Terminal Capacitor Compensation Based Stability Design for DC Microgrids

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***Abstract*—This paper investigates the detailed elements of a DC microgrid that might cause instability, and proposes a stabilizing guidance based on the passive stability criterion. For illustration purpose, the terminal output impedance model of a source side power converter under double loop with droop control is built, and its frequency characteristics are analyzed. It is found that the instant high power absorption from the microgrid might make the source side power converter's output to oscillate. The details of how the circuit and control elements in the source side impact the terminal impedance are illustrated. This paper shows that the stability of plug and play performance of DC microgrid can be guaranteed with the proposed stabilization methods. A Matlab/Simulink model is used to validate the analysis.**

Keywords*—*DC microgrids, output impedance, passive stability criterion, stability

I. Introduction

With the modern power electronics development and rapid penetration of renewable energy sources, microgrid [1] is regarded as an effective power distribution structure for the clean energy. DC microgrids have been popular due to the advantages [2][3] of higher efficiency, reliability and flexibility over AC system. A sample DC microgrid is shown in Fig.1. It mainly includes distributed power generations, energy storage systems, loads and controllable load, such as electrical vehicles (EV), etc.

EVs have started to play an important role in power systems. They can be used to participate in the power regulation and management, and make the system more flexible and reconfigurable. For EV-alike controllable loads, plug and play performance is required. However, when connecting EVs to a DC microgrid, instability might occur during the fast charging process of EVs because of the impedance alteration, which indicates the instant high power consumption from DC Microgrids.

The linear analysis of DC microgrids (or distributed power systems) stability is mainly concentrated on the impedance inequality analysis, which is developed from Middlebrooks' stability criterions [4], and also called minor loop gain (MLG) analysis. Conventional MLG based impedance analysis [5][6] suffers from the component grouping and has limitation on

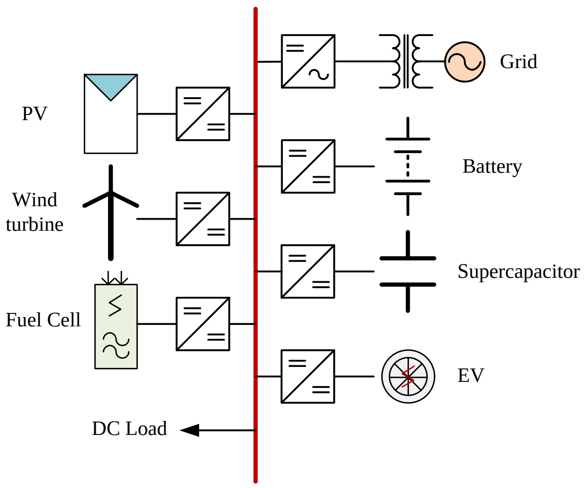

Fig. 1 DC microgrids configurations

system scale stability analysis. The guidance for terminal filter design, which is bulky, complex in configuration and not cost-effective due to its conservativeness. Passive theory based frequency stability criterion [7][8][9] provides an effective way for analysing the meshed complex system. The impedance inequality used in the stability criterions of [5][6] is no longer needed, and only the total terminal impedance of the system needs to be considered. This saves a lot of work on analysing terminal impedance. This criterion points out that if the terminal impedance is passive, then the system is stable. However, the dynamic terminal impedance models of whole system are difficult to attain if it contains different power electronic converters, and normally requires dedicated equipment to measure. Based on this one terminal impedance analysis, paper in [10] furtherly develops the passive stability criterions. The total terminal impedance constraint then can be released to the output impedance (for source side) of each individual interface converters, and a passive controller for the system can be proposed. Self-stable individual power converters can then be more adapted to the DC microgrids, and more correspondent to the requirements of plug and play operation. However, in practical, it is usually difficult to change the internal controllers for commercial off-the-shelf products. This paper mainly focuses on the impedance study from the sources side, but it should be noted that for the load side, the constant power load will react the negative incremental impedance, which is also one of the instability factors of DC microgrid.

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It has been found that the terminal output impedance of interface converter reacts negative values over high frequency range. This paper specifically analyzes the elements on both circuit and control blocks that involves the forms of negative values over high frequency, and find out that the load power is main factor that impacts the negative output impedance. Large load power will lead to larger negative output impedance over high frequency. The output capacitor of interface converter can be used to reduce the value of negative output impedance. Based on this result, this paper proposes a method of terminal capacitor compensation to stabilize the DC microgrid system when the EV carries out fast charging process.

The rest of this paper is organized as follows: Section II briefly introduces the passive stability criterions. Section III provides the terminal output impedance modeling of a Boost converter. Specific elements that involves in high frequency negative impedance are pointed out. A simulation case study based on the analysis is shown in Section IV. Finally, the conclusions and future works are illustrated in Section V.

II. Passive Stability Criterion

A. Brief Introduction

Passivity is an energy-related term and indicates that a passive system tends to consume the power. Considering the one port linear time invariant (LTI) system shown in Fig. *2*,

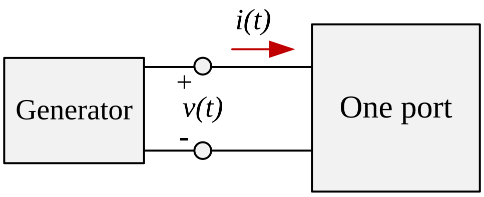

Fig. 2 One port unknown LTI system.

the energy delivered to the one port system from time t_0 to t can be written in equation (1).

$$W(t_0, t) = \int_{t_0}^{t} v(t')i(t')dt' \quad (1)$$

The one port system is said to be passive (otherwise active) if the following energy inequality is satisfied,

$$W(t_0, t) + \varepsilon(t_0) \geq 0 \quad (2)$$

where $\varepsilon(t_0)$ is the energy storage in the one port system at t_0.

The above equation (2) shows that the total energy (stored and delivered) from t_0 to t should be a non-negative under all circumstances, which means the one port system contains the power consumption terms. However, the above form is difficult to be used for linear analysis in real scenario. It is necessary to represent its passivity using transfer functions.

B. Passive Stability Criterion

A impedance transfer function $Z(\cdot)$ of complex variable s is said to be positive real if

- $Z(\cdot)$ is a rational function of s with real coefficients;
- $Re(s) > 0$ implies $Re[Z(s)] \geq 0$

The second constraint implies $Re[Z(j\omega)] \geq 0$ by continuity for all defined ω. In real power electronic applications, ω could be bounded under switching frequency. If the system total impedance is passive, then the system is always stable based on the passive stability criterion.

The DC microgrids is a joint system with many paralleled interface converters. Therefore, the total one port impedance can be easily attained. Considering the DC microgrid shown in Fig. *3* below:

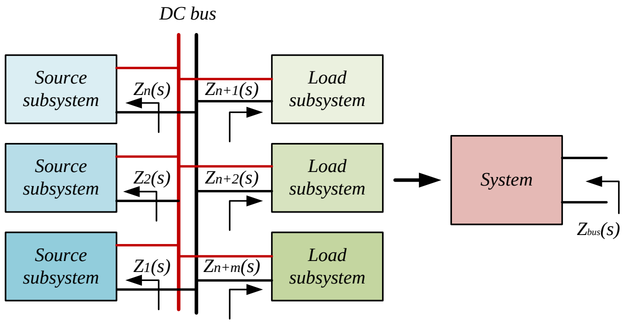

Fig. 3 DC microgrid impedance distribution.

The total DC bus impedance can be written in equation (3):

$$Z_{bus} = \left(\sum_{i=1}^{n} \frac{1}{Z_i} + \sum_{j=1}^{m} \frac{1}{Z_{n+j}}\right)^{-1} \quad (3)$$

where $Z_1, Z_2, \cdots, Z_n$ is the output impedance of source side converters; $Z_{n+1}, Z_{n+2}, \cdots, Z_{n+m}$ is the input impedance of load side converters; Z_{bus} is the total terminal impedance of the whole system.

From the equation (3), it can be seen that the total DC bus impedance is just sum of each individual interface converter. As for the passive stability criterion, the only requirement to guarantee the DC microgrid system stability is the total DC bus impedance is passive, or in the other way, the impedance function is positive real. It can be proved that if $Z(s)$ is passive, then $1/Z(s)$ (admittance) is passive too. This is useful for DC microgrids impedance analysis because all the interface converters are connected in parallel. The total impedance can then be the sum of individual admittance. Besides, it can also be proved that if each individual terminal impedance is positive real, then the total DC bus impedance is positive real bounded. However, if the total DC bus impedance is positive real, it does not require all the interface converters positive real. Therefore, requirement of individual passivity is not necessary. This will be furtherly discussed in the following section.

III. Moedling of Interface Converter

In this section, a bidirectional Boost converter is used as an example to discuss the terminal output impedance of interface converter.

A. Admittance Modeling

The Boost converter circuit diagram is shown in Fig. 4. The inductor and capacitor equivalent series resistance are not considered for calculation convenience.

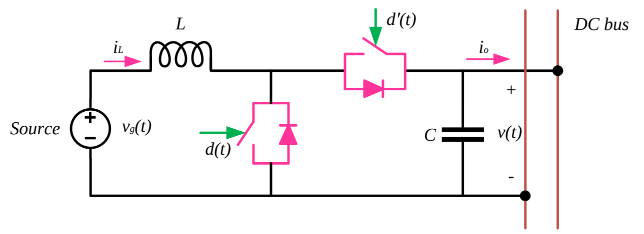

Fig. 4 Circuit of interface converter—bidirectional Boost type.

The average state functions of a Boost converter are:

$$\begin{cases} L\dfrac{di_L(t)}{dt} = v_g(t) - d'(t)v(t) \\ C\dfrac{dv(t)}{dt} = d'(t)i_L(t) - i_o(t) \end{cases} \tag{4}$$

where L is inductor; C is output capacitor; v_g is input source; i_L is inductor current; v is output voltage; i_o is output current; d is the duty cycle; and d' equals to $1 - d$.

Transferring above equations into s domain, equation (5) can be attained:

$$\begin{cases} i_L(s) = \dfrac{v_g(s) - d'(s)v(s)}{sL} \\ v(s) = \dfrac{d'(s)i_L(s) - i_o(s)}{sC} \end{cases} \tag{5}$$

Applying small signalling analysis, the derivative of equation (6) can then be attained:

$$\begin{cases} \Delta i_L(s) = \dfrac{\Delta d(s)V - D'\Delta v(s)}{sL} \\ \Delta v(s) = \dfrac{-\Delta d(s)I_L + D'\Delta i_L(s) - \Delta i_o(s)}{sC} \end{cases} \tag{6}$$

where Δ represents small signal variation of the correspondent parameters. Therefore, the dynamics of circuits functions are attained.

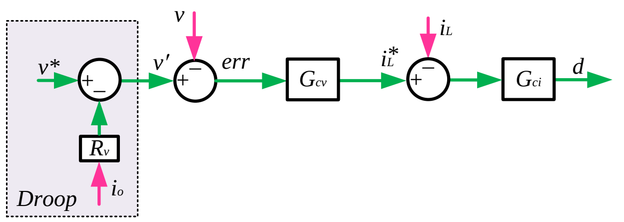

Fig. 5 Control blocks with droop control for interface converter.

Next, considering the closed loop controllers as shown in Fig. 5, the dynamics of the controller can also be attained. The controller contains two parts, the first one is initial double loop controller, and the other one is introduced droop controller. Similarly, applying small signal analysis on the control blocks as shown in Fig. 5, equations (7) and (8) can be attained:

$$\Delta i_L^* = -(R_v\Delta i_o + \Delta v)G_{cv} \tag{7}$$

$$\Delta d(s) = (\Delta i_L^* - \Delta i_L)G_{ci} \tag{8}$$

Combining above two equations, $\Delta d(s)$ can then be calculated by equation (9):

$$\Delta d(s) = -((R_v\Delta i_o + \Delta v)G_{cv} + \Delta i_L)G_{ci} \tag{9}$$

By sorting and solving above equations from (6) to (9), the terminal output admittance can eventually be attained as shown in equation (10),

$$Y_o = -\frac{\Delta i_o(s)}{\Delta v(s)} = \frac{-G_{cv}G_{ci}I_L sL + D'G_{cv}G_{ci}V + D'^2 + G_{ci}I_L D'}{(G_{ci}V + sL) - (sL)R_vG_{cv}G_{ci}I_L + D'R_vG_{cv}G_{ci}V} + \frac{sC(G_{ci}V + sL)}{(G_{ci}V + sL) - (sL)R_vG_{cv}G_{ci}I_L + D'R_vG_{cv}G_{ci}V} \tag{10}$$

where $G_{ci} = G_{im}(1 + \frac{\omega_{zi}}{s})$ is inner loop controller; $G_{cv} = G_{vm}(1 + \frac{\omega_{zv}}{s})$ is outer loop controller.

B. Model analysis

Based on the passive stability criterion, the two terms (denote as A and B) on numerator and dominator in equation (10) that might pose negative value.

$$A = sG_{ci}(CV - G_{cv}I_L L) \tag{11}$$

$$B = (sL)(1 - R_vG_{cv}G_{ci}I_L) \tag{12}$$

Negative value in the numerator is caused by the inner double loop and the negative value in the dominator is introduced by the droop control. Intuitively, the negative values on the numerator is related to the inner loop controller and the two energy storage elements. The negative value on the dominator is virtual resistance directly related, and also load power, both inner on outer loop controllers. However, this positive real constraint only keeps terminal admittance conservatively passive from mathematical perspective while it is useful for engineering analysis.

First of all, if we let $R_v = 0$ and then study the negative values on the numerator. The terminal output impedance is then altered to be as equation (13) shows.

$$Y_o = -\frac{\Delta i_o(s)}{\Delta v(s)} = \frac{-G_{cv}G_{ci}I_L sL + D'G_{cv}G_{ci}V + D'^2 + G_{ci}I_L D'}{(G_{ci}V + sL)} + sC \tag{13}$$

The negative value occurs over high frequency range, so arbitrarily let $s \to +\infty$, the asymptotic of terminal admittance of inductor part is shown in equation (14).

$$Y_o \to \frac{-G_{vm}(s)G_{im}(s)I_L sL}{s^2 sL} = -G_{vm}G_{im}I_L \tag{14}$$

It can be seen that the negative admittance is directly related to the load power. The terminal capacitor can compensate the negative value from equation (11). Adding the terminal capacitor can pull the negative value toward the positive directions based on equation (11).

The diagram of output admittance with increased capacitor is shown in Fig. 6. it can be seen that increasing the capacitor can pull the real part towards the positive axis, which is coincides with the analysis from above equations.

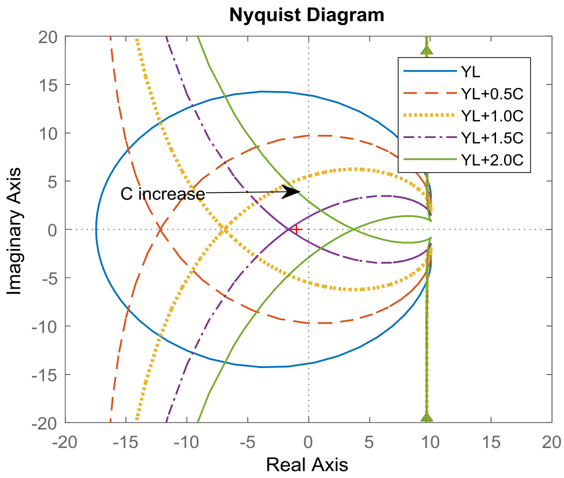

Fig. 6 Nyquist diagram of terminal admittance of double loop control.

The droop control alters the low frequency of terminal admittance without changing the high frequency terminal admittance. The low frequency terminal admittance asymptotic can be written in (15) equation if let $s \to 0$.

$$Y_o \to \frac{D' G_{vm}\omega_{zv} G_{im}\omega_{zi} V}{D' R_v G_{vm}\omega_{zv} G_{im}\omega_{zi} V} = \frac{1}{R_v} \tag{15}$$

This result coincides the equivalent model of interface converters under droop control, which is as expected. The terminal admittance comparison of the droop control with conventional double loop control is shown in Fig. 7.

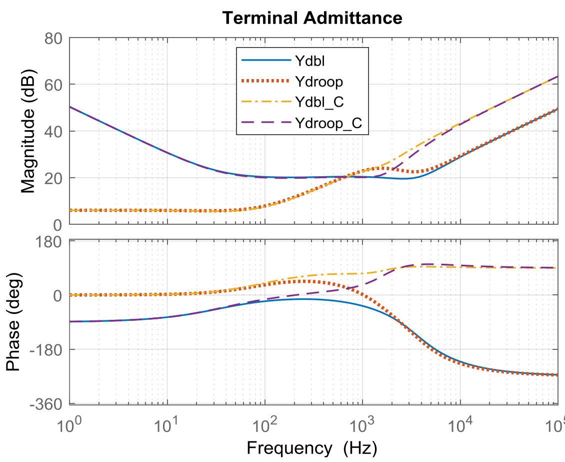

Fig. 7 Terminal admittance shaping by droop control.

It can be seen that the high frequency asymptotic are same on both droop and conventional double loop. The droop control only alters the low frequency impedance. To put it simply, the conventional double loop controller makes the system perform like inductor over low frequency while like resistance in droop control. Besides, when the adding the terminal capacitor, the high frequency negative admittance can then be compensated too.

C. Discussions

There are two things that need to be mentioned. The first one is that studying the admittance of individual interface converters is a conservative method for the system stability as aforementioned. It is possible that the output impedance of an individual interface converter is not passive, but it is still stable. Besides, in a complex system, there are many different interface converters and they have different output impedances. They can compensate each other over some frequencies. For example, the constant power load act negative resistance over low frequency, and it can be compensated by the source side converters to some extent.

The other thing is that the passive stability criterion in real applications, the frequency requirement has already bounded under switching frequency. The admittance over switching frequency can be affected dramatically by the bandwidth of current and voltage transducers. However, if the frequency could be furtherly bounded in real application is still worthy further investigation, especially over resonant frequency.

IV. SIMULATION RESULTS

A simulation model is used for validating above analysis. The configuration of the simulation model is shown in Fig. 8. It contains a droop controlled bidirectional Boost converter, an EV load, and a resistant load. The converter in the EV load is same as the sources converter while only the inner current loop is applied for load power stepping variations.

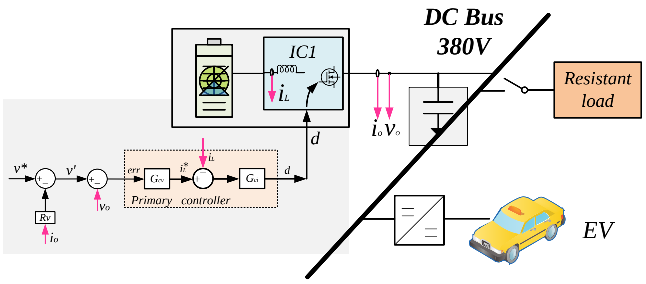

Fig. 8 System model confirmation in simulation.

The circuit and control parameters and values involved in the simulations are listed in Table I.

TABLE I. PARAMETERS AND VALUES OF SIMULATIONS.

Parameters	Values	Parameters	Values
L/C	1.2mH/470uF	f_z/ω_z	400Hz
f_s	10kHz	f_{zv}/ω_{zv}	33.3Hz
R_v/R_L	0.5Ω/200Ω	f_{c1}	100Hz
Input Sources	150~170V	f_{c2}	10Hz
EV Power	0~20kW	v_{bus}	380V

First of all, when the terminal capacitor is 470uF without additional capacitor compensation, the simulation results of EV charging power stepping are shown in Fig. 9. It can be seen that when the EV charging power reaches more than 10kW, the oscillation occurs (at 0.4s). Specifically, the system tends to oscillate at 0.3s, while it is still controlled and eventually converged.

Adding the terminal compensating capacitor with additional 470uF based on above analysis, the same simulation process is conducted, the result is shown in Fig. 10. It can be seen that the system is stable when the large power step occurs. It can be concluded that adding the terminal capacitor compensation can make the EV fast charging more stable.

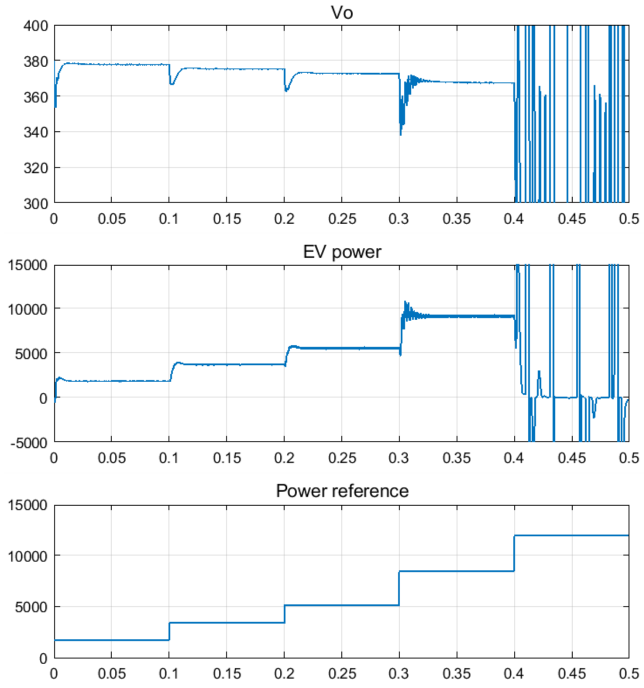

Fig. 9 Oscillation occurs when the EV charging power stepping.

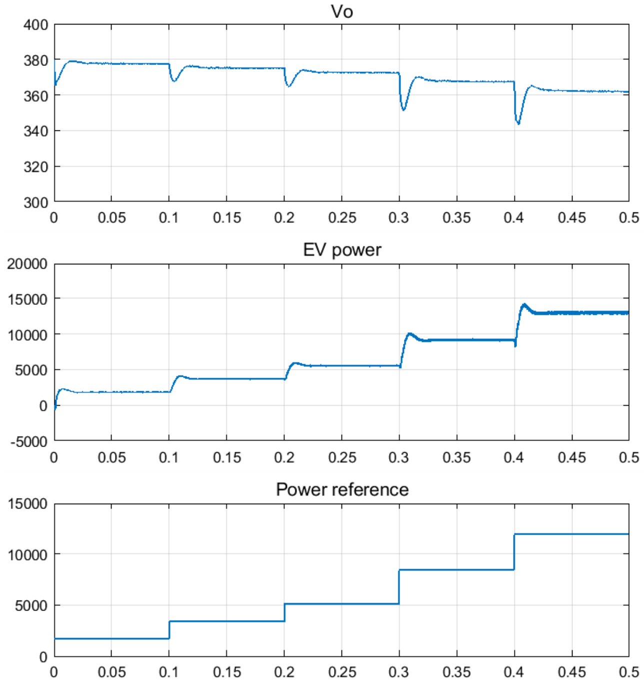

Fig. 10 Terminal capacitor compensation to stabilize the system.

V. CONCLUSIONS

This paper uses passive stability criterion to analyze the EV fast charging scenario in DC microgrids. The admittance model of bidirectional Boost converter is built for the analysis. The analysis results show that the high frequency negative admittance is directly related to the load power and the terminal capacitor can compensate the negative value. When the system supplies the instant heavy load, additional capacitor compensation is required. More research work such as seeking the boundary frequency and investigation on resonant frequency will be carried on in the future.

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