# A Droop Based Controller for Super-capacitor to Compensate the Transient Current and Pulsed Load in DC Microgrid

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***Abstract*—This paper presents a new control method for Supercapacitor (SC) to compensate the transient load current and support the system under the pulsed load. Moreover, the cooperative operation of the multiple SC in DC microgrid is also ensured by proportionally sharing the support current between the SC units. The current sharing between the SC units is achieved by means of the droop control concept which is innovated to adapt in SC control. The conventional droop control is modified so that it can adaptively change its operation mode and parameters in order to compensate the load transient current and regulate the state of charge of the SC. The effectiveness of the proposed method is investigated and evaluated by an experimental DC microgrid prototype. The experimental results prove that the proposed method can achieve high performance and seamless control.**

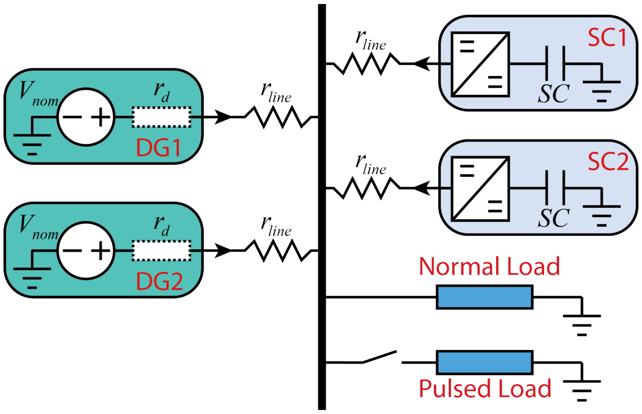


Fig. 1. Typical DC microgrid with Supercapacitor.

## I. INTRODUCTION

Microgrid becomes a spotlight in energy infrastructure development thanks to the ability of various resources combination and flexibility in controlling [1]–[3]. Together with the AC grid system, the AC microgrid has been focused and developed in these days. However, the renewable resources such as solar panel and fuel-cell have the DC characteristic which is hard to integrate into the AC grid system. Nowadays, DC microgrid has been considered to compensate AC microgrid. The energy that is harvested from the renewable resource depends on the nature conditions, so it is necessary to store and stabilize the harvested energy. In order to stabilize the energy in DC microgrid, the battery energy storage system (BESS) is one of the most promising solutions. So, the BESS should has an ability to quickly provide the mismatch power between the reference power and the heavested power with high power density and energy density. However, none of the recent BESS technology can provide high power density together with high energy density. Fortunately, the supercapacitor has high power density which can be used to compensate the fluctuation of the loads and source currents.

Fig.1 shows A DC microgrid composed of different distributed generations (DGs) and the SCs, where each DG unit is connected to a common DC bus via a DC-DC converter. BESS plays an important role in DC microgrid by supporting the transient high-power and dispatching the fluctuation power of RES [4]. To improve the performance of BESS, SC is used to compensate the mismatch current caused by the limitation of BESS power density. The recent proposed control methods for SC converter are divided into two group: 1) high-pass filter method and 2) virtual capacitance method. The high-pass filter method uses a high-pass filter to generate the reference output current [5]–[7]. This method is easily implemented, however, the cooperation of multiple SC units in the system is not guaranteed. To overcome this problem, the virtual capacitance method (VCM) is proposed [8]–[10], and it becomes popular because it has some advantages such as easy control and effective cooperation of multiple SC units. Unfortunately, both of high-pass filter method and VCM are need an additional controller to regulate the state of charge (SoC) of SC, so that the SC unit must change its operation mode from supporting the microgrid mode to regulating the SoC mode. Many methods have been presented to balance and recover the SoC of SC units, but none of them can operate seamlessly [10]. In low-voltage DC microgrid, the pulsed load should be considered [11]; the pulsed load such as the laser head, drill head, and motor drivers, withdraws a large amount of current in a short time. It makes the system operate under overload condition and unstable. Because of the limited power density, the BESS cannot supply and support the microgrid under the pulsed load condition, and also the recent SC control methods is hard to supply DC current in short interval to support the BESS. In this paper, we propose a droop based control method to compensate the transient load current for the pulsed load, and to seamlessly regulate the SoC

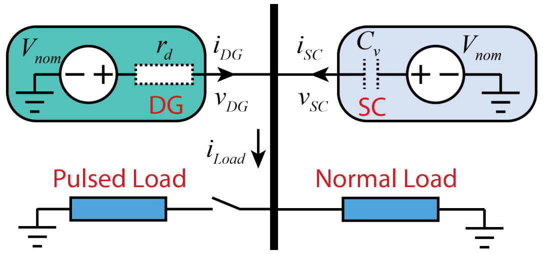


Fig. 2. Conventional virtual capacitance control method for SC.

of SC without any interruption. According to the SoC of SC and load condition, the nominal voltage of droop control is adjusted, and it helps SC converter to change its operation mode and provide the current to compensate the load variation and regulate the SoC at the same time. The effectiveness of the proposed method is evaluated by a typical DC microgrid prototype.

## II. SYSTEM CONFIGURATION AND CONVENTIONAL CONTROL METHOD

A typical DC microgrid including the SC units is shown in Fig. 1, where the sources and loads are connected to a common DC bus. The SC units are used to compensate the current mismatch between the DGs and the loads to operate the microgrid system effectively. In DC microgrid, the droop control is commonly used for the load sharing among the DGs. The relationship between the output voltage and output current of ith DG is expressed as

$$v_i = V_{nom} - i_i r_{di} \tag{1}$$

where and are the output voltage and the current of $i^{th}$ DG, respectively, and is the droop coefficient which is regarded as the virtual resistance of ith DG. By replacing the virtual resistance by virtual capacitance, the virtual capacitance method (VCM) is used for SC to compensate the transient current of the loads. As shown in Fig. 2, the conventional VCM is modeled as a voltage source connected with a series capacitor.

The relationship between the output voltage and the current of SC unit is expressed as

$$v_j = V_{nom} - \frac{1}{C_j s} i_j \tag{2}$$

where $v_j$ and $i_j$ are the output voltage and current of $j^{th}$ SC unit, respectively, and $C_j$ is the virtual capacitance of VCM. As the droop coefficient is much higher than the line impedance, the line impedance is neglected in these following calculations. From Fig. 2, the output voltages and currents are expressed as

$$\begin{cases} v_{DG} = V_{nom} - r_d i_{DG} \\ v_{SC} = V_{nom} - \dfrac{1}{C_v s} i_{SC} \\ i_{Load} = i_{DG} + i_{SC} \end{cases} \tag{3}$$

When the SC is used to compensate the transient loads current, the sharing currents between DGs current and SC current are obtained in (4) from (3):

$$\begin{cases} i_{DG} = G_1(s) i_{Load} = \dfrac{1}{s r_d C_v + 1} i_{Load} \\ i_{SC} = G_2(s) i_{Load} = \dfrac{s r_d C_v}{s r_d + 1} i_{Load} \end{cases}. \tag{4}$$

From (4), we can see that the loads current is shared between SC and DG by a low pass (LP) filter and a high pass (HP) filter. The low frequency component is handled by DG while the high frequency component is handled by SC. The cut-off frequency of LP and HP filter is calculated as

$$\omega_c = \frac{1}{r_d C_v} \tag{5}$$

From (5), the current rate change, which is affected by the cut-off frequency of , depends on the droop coefficient . On other hand, the current rate change is secured by the characteristic of the DG source (such as battery, fuel cell…). However, the droop coefficient is chosen by the rated current of DG, and it can be changed by the system reconfiguration. Thus, the cut-off frequency is changed and it affects the performance of the system.

Moreover, because the output current of the SC converter only contains the high frequency component of the load current from (4), the SC converter cannot supply a DC current to support the microgrid when a pulsed load is connected to the DC bus. As a result, the DC bus voltage is highly dropped because the DG converters operate under the overload condition.

In practical applications, the losses of DC-DC converters and the random connection of the loads makes the SC units operate with unbalanced power flow from the charge and discharge modes. Therefore, the SoC of SC unit is not regulated after an interval of operation.

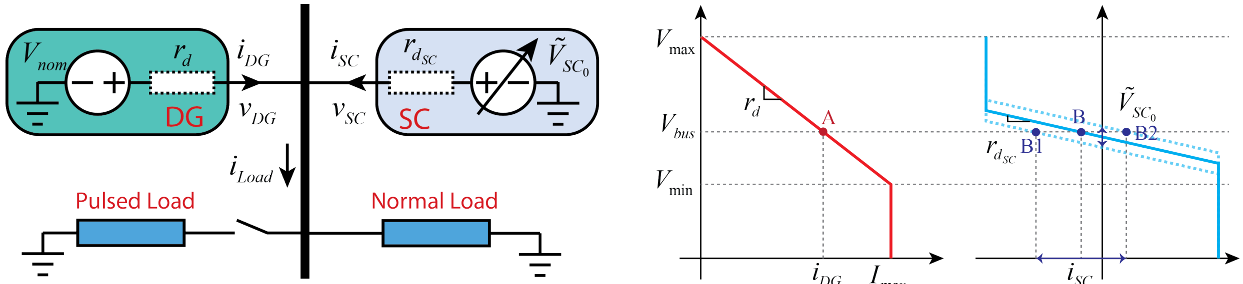
## III. PROPOSED DROOP BASED CONTROLLER FOR SC CONVERTER

### *A. Droop Conntrol Method for SC*

As shown in Fig. 3, the SC converter in our proposed method is modelled as a variable voltage source $\tilde{V}_{SC_0}$connected in series with a resistor $r_{d_{SC}}$ as

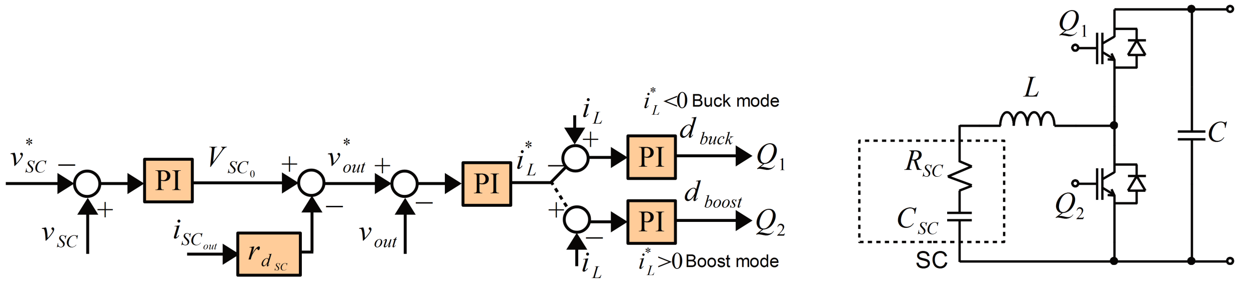
$$v_{SC} = \tilde{V}_{SC_0} - r_{d_{SC}} i_{SC} \tag{6}$$

The SC converter controls to compensate the load transient current and the SC state of charge (SoC) simultaneously; the objective of the proposed method is compensating the load transient current as well as regulating the SoC of SC. The droop coefficient of SC converter is chosen to be very small compared with the droop coefficient of DG converter. From Fig. 3(a), the output current of DG and SC are given as follows:



(a) (b)

Fig. 3. Proposed control method (a) model and (b) droop curves.



(a) (b)

Fig. 4. (a) Control diagram of the proposed method, and (b) SC converter.

$$\begin{cases} i_{DG} = i_l \dfrac{r_{d_{SC}}}{r_d + r_{d_{SC}}} + \dfrac{V_{nom} - \tilde{V}_{SC_0}}{r_d + r_{d_{SC}}} \\ i_{SC} = i_l \dfrac{r_d}{r_d + r_{d_{SC}}} - \dfrac{V_{nom} - \tilde{V}_{SC_0}}{r_d + r_{d_{SC}}} \end{cases} \tag{7}$$

where $i_l$, $i_{DG}$ and $i_{SC}$ are the load current, DG and SC output currents, respectively. From (7), as $r_{d_{SC}}$ is very small compared with $r_d$, the high frequency component of $i_l$ much reduces its effect on the DG current $i_{DG}$ because $r_{d_{SC}}/(r_d + r_{d_{SC}})$ is neglectable. Hence, the output current of DG is dependent on the variable voltage source $\tilde{V}_{SC_0}$.

On the other hand, the output current of the SC converter has only high frequency component of the load current $i_l$ as the ratio $r_d/(r_d + r_{d_{SC}})$ is approximated as unity. Therefore, by properly controlling the variable voltage $\tilde{V}_{SC_0}$, the load current can be shared between DG and SC based on the frequency range.

The SoC of SC is indicated by the SC voltage level. So, by regulating the SC voltage $v_{SC}$, the SoC of SC is also guaranteed at nominal level. In this paper, the nominal operation point of SoC is 70% which is regarded as the SC voltage level at $v^*_{SC}$. For illustrating the operation of the proposed method, the droop curves of DG and SC converter are shown in Fig. 3 (b). Initial, the operation point of DG is at point A and the SC is at point B. If the SoC of the SC is higher than rated level, the value of $\tilde{V}_{SC}$ is adjusted slowly so that the operation point of bSC is changed to B2, where the SC operates at discharge mode. In vice versus, if the SoC of SC is lower than rated level, the operation point of SC is slowly changed to B1where the SC operates in charge mode. Therefore, the SoC of SC can be automatically restored. Moreover, by using droop control, multiple SC converter can operate normally.

## B. Controller Design

Fig. 4 shows the control diagram of the proposed method; there are three control loops: inner current control loop, inner voltage control loop and outer SC voltage control loop.

The inner current and voltage control loops are implemented by PI controllers. The output of the voltage control loop is the inductor current reference $i^*_L$and it is described as

$$i^*_L = \left(k_{Pv} + \frac{k_{Iv}}{s}\right)\left(v^*_{out} - v_{out}\right), \tag{8}$$

where $k_{Pv}$and $k_{Iv}$are PI gains of voltage controller, $v^*_{out}$ and $v_{out}$ are the output voltage reference and actual output voltage, respectively. There are two operation modes for the bidirectional Buck-Boost converter (BBBC), therefore, the current control loop must be implemented for two modes. When the inductor current reference is greater than zero, the BBBC operates in Boost mode and the inner current loop can be described as

$$d_{boost} = \left(k_{P{c_{boost}}} + \frac{k_{I{c_{boost}}}}{s}\right)\left(i^*_L - i_L\right), \tag{9}$$

where $d_{boost}$ is the duty cycle for the switch $Q_2$, $k_{P{c_{boost}}}$and $k_{I{c_{boost}}}$are the gains of PI for Boost mode current controller. When the inductor current reference is smaller than zero, the

BBBC operates in Buck mode and the inner current loop can be described as

$$d_{buck} = \left( k_{P c_{buck}} + \frac{k_{I c_{buck}}}{s} \right) \left( -i_L^* + i_L \right), \qquad (10)$$

where $d_{buck}$ is the duty cycle for the switch $Q_1$, $k_{P c_{buck}}$ and $k_{I c_{buuck}}$ are gains of PI for Buck mode current controller.

The inner current and voltage control loops are designed as follows: The cut-off frequency of the inner current loop $\omega_{cc}$ is $1/10$ of the switching frequency $\omega_s$, and the cut-off frequency of the voltage loop $\omega_{vc}$ is $1/10$ of $\omega_{cc}$ . For choosing the gains of inner current and voltage loop controllers, the method in [12] can be used. With the chosen gains, the closed loop gain $G_{inner}(s)$ of the inner loop controller can be seem as unity when designing the outer SC voltage control loop.

As we can see in (7), the changing rate of the variable voltage $\tilde{V}_{SC_0}$ decides the changing rate of DG current. Hence, the outer voltage control loop should be designed to make its changing rate close to the desired value of the changing rate of DGs current, which is decided by the cut-off frequency of the SC voltage control loop. The outer SC voltage control loop can be described as

$$\tilde{V}_{SC_0} = \left( k_{Pvsc} + \frac{k_{Ivsc}}{s} \right) \left( v_{SC} - v_{SC}^* \right) \qquad (11)$$

where $k_{Pvsc}$ and $k_{Ivsc}$ are the PI controller gains, $v_{SC}$ and $v_{SC}^*$ are the output and reference voltage level of SC. The PI gains are chosen so that the cut-off frequency of outer voltage control loop is satisfy the changing rate of DG current.

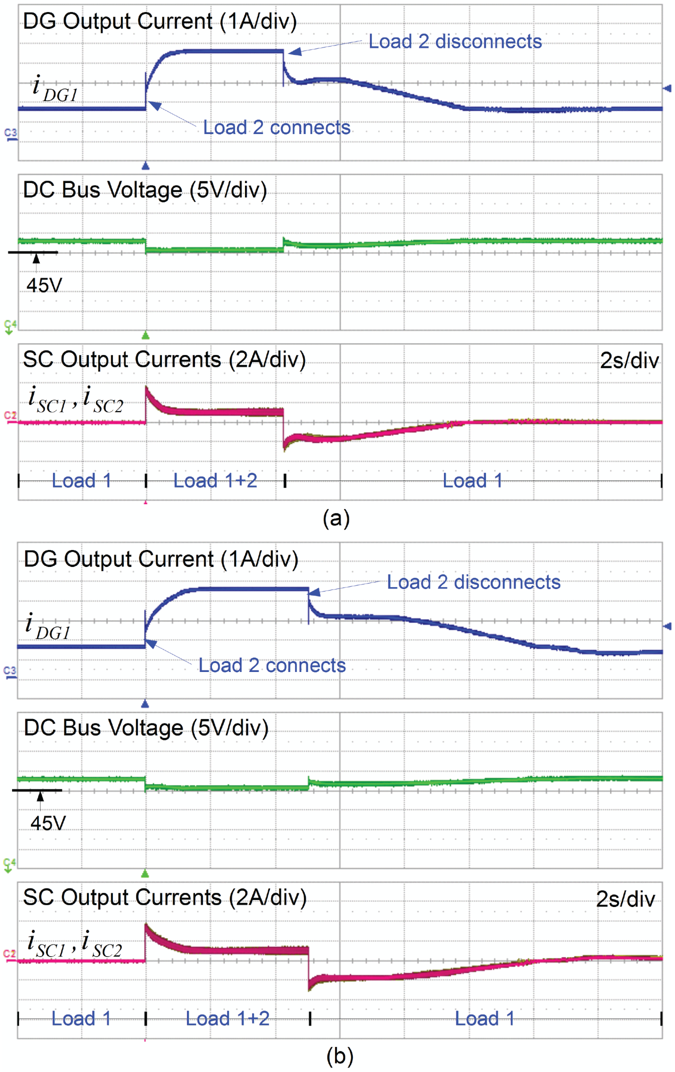
## IV. Experimental Results

In order to evaluate the proposed method, the DC microgrid in Fig. 1 is implemented. Two DG converters are controlled by a DSP TMS320F28379D control board and another DSP control board is used for two SC converters. The parameters of SC converters and microgrid are shown in table I. The normal load is always connected to the DC bus while the pulsed load is connected with a short interval. The performance of the proposed method is evaluated with different conditions: different PI gains of the outer SC voltage control loop; different droop coefficients and initial SoC values.

The dynamic performance of the proposed method with different gains of the outer SC voltage control loop is shown in Fig. 5. In this case, the SC converter droop coefficients are set the same between SC1 and SC2. With higher PI gains, the cut-off frequency of the outer SC voltage also becomes higher. Then, the output currents of DGs and SCs reach its steady state in Fig. 5(a) faster than those shown in Fig. 5(b). By means of the SC converter, the DC bus voltage is regulated within the allowable range in Table I under the pulsed load condition. Moreover, the when pulsed load is disconnected, the proposed method regulates the SC converter to restore the SoC, and also keeps the change rate current of DG within its limitation.

TABLE I
THE PARAMENTER OF DC MICROGRID.

| Parameters | Symbol | Value |
|---|---|---|
| DC bus voltage | $V_{bus}$ | $45-48V$ |
| DG droop coefficient | $r_d$ | 0.5 |
| SC droop coefficient | $r_{dSC}$ | 0.05 or 0.1 |
| SC specification | $V_{SCi_{rated}}, C_{SCi}$ | $32V, 28F$ |
| Normal load | Load 1 | $10\Omega$ |
| Pulsed load | Load 2 | $5\Omega$ |



(a)

(b)

Fig. 5. Dynamic performance of the proposed method when PI gains of the outer voltage loop are (a) $k_{Pvsc} = 3$ and $k_{Ivsc} = 7.5$, (b) $k_{Pvsc} = 1.5$ and $k_{Ivsc} = 3.75$

In order to evaluate the cooperative operation of the proposed method, two SC converters are set the different droop virtual impedance as $r_{d_{SC1}} = 0.1$ and $r_{d_{SC2}} = 0.05$ while the PI gains of the outer SC voltage control loop are $k_{P_{vsc}} = 0.5$ and $k_{I_{vsc}} = 1.25$. As shown in Fig. 6, the output current $i_{SC1}$ of SC1 is half of $i_{SC2}$ as the droop coefficient $r_{d_{SC1}} = 2r_{d_{SC2}}$. The output currents of the SC converters are kept at the deserved ratio 1:2 which is decided by the droop coefficient in both charge and discharge mode.

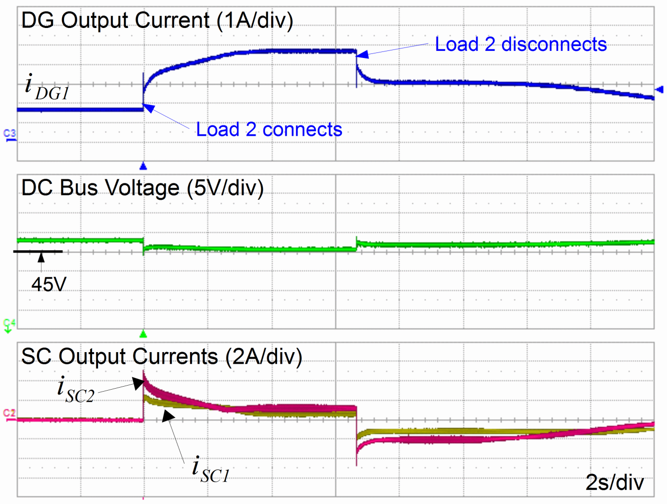


Fig. 6. Current sharing of SCs when droop coefficients are $r_{d_{SC1}} = 0.1$ and $r_{d_{SC2}} = 0.05$

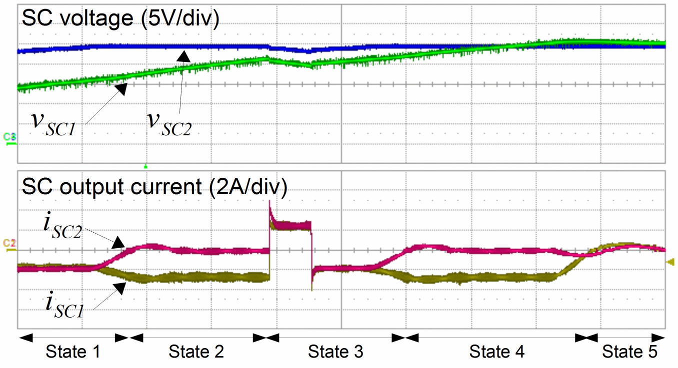


Fig. 7. SoC regulation of the proposed method.

The operation of the proposed method with difference of initial SoC values is tested and the result is shown in Fig. 7. In state 1, both SC1 and SC2 are charged to restore their SoCs. When the SC2 is fully restored, the proposed method changes to state 2; the current of SC2 reduces to zero, while SC1 increases its charging current. In state 3 when a pulsed load is connected, both SC1 and SC2 are controlled to support the DC microgrid with a same sharing ratio; at the moment that pulsed load is disconnected, both SC1 and SC2 automatically change their mode to regulate the SoCs in state 4. When both SCs are fully charged, it changes to state 5; SC1 and SC2 reach their steady state with zero output current. So, the SoCs of SC1 and SC2 are balanced even the initial values are different.

The experimental results show that the proposed method can effectively compensate the load current variation due to the normal load as well as the pulsed load, and also the SoC of SC is automatically regulated.

## V. CONCLUSIONS

This paper presented a droop based control method for the SC converter to compensate the transient normal load current as well as the pulsed load current together with the automatic SoC restoration. By actively adjusting the nominal voltage of the droop controller, the proposed method supplies the spike current to compensate the transient load current and support the system under the pulsed load condition. Moreover, the SoC of the SC units are automatically regulated to be balanced. By using the droop control concept, the parallel operation of multi SC units is guaranteed, and the power sharing ratio is manipulated by the droop coefficient. The performance and effectiveness of the proposed control method are verified by the experimental results.

## ACKNOWLEDGMENT

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