light intensity or increasing of loads cause the power shortage in a long time, battery based systems supply the power difference and the SC supply the wave power; when the light intensity returns to normal or the loads decrease, the battery should be charged first and then the SC will be charged.

Mode3: In Mode 2, if the energy stored in the SC is insufficient, the battery based systems supply the power difference; when the light intensity returns to normal or loads decrease, the battery should be charged first and then the SC will be charged.

Mode4: When PV generation system is shutdown at night, cloudy or rainy days, the SC based systems supply power to DC microgrid; when PV generation system generates sufficient power during the day time or sunny day, then the SC will be charged.

Mode5: On rainy days and heavy night loads, the battery based system supplies average power to DC microgrid, and SC provide the wave power; on sunny days, when the PV generation system is sufficient, the battery is charged first, and then the SC are charged.

Mode6: In Mode5, if the energy stored in the SC is insufficient, the battery based systems supply power to DC microgrid; when the PV generation system is sufficient, the battery is charged first, and then the SC are charged.

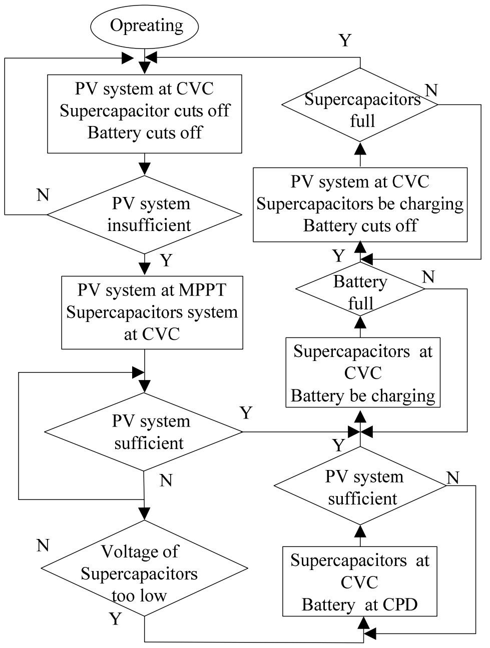
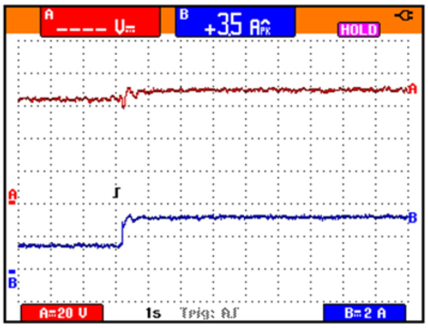


Figure 4. Flowchart of dynamic operation of the PV-hybrid storage based DC microgrid.

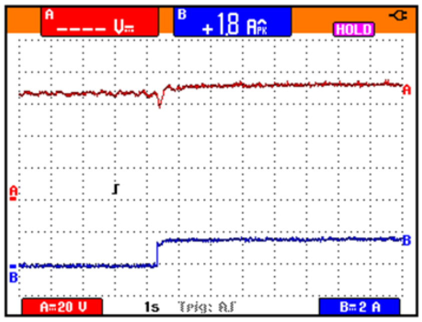
When the external factors such as day and night, weather, light intensity, load and the current state of each subsystem change, DC microgrid needs to switch its operation mode in the above six modes to maintain a constant voltage of DC bus. Considering switching conditions of each mode, the flow diagram of dynamic operation of the PV-hybrid storage based DC microgrid is shown in Figure 4. In this energy management strategy, the SC are mainly used to absorb the power fluctuation and the battery is mainly used to balance the long-term power between the PV panels and the loads. The reason is to reduce the overall cost of the DC microgrid and avoid the frequent charging/discharging of the battery to prolong its life time. In theory, the DC bus voltage can be constant if the power always keeps balance between the sources and loads. Considering that the control error and the line loss, in some situation, the PV panels, battery or SC should work at constant voltage control mode (CVC) to keep the DC bus voltage constant.

4. Experimental verification and discussion

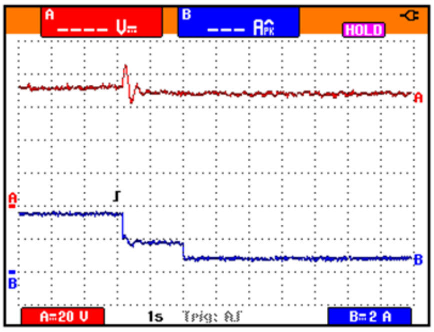
In order to verify the above theoretical analysis and presented dynamic energy management strategy, a downscaled experimental prototype of DC microgrid containing a PV generation system and a battery and SC energy storage systems driving a resistive load is built. The DC link bus voltage is set as 70V. Limited by the page space, only the case that the maximum generation power of the PV panel is less than the step-increasing load is considered. The corresponding experimental results are shown in Fig. 5. First, a resistor is connected suddenly to the DC bus. In this case, both PV and SC should output the power to balance the load power and keep the DC bus voltage constant. Furthermore, the PV generation system works at it's the maximum power point and the rest power is complemented because the actual load power is greater than the maximum generation power of the PV panel. From Fig. 5(a) and (b), when the resistor is suddenly connected to the DC bus, the actual DC link voltage reduces first for a short time and returns to the reference immediately. The PV panel outputs its maximum power and the sum of the output power of the PV panel and SC is equal to the load power. In addition, the performance of the load step down is tested and the corresponding experimental results are shown in Fig. 5(c) and (d). From Fig. 5(c) and (d), after the resistor is removed from the DC bus, the DC link voltage increases first and then returns to the reference because the PV generation systems reduces its output power immediately. It is worth to notice that the output current of the SC is less than zero but not equal to zero. It is because that the supercapicatior should be charged as soon as possible after the load power is less than the maximum output power of the PV panel so that the SC can get ready for the next dynamic process.



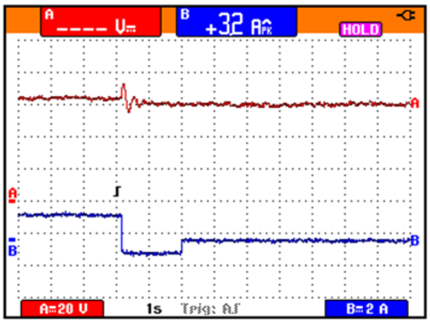
(a) Output current of PV generation system when load step up



(b) Output current of SC when load step up



(c) Output current of PV generation system when load step down



(d) Output current of the SC when load step down

Figure 5. Experimental waveform of PV-hybrid storage based DC microgrid.

In addition, from Fig. 5, in these various scenarios, the DC bus voltage always keeps constant and there is no resonant components in it. It means that the dynamic management strategy realizes the effective energy control and the DC bus voltage control. More importantly, the parameters of various subsystems are designed based on the impedance constraint and thus the entire DC microgrid is stable and the experimental results also validate it.

5. Conclusions

By analyzing the impedance characteristics of the PV-hybrid storage based DC microgrid, the general impedance constrained qualification between the source output impedance and the load input impedance is obtained to ensure the small-signal stability of the DC microgrid. Furthermore, the dynamic energy management strategy of the entire DC microgrid considering various operation modes is presented to ensure the stable operation even when the actual PV generation power and load power vary in a wide range. The research results are helpful to guide the design and control of the PV-hybrid storage based DC microgrid and finally realize the operation of the DC microgrid with a high performance.

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