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COMPENSATION OF LOW-FREQUENCY OSCILLATIONS DAMPING IN MULTIBUS DC MICROGRIDS APPLICATIONS

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***Abstract*— This paper proposes a new active method for low frequency (LF) current/power oscillations damping in droopcontrolled dc microgrids. Since, LF oscillations are mainly affected by droop controllers of voltage controlled (VC) DGs, detailed small-signal analysis of VC-DGs is provided. Analysis shows that each droop-controlled VC-DG creates a pair of LF complex conjugate zeros. In the proposed method, these zeros are damped by a negative feedforward of the disturbance variables (output currents) of VC-DGs. Stability analysis of the overall dc microgrid reveals that the LF zeros of VC-DGs can affect the LF modes of the system. Therefore, in the proposed method, the effective tuning of feedforward gain of each VC-DG can increase the damping factor of microgrid LF modes and consequenctly improve the dynamic response of the whole system. Moreovere, to gurantee the plug-and-play performance of DGs, a coordinanted tuning criterion for adjusting the proper feedforward gains is presented. It is shown that the proposed method is also robust against structural changes in dc microgrids. A complete set of simulation studies using MATLAB/Simulink is provided which further**

I. INTRODUCTION

DC MICROGRIDS have recently attracted a great deal of attention mainly due to the increasing tendency toward using renewable energy resources along with proliferation of dc loads. This necessitates exploring different technical aspects such as protection, stability and power sharing associated with dc microgrids. Some of these challenges are rather subtle and are not still very well understood. As a common practice, droop control is used for power sharing among dispatchable sources of islanded microgrids.

A new adaptive control method is also presented in [5], which satisfies accurate current sharing, without using any communication link among DGs. Another important challenge of droop-controlled dc microgrids, is the low-frequency (LF) oscillation of power/current mainly arising from droop controllers of VC-DGs [9]. This implies that a droop-controlled dc microgrid is likely to subject to LF eigenvalues with low damping factor, which can be excited by different factors such as load changes. A conventional method for damping the LF oscillatory modes of the system is based on the augmentation of passive elements. Therefore, according to, increasing the line impedances can be viewed as a passive damping method.

This Thesis is organized as follows: we describes the understudy dc microgrid and its building components. We discusses the operational principles of the proposed damping method for VC-DGs, overall stability of dc microgrid, the criteria of the coordinated tuning of feedforward gains, and the robustness of the proposed method against microgrid structural changes. Simulation results are presented in Section IV, where the dc microgrid is simulated in MATLAB/Simulink environment. Finally, the conclusion remarks are provided

II. INTRODUCTION TO POWER QUALITY

Power quality is the set of limits of electrical properties that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly with that electric power. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power.

The electric power industry comprises electricity generation (AC power), electric power transmission and ultimately electricity distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised.

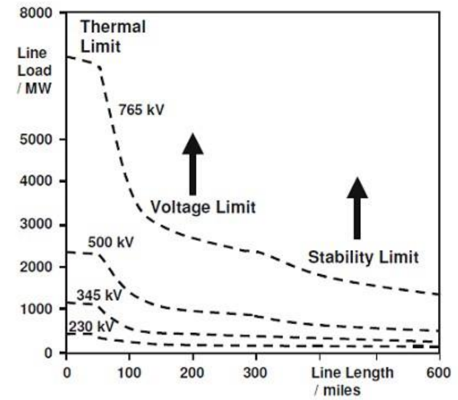
While "power quality" is a convenient term for many, it is the quality of the voltage—rather than power or electric current—that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable.

FACTS:

Flexible AC Transmission Systems, called FACTS, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice.

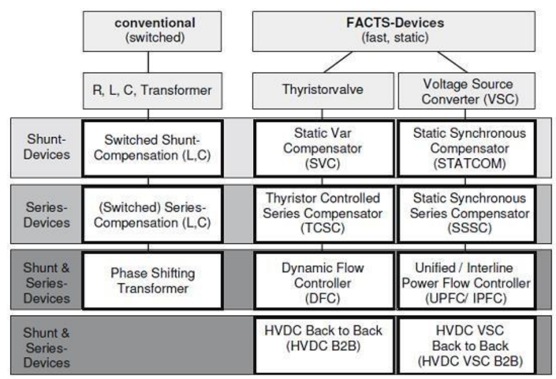
FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices are:

- Power flow control,
- Increase of transmission capability,
- Voltage control,
- Reactive power compensation,
- stability improvement,
- Power quality improvement,
- Power conditioning,
- Flicker mitigation,
- Interconnection of renewable and distributed generation and storages.



Operational limits of transmission lines for different voltage levels

TYPES OF CONTROL DEVICES:



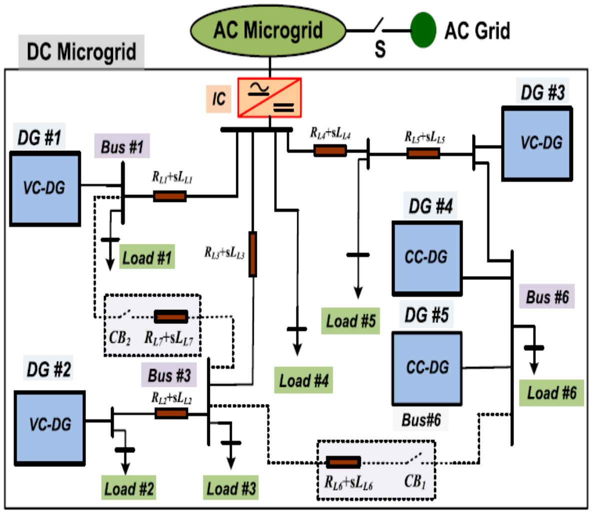
Control methods of harmonics

III. DESCRIPTION OF THE UNDERSTUDY

Controllers	Symbols	Parameters value
Voltage controller of Interlink	C_{IC}	$G_0 = 0.0052, \omega_z = 412.8\pi, \omega_l = 600\pi, \omega_p = 8712\pi$
Voltage controller of DG#1	$C_{DG\#1}$	$G_0 = 0.006, \omega_z = 536.64\pi, \omega_l = 600\pi, \omega_p = 11325.6\pi$
Voltage controller of DG#2, 3	$C_{DG\#2}, C_{DG\#3}$	$G_0 = 0.0048, \omega_z = 503.6\pi, \omega_l = 600\pi, \omega_p = 10628.6\pi$
Current controller of DGs#4,5	$C_{DG\#4}, C_{DG\#5}$	$G_0 = 0.048, \omega_l = 240.02\pi$
Current Controller of CCL	C_{CCL}	$G_0 = 0.15, \omega_l = 200\pi$
Voltage controller of CPL	C_{CPL}	$G_0 = 0.062, \omega_z = 61.92\pi, \omega_l = 40\pi, \omega_p = 435.6\pi$
Droop Coefficients	C_{C-d}	$\omega_c = 20\pi, R_{IC} = 0.0126$ $R_{DG1} = 0.0414,$ $R_{DG2,3} = 0.0828$

MULTIBUS DC MICROGRID

Fig. 1 shows the structure of a typical multibus dc microgrid involving three VC- DGs (i.e., DG#1, DG#2, and DG#3) and an interlinking converter (IC) which integrates the dc microgrid with the main ac grid. The operation mode of the IC depends on the condition of the interconnected ac microgrid. In the grid-connected mode of the ac microgrid, IC usually works as a VC-DG for the dc microgrid; when the ac microgrid is in islanded mode, the IC works as a current-controlled (CC) DG for the dc microgrid. The studied dc microgrid also includes two similar

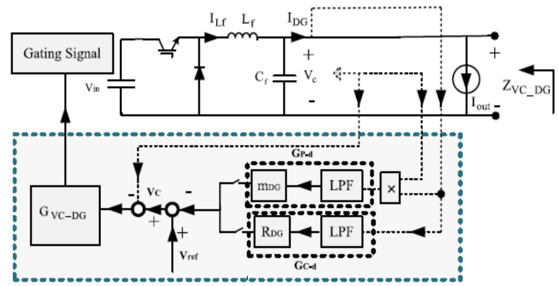


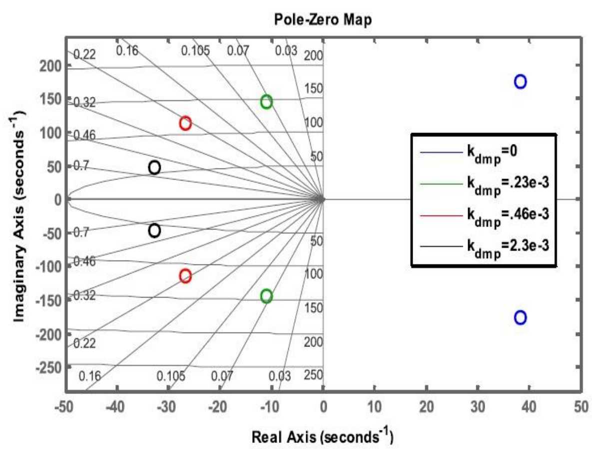
CC-DGs (i.e., DG#4 and DG#5). In addition, there are different types of loads in the studied dc microgrid: load#1, load#3,Load#4, and load#6 are resistive loads; while load#2 and load#5, are respectively a constant current load (CCL) and a constant power load (CPL).To study

Schematic of the studied dc microgrid

	Parameters	Value
IC	P_{IC}	5 kW
	L_f, r_L, C_f	0. 104mH, .0091Ω, 350μF
DG#1	$P_{DG\#1}$	1.5 kW
	L_f, r_L, C_f	0. 27 mH, 0.026Ω, 126μF
DG#2, 3	$P_{DG\#2}, P_{DG\#3}$	750 W
	L_f, r_L, C_f	0. 512 mH, 0.052Ω, 72.6μF
DG#4, 5	$P_{DG\#4}, P_{DG\#5}$	1 kW
	L_f, r_L, C_f	0.52mH, .03Ω, 50μF
Load#2 (CCL)	P_{CCL}	1 kW
	L_f, r_L, C_f	2.2mH, 0.03Ω, 100μF
Load#5 (CPL)	P_{CPL}	2 kW
	L_f, r_L, C_f	1mH, .02Ω, 100μF
Loads#1, 3, 4, 6 (Resistive Loads)	R_1	4.6 Ω (0.5 kW)
	R_3	4.6 Ω (0.5 kW)
	R_4	2.3 Ω (1.0 kW)
	R_6	4.6 Ω (0.5 kW)
DC Microgrid Voltage	V_g	48 V
Switching frequency	f_{sw}	20 kHz
Line Impedances	$Z_{line1,3,7}$	0.02 Ω, 12.74 μH
	$Z_{line2,4,5}$	0.01 Ω, 6.37 μH
	Z_{line6}	0. 26 Ω, 169.8 μH
	Z_{line7}	0. 026 Ω, 16.98 μH

the dc microgrid dynamics, detailed modeling of the microgrid components is needed. Therefore, averaging-linearization techniques are employed to obtain the closed-loop model of dc microgrid components. To this aim, averaging method is first applied to each converter model of DGs or loads one by one. Then because of the nonlinear nature of the averaged models, their small-signal linear model is derived. So, linearization around an operating point is performed. Tables I and II shows a summary of the parameters of the considered dc microgrid including DGs, loads and controllers. Further explanations about different types of DGs and loads will be presented in the upcoming subsections





Schematic of buck-type VC-DG and its control loops.

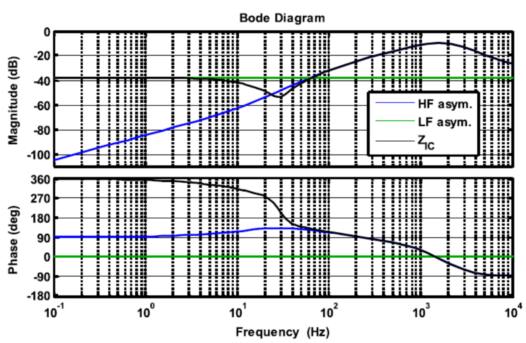
IV. OPERATION PRINCIPLES OF THE PROPOSED ACTIVE DAMPING METHOD

LF power/current oscillations in dc microgrids are mainly caused by power sharing control loops; therefore, active damping of LF oscillations can be implemented in control loops of VC-DGs equipped with the droop controllers. With this regard, Subsection A goes into elaborate details about the principles of the proposed LF oscillation damping method. Then the small-signal analysis of the overall dc microgrid is provided in Section III-B. The dominant LF eigenvalues of the overall dc microgrid, with and without the proposed active damping method are also compared. Furthermore, to fulfill the plug-and-play feature of VC-DGs, represents the coordinated tuning criterion of feedforward gains for the proposed active damping method. The robustness of the proposed method against the structural changes of dc microgrid is discussed

Analysis of the Proposed Active Damping Method

Fig. 4.1 shows the frequency response of the output series impedance of a VC- DG. As shown in this figure, the output impedance of each VC-DG at low frequencies is mainly determined by its droop controller. While, at higher frequencies, due to the negligible effect of the LPF of the droop controller, the output series impedance takes values equal to the impedance without the droop controller.

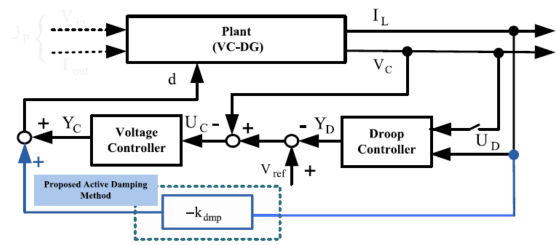
The impedance curve shown in Fig. 4.1, affected by the droop controller, creates complex conjugate LF zeros at the output impedance of each VC-DG. In fact as it is seen from



Frequency response of the output series impedance of a droopcontrolled single VC-DG (IC), and its asymptotes

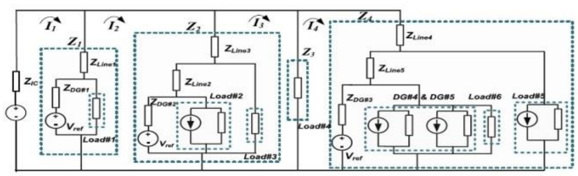
Dominant LF zeros resulted by 5 kW VC-DG (IC), for different values of*kdmp*

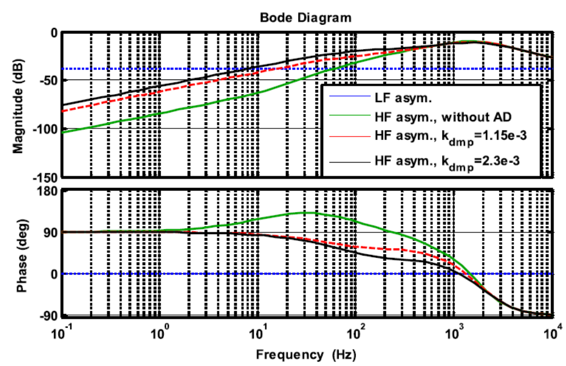
To study the operational principle of the proposed method, detailed modeling of closedloop VC-DGs is required.Considering Fig.4.6, the mentioned structure includes the plant model (with arbitrary convertertopology) of a VC-DG, and its control loops. As known, linear state-space representation of both plant model and the models of controllers are required to obtain the closed-loop model of each converter-based DG or load. Hence, having obtained the individual linear models of the plant and its controllers, these models are integrated to make the overall closed-loop state-space model.



Structure of the proposed control system for VC-DGs of dc microgrid

It should be noted that since the proposed damping loop is independent of the droop loop, the proposed damping method is applicable to both types of current and power droop controllers

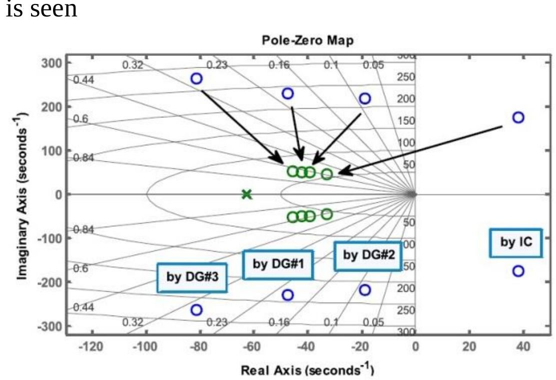




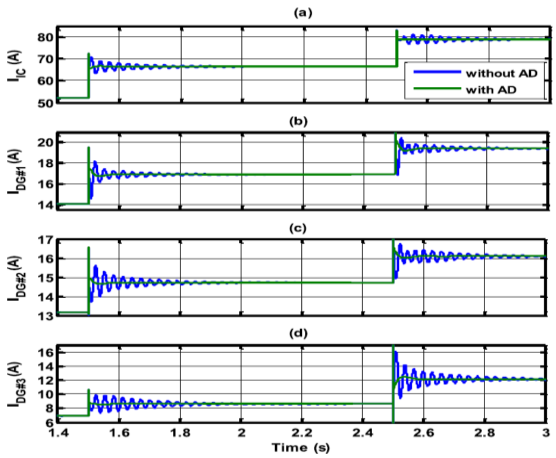
Frequency response of LF and HF asymptotes of the output series impedance of a single VC-DG (IC), for different values of *k*dmp

Coordinated Tuning of Damping Gains

Fig. shows LF zeros of the dc microgrid, with andwithout the proposed active damping method. As it is seen



Displacement of LF zeros of dc microgrid, when the proposed active damping method is utilized in VC-DG.



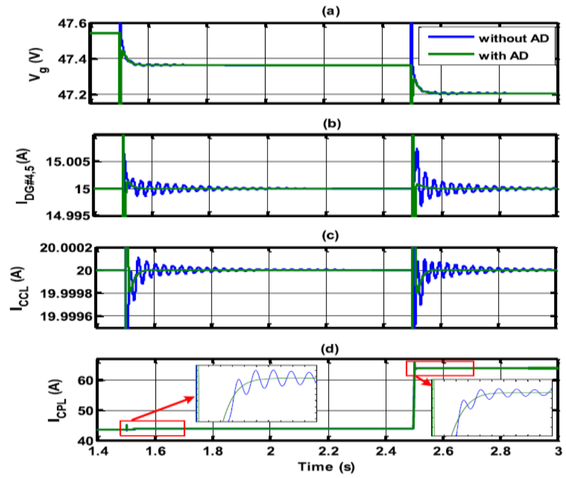
(a) Output currents of IC, (b) DG#1, (c) DG#2, and (d) DG#3, with and without the proposed active damping method, with a 1 kW load change of load#4 at t = 1.5 s, and a 1 kW load change of load#5 at t = 2.5 s.

In sum, the proposed active damping method features the following capabilities:

- capability of power oscillation damping;
- providing a Plug-and-play feature of VC-DGs;
- robustness against structural changes.

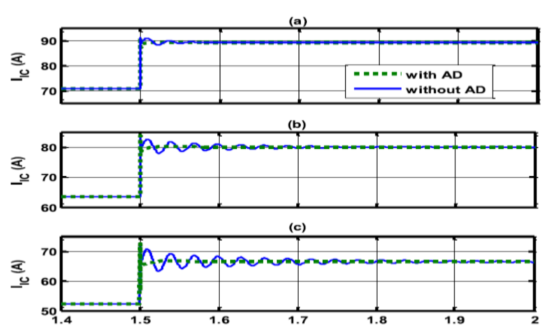
V. SIMULATION MODELS AND RESULTS

To evaluate the performance of the proposed active damping method, the microgrid shown in Fig. 2.1is simulated in MATLAB/Simulink software environment. As discussed earlier, the dc microgrid contains an IC which works as a VC-DG for the dc microgrid; moreover, there are three other dispatchable VC-DGs (DG#1, DG#2, and DG#3). Besides this, DG#4 and DG#5 are considered as nondispatchable DGs; hence, they do not have the capability to contribute to the power management of the dc microgrid. In this microgrid, there are different types of loads: load#2 and load#5 are respectively CCL and CPL types; and the other loads are of resistive type. The parameters of the microgrid are summarized. As known, change of any type of loads can excite dominant modes of the whole dc microgrid. Hence, to examine the performance of the proposed method, it is assumed that at t = 1.5 s, the microgrid is subjected to a sudden small



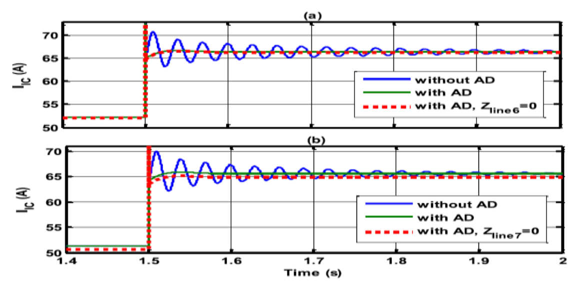
(a) Grid voltage, (b) currents of DGs#4,5, (c) CCL (load#2), and (d) CPL (load#5), with and without the proposed active damping method, with a 1 kW load change of load#4 at t = 1.5 s, and a 1 kW load change of load#5 at t = 2.5 s. (1 kW) load change of load#4, and then at t = 2.5 s, to a sudden small (1 kW) load change of load#5.

It is noted that higher load changes will lead to higher amplitude of LF oscillations in the dc microgrid. Fig.5.1 (a)–(d) respectively show the output current of IC, DG#1, DG#2, and DG#3 with and without the proposed active damping method. Moreover,. 5.1(a)–(d) respectively show the dc microgrid voltage, current of CC-DG (DG#4 and DG#5), CCL and CPL, with and without the proposed active damping method.

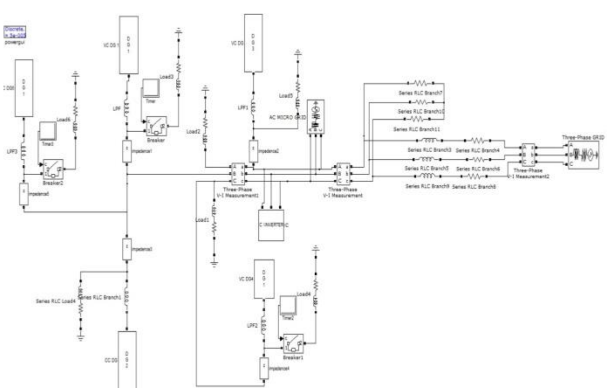


Output currents of IC, for three states: (a) $S9$, (b) $S2$, and (c) $S0$, with (green) and without (blue) the proposed active damping method, with a 1 kW load change of load#4 at t = 1.5 s.

As expected, different types of load changes (resistive at t = 1.5 s, and CPL at t =s) lead to similar dynamic responses of the dc microgrid. According to Fig. 4.6, when no active damping method is adopted, due to the low damping factor of the dominant LF modes, significant LF oscillations are expected. The mentioned low-damping oscillations can be observed at output currents of VC-DGs, CC-DGs and currents of different types of loads (see Figs. 11 and 12); however, due to the low output impedance of VC-DGs, main current oscillations belong to these DGs. Moreover, as it is shown in Fig. 4.8, when the proposed active damping method is in service, due to the high damping factor of the dominant LF modes, LF oscillations are effectively damped without affecting droop coefficients. This fact is confirmed by Figs. 5.1and 4.8 Fig.5.2 shows the output current of IC for three states of *S*0, *S*2 and *S*9 of removed DGs, based on Table III. Moreover, it is similarly assumed that at t = 1.5 s, the microgrid is subjected to a sudden small (1 kW) load change of load#4. According to the results of Table III, by the proposed coordinated tuning of the damping gains, the plug-and-play feature of VC-DGs is expected. As shown in Fig. 5.2, when there is no active damping method, each state has its own dynamics;



Output currents of IC, when (a) CB1 is closed and CB2 is open, (b) CB2 is closed and CB1 is open, with and without the proposed active damping method**,**



when a 1 kW load change of load#4 at t = 1.5 s is occurred. different LF damping factors of 0.0272, 0.0392, and 0.152, respectively for states *S*0, *S*2, and *S*9 are obtained. However, at the presence of the active damping method, LF dominant modes have similar damping factors and frequencies, for the same staes. Therefore, according to Fig. 13, by the proposed method, LF dynamics of dc microgrid is to a great extent independent of the given states; and the plug-and-play feature of VC-DGs in the dc microgrid is guaranteed. To evaluate the effect of microgrid structural changes on the operation of the proposed damping method, according to the states of CBs shown in Fig. 2.1, two situations are studied in this Section: (a) when CB1 is closed and CB2 is open; and (b) when CB2 is closed and CB1 is open. Fig. 5.3(a) and (b) show the output current of IC for these situations. To evaluate the LF dynamics of the dc microgrid, it is assumed that at t = 1.5 s, the dc microgrid experiences a sudden small (1 kW) load change of load#4. According to the results of Table IV, the proposed method is expected to be robust against the structural changes of dc microgrids. As shown in Fig. (a) and (b), when there is no damping method, by closing each CB, low damping oscillations appear at the output current of IC (and also other DGs). While, in the presence of the proposed damping method, by closing each CB, oscillations are properly damped for different values of *Z*line6 and *Z*line7. In particular, the efficient performance of the proposed active damping method for line impedances with zero value accentuates the robustness of the proposed method against the structural changes of multibus dc microgrid, see Fig. 14(a) and (b). Simulink model of system

VI. CONCLUSIONS

A novel active damping method has been proposed to improve the dynamic response of droop-controlled dc microgrids. The proposed method relies on implementing a damping loop into the control system of VC-DGs. This is owing to the fact that LF modes of dc microgrids are mainly imposed by droop controllers. From the impedance-based analysis of VC-DGs it was shown that damping factor of the resulted LF modes, is affected by many parameters including: droop coefficient, and also the output impedance of each corresponding VC-DG at higher frequencies (droop-less output impedances). The principle of the proposed active damping method is based on adjusting the output impedance of each VC-DG at higher frequencies, without manipulating its droop coefficients. To this aim, a damping loop which is composed of negative feedforward of disturbance variable of each VC-DG has been applied to each of them. From parametric analyses and simulation studies, it was found that the proposed method has the following capabilities:

- satisfactorily efficient performance for damping the dominant LF modes of the overall dc microgrid;
- efficiency to deal with different types of loads;
- applicable for other types of dc/dc converters with different topologies;
- applicable to both types of current and power droop controllers;
- providing a plug-and-play platform for VC-DGs in a dc microgrid;
- robustness against structural changes of a dc microgrid.

It is worth noting that the proposed criteria of coordinated tuning for plug-and-play performance of VC-DGs and the robustness against structural changes, can be easily implemented in any LF damping methods.

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