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Large Signal Stabilization Method of Constant Power Loads

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***Abstract*-The electrical motor drives and power electronic converters of More Electric Vehicles usually behave as constant power loads (CPLs), and cause negative impedance instability. This paper introduced R parallel damping filters to stabilize the CPLs systems, and derived large signal stability criteria depending on Brayton-Moser's mixed potential theory. The simple criteria utilize the maximum negative impedance of the CPLs to give quantitative constraints on the filter parameters. Comparisons indicate the stability criterion for the CPLs with a LC filter can be regarded as a special case of the proposed criteria. The experimental results confirm the validity of the large signal stability method.**

Keywords-Constant power loads (CPLs); R parallel damping filters; negative incremental impedance; Moser and Brayton's mixed potential theory

I INTRODUCTION

In the DC power systems of More Electric Vehicles [1], electrical power is increasingly utilized, and the system evolves to include more electrical motor drives and power electronic converters. These loads usually behave as constant power loads (CPLs), and exhibit negative incremental impedance. This nonlinear characteristic tends to destabilize the power systems [2].

The stability investigations of the CPLs can be classified into active methods and passive methods. In the first group, various stabilization strategies [3-8] or compensation blocks [9,10] are introduced to the control loops of the feeder converters, which may modify the source and/or the CPLs control characteristics [11, 12]. These techniques usually lead to high requirements of the system control properties, and would affect the dynamic performances of the source or the load, which may not be acceptable in high reliability applications. In the second group, passive filters are added at the input terminals of the CPLs[13, 14], which would not cause these disadvantages. Reference [15] proposes three different passive damping filters to stabilize the CPL system. But the presented criteria are not useful for large disturbances.

R parallel damping filters are the simplest structure of damping filters, and could be applied in the vehicle power systems for the favorable filtering effect and simple design. Based on Brayton-Moser's mixed potential theory, this paper develops simple stability criteria for a CPL with the R parallel damping filter. The proposed criteria employ the negative incremental impedance of the CPL to constrain the filter parameters, and can guarantee the system stability under large disturbances.

II THE STABLE OPERATING POINTS

An equivalent circuit of a typical DC power system model is adopted and shown in Figure1. A constant DC supply V_s with a diode D and a Thevenin resistor R_0 in series denotes a controlled DC source. The R parallel damping filter is used for noise attenuation. The CPL here is represented by the ideal model (P_o= constant = V_oI_o)

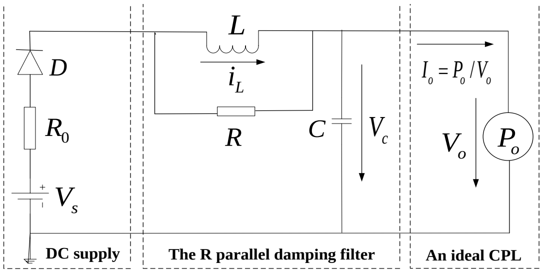


FIGURE I. THE DC POWER SYSTEM CONTAINING THE IDEAL CPL AND THE R PARALLEL DAMPING FILTER

The steady-state equations of the system can be described as

$$\begin{cases} V_o = V_s - V_D - I_o R_0 \\ I_o = \dfrac{P_o}{V_o} \end{cases} \tag{1}$$

An equilibrium point is regarded as stable when the operation is restored to it after a small disturbance [13]. Based on (1), the voltage and current of the stable equilibrium point are given by:

$$\begin{cases} V_B = \dfrac{V_s - V_D}{2} + \sqrt{\left(\dfrac{V_s - V_D}{2}\right)^2 - R_0 P_o} \\ I_B = \dfrac{P_o}{V_B} \end{cases} \tag{2}$$

In order to avoid the complex equilibrium points, the following condition has to be satisfied:

$$P_{\max} < \frac{(V_s - V_D)^2}{4R_0} \tag{3}$$

The stable equilibrium point criterion in (3) places an upper limit on the amount of constant power Po that a DC power system can supply.

III LARGE SIGNAL STABILIZATION METHOD OF CPLS

A. The Mixed Potential Model of the CPL System

In 1960s, Brayton and Moser proposed the mixed potential theory [16], which is applicable to determine stability criteria for nonlinear electrical networks, especially those containing negative resistance. The mixed potential function P is defined as

$$P(i,v) = -A(i) + B(v) + N(i,v) \tag{4}$$

where $A(i)$ represents the current potential, and $B(v)$ is the voltage potential.

The elements are classified into three categories in Figure 1: the dc supply V_s, the diode voltage V_D, the equivalent resistor R_0 and the damping resistor R are in group I ; the CPL is in group II while the capacitor C is in group III;

The mixed potential model of the dc supply V_s cannot be directly constructed, and a virtual inductor L_1 is added in series with the dc supply. The state equation of the inductor L_1 is:

$$L_1 \frac{di}{dt} = V_s - R_0 i - V_c - V_D - (i - i_L)R \tag{5}$$

The mixed potential model of the CPL system with virtual inductor L_1 is:

$$P(i,v) = -\frac{1}{2}R_0 i^2 + (V_s - V_D)i + \int_0^{V_o} \frac{P_o}{v} dv - \frac{1}{2}R(i - i_L)^2 - V_c i \tag{6}$$

The inductance of L_1 equals zero actually, then i can be derived from (5):

$$i = \frac{V_s + Ri_L - V_c - V_D}{R + R_0} \tag{7}$$

Using (7), the mixed potential model in (6) is transformed as

$$P(i,v) = -\frac{R_0 R}{2(R+R_0)} i_L^2 + \frac{V_c^2}{2(R+R_0)} + \int_0^{V_o} \frac{P_o}{v} dv + \frac{(V_s - V_D)^2 - 2V_c(V_s - V_D) + 2Ri_L(V_s - V_D - V_c)}{2(R+R_0)} \tag{8}$$

B. The Large Signal Stability Analysis of the CPL System

Based on the comparison between (4) and (8), $(-R_L)_{max}$ is introduced to denote the maximum of the negative impedance of the CPL, and based on theorem 5 of mixed potential theory, the design constraint on the filter parameters is derived:

$$\frac{C}{L} > -\frac{1}{(-R_{CPL})_{\max}}\left(\frac{1}{R_0} + \frac{1}{R}\right) - \frac{1}{R_0 R} \tag{9}$$

In order to restore stable operation, the mixed potential stability criterion in (9) utilizes the negative impedance of the CPL to give important design guideline of R parallel damping filters. The stable equilibrium point criterion in (3) and the mixed potential stability criterion are combined together as

$$\begin{cases} \dfrac{(V_s - V_D)^2}{4R_0} > P_{\max} \\ \dfrac{C}{L} > -\dfrac{1}{(-R_{CPL})_{\max}}\left(\dfrac{1}{R_0} + \dfrac{1}{R}\right) - \dfrac{1}{R_0 R} \end{cases} \tag{10}$$

The stable equilibrium point exists if CPL system satisfies the first inequation in (10), and the system would be stable during large disturbances when it simultaneously satisfy the second inequation in (10).

IV SIMULATION AND EXPERIMENTAL RESULTS

A DC power system contains a DC power supply, the R parallel damping filters, and a CPL, is constructed and shown in Figure 2. The equivalent source resistor is 0.01Ω. The power of the CPL is 5kW, and the switching frequency is 20kHz. Based on MIL-STD-704F, the noise attenuation at 20kHz is 25dB. On the same condition, two R parallel damping filters and a LC filter in Table 1 were designed. Filter A satisfy the mixed potential stability criterion in (10), while filter B do not. The parameters of filter C satisfy (11).

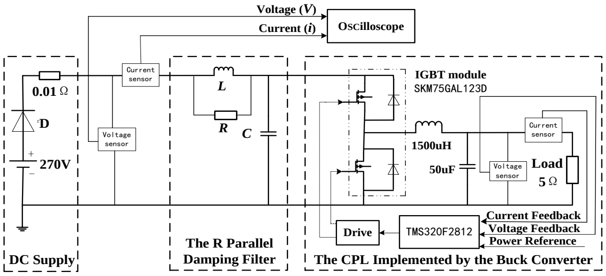
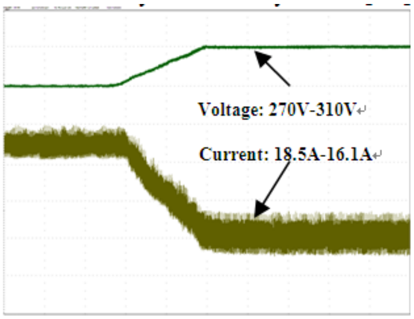


FIGURE II. THE DC POWER SYSTEM SCHEMATIC

TABLEI. THE PARAMETERS OF THREE FILTERS

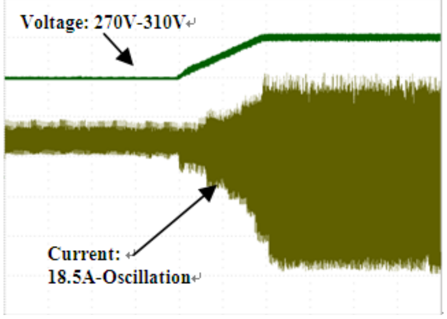
Parameters	R Parallel Damping Filter A	R Parallel Damping Filter B	LC Filter C
L/μH	500	500	0.4
C/μF	30	7	4100
R/Ω	5	25	none

Figure 3 and Figure 4 depict the supply current responses to 40V variation of the supply voltage. Compared with the steady increase or decrease of the current when the filter A is used, wild oscillations occur in the current as the filter B is adopted. It can be concluded from Figure 3 and Figure 4 that the CPL with the filter A is stable during 40V voltage variation, while with the filter B is not stable. The measured responses in Figure 3 and Figure 4 show close correspondence with the region of asymptotic stability (RAS) in Figure 3, and the results verify the validity of the proposed criteria in (10).



t **(0.5s/div)**

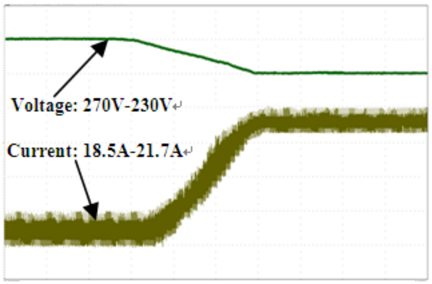
(a)voltage and current waveform after adding filter A



t **(0.5s/div)**

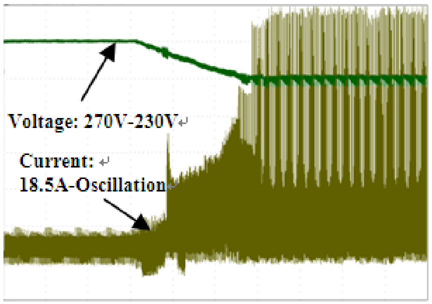
(b)voltage and current waveform after adding filter B

FIGURE III. THE DC SUPPLY CURRENT RESPONSES TO VOLTAGE VARIATION FROM 270V TO 310V



t **(0.5s/div)**

(a)voltage and current waveform after adding filter A



t **(0.5s/div)**

(b) voltage and current waveform after adding filter B

FIGURE IV. THE DC SUPPLY CURRENT RESPONSES TO VOLTAGE VARIATION FROM 270V TO 230V

As shown in Table I, the capacitor of filter A (30μF) is much smaller than filter C (4100μF). R parallel damping filters significantly reduce the capacitance, avoiding the use of electrolytic capacitors, and are applicable in vehicle high reliability power systems.

V CONCLUSION

This paper introduces appropriate R parallel damping filters to prevent the negative impedance instability of the CPLs. The stable equilibrium operating points of the system were obtained. Then based on Brayton-Moser’s mixed potential theory, the mixed potential model was constructed, and design criteria were derived to guarantee large signal stability. The presented criteria utilize the maximum negative incremental impedance of the CPL to constrain the filter elements, and consequently, provide important design guidelines for R parallel damping filters. Comparisons demonstrate the stability criteria of the CPL with the LC filter can be regarded as special case of the proposed criteria. The criteria are very simple and easy to implement, and verified through simulation and experimental results.

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REFERENCES

[1] D. Izquierdo, R. Azcona, F. Del Cerro, C. Fernandez, and B. Delicado, "Electrical power distribution system (HV270DC), for application in more electric aircraft," in *Applied Power Electronics Conference and Exposition (APEC)*, Yokohama, Japan, 2010, pp. 1300-1305.

[2] Emadi A. , Khaligh A. , Rivetta C.H. ,Williamson G.A. "Constant power loads and negative impedance instability in automotive systems: definition, modeling, stability, and control of power electronic converters and motor drives."Vehicular Technology, IEEE Transactions on, 2006, 55 (4): 1112-1125

[3] Zhang. Xuhui, Wen Xuhui, Zhao Feng. The Control Scheme Counteracting Negative Impedance of Constant Power Load for Bi-Directional Buck/Boost [J]. Transactions of China Electro technical Society, 2013, 31(27): 195-201.

[4] Zhang Yang, Zhang Junming, Du Weijing. Large-Signal Stability of Cascaded System under Load Transient [J]. Transactions of China Electro technical Society, 2012, 27(10): 170-175.

[5] Kwasinski A. , Onwuchekwa C.N.. Dynamic Behavior and Stabilization of DC Microgrids With Instantaneous Constant-Power Loads [J]. Power Electronics, IEEE Transactions on, 2011, 26(3): 822-834.

[6] Magne P. , Nahid-Mobarakeh B. , Pierfederici S..Active Stabilization of DC Microgrids Without Remote Sensors for More Electric Aircraft [J]. Industry Applications, IEEE Transactions on, 2013,49(5): 2352-2360.

[7] Magne P. , Nahid-Mobarakeh B. , Pierfederici S. . Dynamic Consideration of DC Microgrids With Constant Power Loads and Active Damping System: A Design Method for Fault-Tolerant Stabilizing System [J]. Emerging and Selected Topics in Power Electronics, IEEE Journal of, 2014, 2(3): 562-570, 2014.

[8] Fangcheng Liu. G-norm and Sum-norm Based Stability Criterion for Three –phase AC Cascade Systems [J]. Proceedings of the CSEE, 2014, (24): 4092-4100.

[9] Rahimi A.M., Williamson G.A., Emadi A.. Loop-Cancellation Technique: A Novel Nonlinear Feedback to Overcome the Destabilizing Effect of Constant-Power Loads[J]. Vehicular Technology, IEEE Transactions on, 2010, 59(2): 650-661.

[10] Wang Na, Yuanjun Zhou. Impedance Characteristics Analysis of Speed Regulation Systems with Negative Input-resistance Compensators [J]. Proceedings of the CSEE, 2013, (33): 50-56.

[11] Rahimi A.M. , Emadi A.. Active Damping in DC/DC Power Electronic Converters: A Novel Method to Overcome the Problems of Constant Power Loads[J]. Industrial Electronics, IEEE Transactions on, 2009, 56(5):1428-1439.

[12] Liutanakul P., Awan A.-B., Pierfederici S.,Nahid-Mobarakeh B., Meibody-Tabar F.. Linear Stabilization of a DC Bus Supplying a Constant Power Load: A General Design Approach[J]. Power Electronics, IEEE Transactions on, 2010, 25(2): 475-488.

[13] Xinbo Liu, Yuanjun Zhou, Wei Zhang, Shuohan Ma. Stability Criteria for Constant Power Loads with Multi-Stage LC Filters [J]. Vehicular Technology, IEEE Transactions on, 201, 60(5): 2042-2049.

[14] Xinbo Liu, Yuanjun Zhou. Large Signal Stability Criteria for Constant Power Loads with Double-Stage LC Filters [J]. Proceedings of the CSEE, 2011. 31(27): 29-35.

[15] Cespedes M., Lei Xing, Jian Sun. Constant-Power Load System Stabilization by Passive Damping [J]. Power Electronics, IEEE Transactions on, 2011, 26(7): 1832-1836.

[16] Brayton RK, Moser JK. A theory of nonlinear networks, part I [J]. Quart, Appl, Math, 1964, 22(1): 1-33.

[17] Rahimi A.M., Emadi A. .An analytical investigation of DC-DC power electronic converters with constant power loads in vehicular power systems [J]. IEEE Transactions on Vehicular Technology, 2009, 58(6): 2689-2702.