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

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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 is 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.

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 \(\bar{x}(t) = [\bar{I}_1(t) \ \bar{V}_C(t)]^T\), the input vector \(u = [V_1 \ I_2]^T\), 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:

\[
G_{vvo}(s) = \frac{\Delta V_2(s)}{\Delta V_1(s)}\bigg|_{\text{open}} = \left[c(sI - A)^{-1}B + e\right]_{10}^T \tag{2}
\]

\[
G_{vio} = \frac{\Delta V_2(s)}{\Delta I_2(s)}\bigg|_{\text{open}} = \left[c(sI - A)^{-1}B + e\right]_{01} \tag{3}
\]

\[
G_{vdo}(s) = \frac{\Delta V_2(s)}{\Delta D(s)}\bigg|_{\text{open}} = c(sI - A)^{-1}b + e_p \tag{4}
\]

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:

\[
T(s) = \text{PWM} \cdot G_c(s) \cdot G_{vdo}(s) \tag{5}
\]

where:

\[
\text{PWM} : \text{PWM gain} \quad \quad G_c(s) : \text{Gain of compensator}
\]

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

\[
Z_2(s) = -\frac{\Delta V_2(s)}{\Delta I_2} = -\frac{G_{vdo}(s)}{1 - T(s)} \tag{6}
\]

### 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:

\[
Z_L(s) = \frac{\Delta V_2(s)}{\Delta I_2}\bigg|_{\text{feedback}} \tag{7}
\]

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

\[
T_L(s) = \frac{T(s)}{1 - T_L(s)} \tag{8}
\]

The characteristic equation as in (9)

\[
1 - T_L(s) = 0 \tag{9}
\]
Using (6) and (8) results in:

\[ 1 + \frac{Z_2(s)}{Z_L(s)} = 0 \]  

(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 radial 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.

![Fig. 5 Application of BDC in dc power supply.](image)

4. Nodal impedance and system stability

Regarding Fig. 6, when small current \( \Delta I_t \) is injected into the node; it will cause small change in the voltage \( \Delta V_2 \). Hence, node impedance \( Z_N \) can be calculated as follows:

\[ Z_N \approx \frac{\Delta V_2}{\Delta I_t} \]  

(11)

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

\[ Z_N(s) = \frac{Z_2(s)}{1 + Z_2(s)/Z_L(s)} \]  

(12)

When, \( \Delta I_t \) is an input and \( \Delta V_2 \) is considered output; therefore the characteristic equation is:

\[ 1 + \frac{Z_2(s)}{Z_L(s)} = 0 \]  

(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 $Z_L(s)$ is:

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

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

$$G_c(s) = -K \frac{1+s/\omega_z1}{1+s/\omega_p1} \frac{1+s/\omega_z2}{1+s/\omega_p2}$$  \hspace{1cm} (15)

where, $K = 0.0656$, $\omega_p1 = 417$ rad/s, $\omega_z1 = 64.9$ rad/s, $\omega_p2 = 3.44$ krad/s and $\omega_z2 = 37.9$ 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 11 dB, 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.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_b$</td>
<td>Battery voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>$V_1$</td>
<td>Voltage at node 1</td>
<td>24 V</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Voltage at node 2</td>
<td>12 V</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Inductance of the first converter</td>
<td>120 $\mu$H</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Inductance of the virtual conductor</td>
<td>80 $\mu$H</td>
</tr>
<tr>
<td>$C_1$</td>
<td>capacitance</td>
<td>100 $\mu$F</td>
</tr>
<tr>
<td>$C_2$</td>
<td>capacitance</td>
<td>200 $\mu$F</td>
</tr>
<tr>
<td>$C_3$</td>
<td>capacitance</td>
<td>330 $\mu$F</td>
</tr>
<tr>
<td>$C_4$</td>
<td>capacitance</td>
<td>100 $\mu$F</td>
</tr>
<tr>
<td>$F$</td>
<td>Switching frequency</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

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 $I_N = +2$ A.

Fig. 9 Frequency characteristics of the loop gain $T_L$.

Fig. 10 $Z_N$ is expressed in the complex plane.
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 its stability.

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