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Stability Considerations for DC Power Systems with Multi-level Virtual Conductors

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Abstract: A new stability criterion for bidirectional DC-DC converters in a dc power system is presented in this paper. This proposed criterion gives an overall indicator for the stability at each node in the dc power system. It based on perturbing the system at a certain node by injecting a small ac current at this node, and accordingly monitoring the variation of the voltage at this node. Then, the node impedance can be calculated. This node impedance implies the stability status of the system at that node. The concept of the node impedance stability criterion is introduced, and the application of this criterion to a dc power system is investigated, as well.

Keywords: Bidirectional dc-dc converter, Dc power system, Node impedance stability, Loop gain, Seamless model

1. Introduction

Recently, bidirectional DC-DC converters (BDCs) have gained a great attention due to the increasing need to systems with the capability of bidirectional energy transfer between two dc buses. BDCs have various applications that include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles (HEVs) and uninterruptible power supplies (UPSs) [1)-7)].

The fluctuation nature of most renewable energy sources [6)-7)], like wind and solar, makes them unsuitable for standalone operation. A common solution to overcome this problem is to use an energy storage device besides the renewable energy resource to compensate these fluctuations and maintain a smooth and continuous power flow.

As the most common and economical energy storage devices, in medium-power range, are batteries and super-capacitors; a DC-DC converter is usually required to allow energy exchange between storage device and the rest of the system. Such converters must have bidirectional power flow capability with flexible control in all operating modes.

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One of the problems for a DC distribution is the potential stability degradation due to interactions among converters connected to a common bus [8)-10)]. Typically, when tightly regulated, converters behave at their input terminals as constant power loads (CPLs) within their control loop bandwidth [8)-10)]. CPLs create the so-called negative incremental input impedance, which is the cause of the subsystem interaction problem and origin of the undesired destabilizing effect [9)].

The conventional criteria for stability assessment; such as Nyquist criteria and bode diagram are convenient for a single converter model, but in case of a system contains many BDCs connected together with loads and sources, it becomes very complicated to use these criteria. Therefore, this paper introduces a new criterion suits such complex dc power systems. This criterion is called node impedance criterion. Mathematical analysis, experimental analysis and the concept of node impedance criterion are presented. Simulation and experimental results for this criterion are compared with those of the conventional criterion to show its validity. Ultimately, an experimental setup has been implemented for a dc power system, and the node impedance criterion is applied to this dc power system to judge its stability.

2. Analysis of Bidirectional DC-DC Converter

Analytical model of bi-directional converter is shown in **Fig.1.** Seamless model of bi-directional converter is derived by state-space averaging method [1].

2.1 Small Signal model

Considering the averaged state-space vector $\bar{x}(t) = [\bar{i_L}(t) \quad \bar{v_c}(t)]^T$, the input vector $u = [V_1 \quad I_2]^T$, and the output variable $\Delta V_2(s)$, small signal model are derived as shown in (1).

$$\Delta V_2(s) = G_{vvo}(s)\Delta V_1(s) + G_{vio}\Delta I_2(s) + G_{vdo}(s)\Delta D(s) \tag{1}$$

where;

$$G_{vvo}(s) = \left.\frac{\Delta V_2(s)}{\Delta V_1(s)}\right|_{open} = \{c(sI - A)^{-1}B + e\}\begin{bmatrix}1\\0\end{bmatrix} \tag{2}$$

$$G_{vio}(s) = \left.\frac{\Delta V_2(s)}{\Delta I_2(s)}\right|_{open} = \{c(sI - A)^{-1}B + e\}\begin{bmatrix}0\\1\end{bmatrix} \tag{3}$$

$$G_{vdo}(s) = \left.\frac{\Delta V_2(s)}{\Delta D(s)}\right|_{open} = c(sI - A)^{-1}b_p + e_p \tag{4}$$

Block diagram of bi-directional converter including feedback loop is shown in **Fig.2**. The voltage of current source $\Delta V_2(s)$ is fed back to the duty ratio $\Delta D(s)$. Loop gain $T(s)$ become;

$$T(s) = PWM \cdot G_c(s) \cdot G_{vdo}(s) \tag{5}$$

where;

PWM ：PWM gain

$G_c(s)$ ：Gain of compensator

From (1) and (5), equivalent inside impedance of bi-directional DC-DC converter is obtained as shown in (6).

$$Z_2(s) \triangleq -\left.\frac{\Delta V_2}{\Delta I_2}\right|_{feedback} = -\frac{G_{vio}(s)}{1 - T(s)} \tag{6}$$

2.2 Small Signal Model considering AC Impedance of Load/Source Modules

In the real system, load/source modules have AC impedance, as shown in **Fig.3.** They affect characteristics of bi-directional DC-DC converter. Seamless model can be extended in this case. Considering AC impedance $Z_L(s)$ of load/source modules, the transfer function becomes;

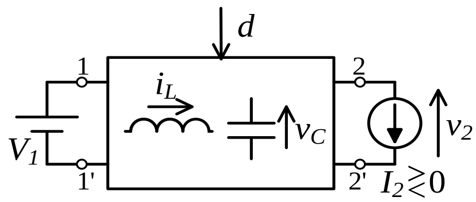


Fig. 1 Analytical model of bi-directional DC-DC converter.

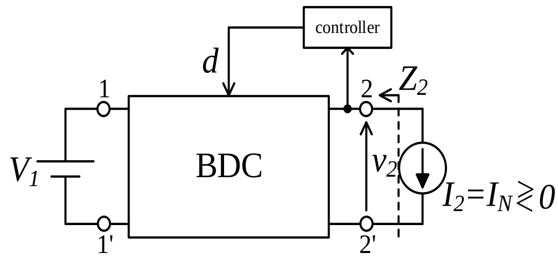


Fig. 2 Block diagram of seamless model of bi-directional DC-DC Converter.

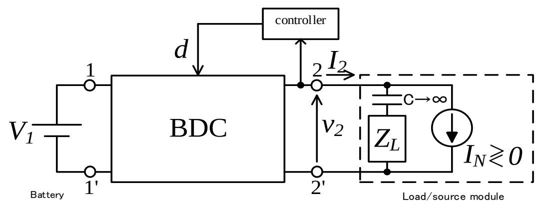


Fig. 3 Seamless model considering AC impedance of load/source modules.

$$Z_L(s) = \frac{\Delta V_2(s)}{\Delta I_2(s)} \tag{7}$$

In this case, loop gain $T_L(s)$ and block diagram are rewritten as shown in (8) and **Fig.4.**

$$T_L(s) = \frac{T(s)}{1 - \frac{G_{vio}(s)}{Z_L(s)}} \tag{8}$$

The characteristic equation as in (9)

$$1 - T_L(s) = 0 \tag{9}$$

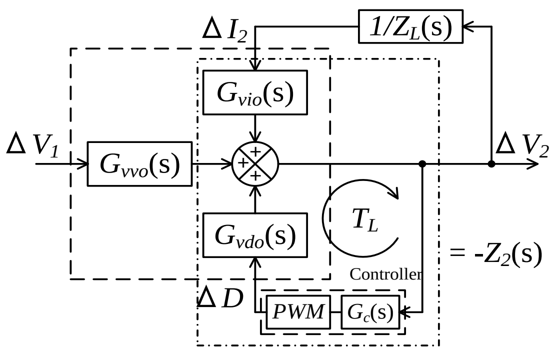


Fig. 4 Block diagram of seamless model considering AC impedance of load/source modules.

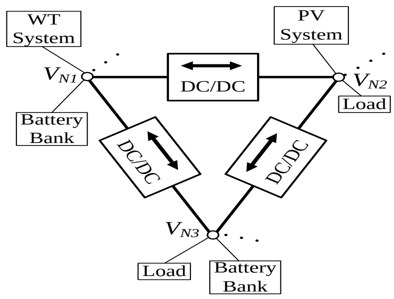
Using (6) and (8) results in:

$$1+\frac{Z_2(s)}{Z_L(s)}=0 \tag{10}$$

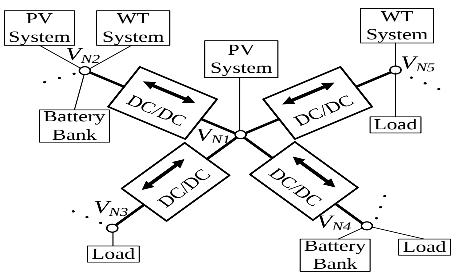
3. Applications bidirectional DC-DC converters in dc power systems

Figure 1 shows the configuration examples of a BDC, called a multi-level virtual conductor (MLVC) [2], in dc power systems. The loop connection is presented in **Fig. 5 (a)**, while the redial connection at a central node is revealed in **Fig. 5 (b)**.

For these dc power system configurations with various voltage sources, loads, and BDCs connected together, it is so difficult to assess the stability by the conventional method. By using node impedance criterion, it becomes easy to have a clear image for the stability of the system at each node.



(a) Loop connection



(b) Redial connection

Fig. 5 Application of BDC in dc power supply.

4. Nodal impedance and system stability

Regarding **Fig. 6**, when small current ΔI_t is injected into the node; it will cause small change in the voltage ΔV_2. Hence, node impedance Z_N can be calculated as follows:

$$Z_N \triangleq \frac{\Delta V_2}{\Delta I_t} \tag{11}$$

From the block diagram of node impedance Z_N in **Fig. 7**, the following equation can be expressed.

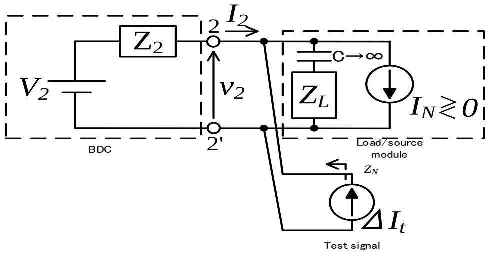


Fig. 6 Measurement method of the node impedance.

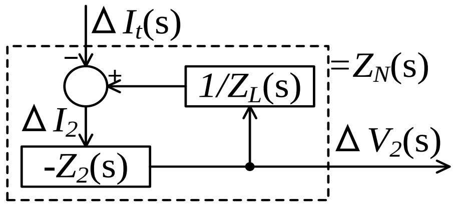


Fig. 7 Block diagram of the node impedance.

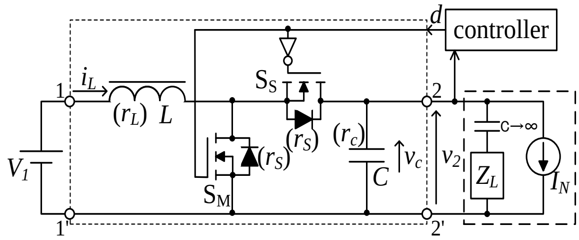


Fig. 8 Bi-directional DC-DC converter to be analyzed.

$$Z_N(s)=\frac{Z_2(s)}{1+\frac{Z_2(s)}{Z_L(s)}}=Z_2(s)//Z_L(s) \tag{12}$$

When, ΔI_t is an input and ΔV_2 is considered output; therefore the characteristic equation is:

$$1+\frac{Z_2(s)}{Z_L(s)}=0 \tag{13}$$

According to Nyquist criterion of stability, when the locus plot of the open loop transfer function $\frac{Z_2(jw)}{Z_L(jw)}$ passes in the right side than the point -1 in the complex plan, the system is stable. In other words, it is possible to have information about the system stability from the frequency characteristics of $\frac{Z_2(jw)}{Z_L(jw)}$. Considering (10) and (13), the loop gain T_L and the node impedance Z_N have the same characteristic equation. Therefore, it is possible to use Z_N as a stability criterion. Based on (12), the larger is the value of Z_N; the closer is the system to instability and vice versa.

4.1 Numerical analysis

The circuit to be analyzed is shown in **Fig. 8.** The numerical analysis is done based on these parameters. It should be noted that, in this analysis, impedance ZL of the connected device (s) is:

$$Z_L(s) = 2 + \frac{1}{s \cdot 66 \times 10^{-6}} \tag{14}$$

For stabilization of the circuit the lead-lag compensator is chosen as follows:

$$G_c(s) = -K \cdot \frac{1+s/\omega_{z1}}{1+s/\omega_{p1}} \cdot \frac{1+s/\omega_{z2}}{1+s/\omega_{p2}} \tag{15}$$

where, K = 0.0656, ωp1= 417 rad/s , ωz1= 64.9 rad/s, ωp2= 3.44 krad/s and ωz2= 37.9 krad/s.

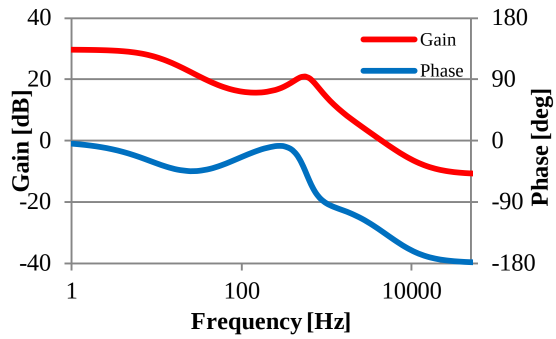
Figure 9 shows the frequency characteristics for the loop gain T_L . Two cases are studied: (a) $I_N = +2$ A, and at $I_N = -2$ A. The gain margin and the phase margin of case (a) are 11dB, 47.3 deg , respectively, and for case (b) are inf. dB , 105 deg, respectively. Results of Z_N is shown in **Fig. 10**. It is clear that Z_N for $I_N = +2$ (case (a) in T_L) is bigger than that for $I_N = -2$ (case (b) in T_L). Hence, Z_N conveys similar information for stability like the conventional one. Consequently, it is possible to use Z_N as stability criterion for dc power systems.

Table 1 The simulation and experimental circuit parameters.

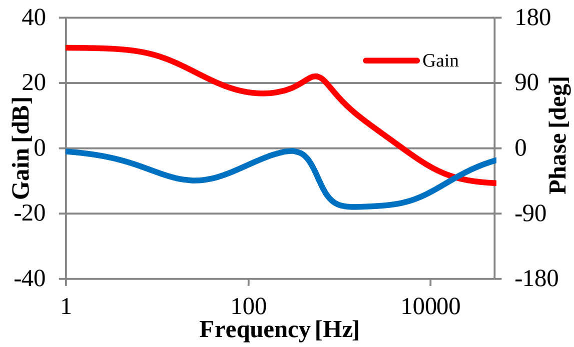
Symbol	Description	Value
V_B	Battery voltage	48 V
V_1	Voltage at node 1	24 V
V_2	Voltage at node 2	12 V
L_1	Inductance of the first converter	120μH
L_2	Inductance of the virtual conductor	80 μH
C_1	capacitance	100 μF
C_2	capacitance	200 μF
C_3	capacitance	330 μF
C_4	capacitance	100 μF
F	Switching frequency	100 kHz

4.2 Application example

Node impedance criterion is applied to a dc power system using a multi-level virtual conductor (MLVC) as shown in **Fig. 11**, at node (V_1). The MLVC is connected at

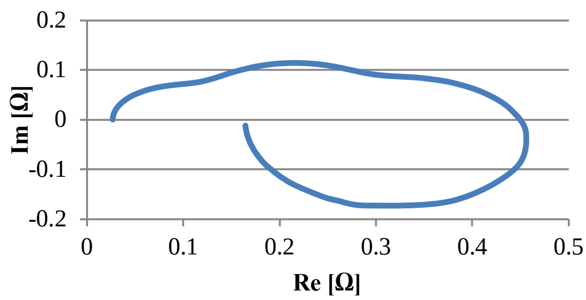


(a) I_N= + 2A

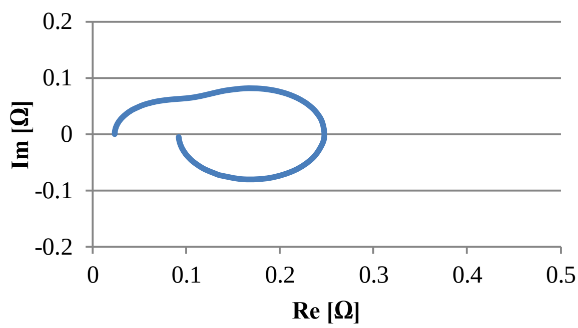


(b) I_N= - 2A

Fig. 9 Frequency characteristics of the loop gain T_L.



(a) I_N= + 2A



(b) I_N= - 2A

Fig. 10 Z_N is expressed in the complex plane.

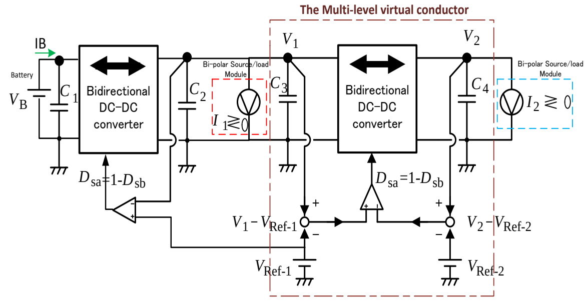


Fig. 11 Dc power supply using MLVC.

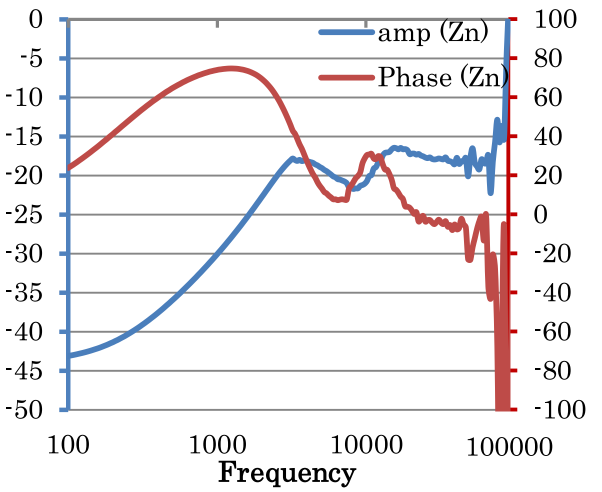


Fig. 12 Application of Z_N to dc power system to assess its stability (Analytical).

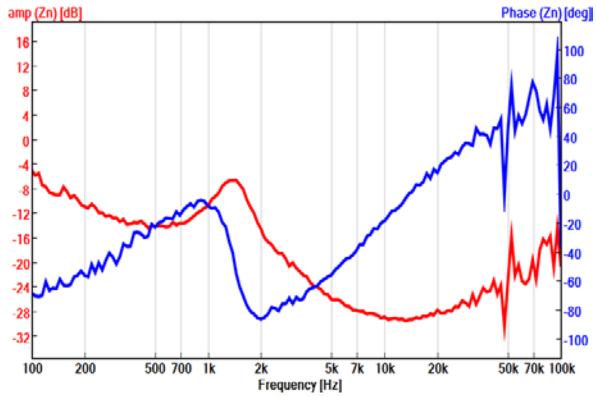


Fig. 13 Application of ZN to dc power system to assess its stability (Experimental).

its one end to a bi-polar current source (load/ source), and at the other end to another bi-polar current source and a battery via bidirectional converter. The circuit parameters are shown in **Table 1**. Simulation results for this node are shown in **Fig. 12**. Moreover, the experimental results, for the same node, are shown in **Fig. 13**. Based on these results together with applying the Z_N criterion; the system is stable at this node.

5. Conclusion

A new criterion for stability assessment in dc power system is presented in this paper. This criterion is node impedance criterion. The concept, mathematical, simulation, and experimental analysis of node impedance criterion, are investigated, as well. The results of node impedance criterion are compared with those of the conventional criterion. The comparison shows the validity of node impedance as a stability criterion. Moreover, node impedance criterion is applied to a dc power system using a MLVC to assess it stability.

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