Design and simulation of DC distributed power supply with power balance control technique

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ABSTRACT

This paper presents the analysis, design and simulation of DC distributed power supply controlled with power and energy balance control technique. The proposed system consists of 5 connection structures of DC to DC converters which are parallel, cascade, source splitting, load splitting, and stack. The system mathematical model is analyzed by the average small-signal method. The proposed power balance control technique is used in the instance where the main sources supply the load of the system. The energy balance control technique is used in the case that the load at the 24 V and 12 V bus is backed up with a battery. The DC Distributed system is simulated by MATLAB/Simulink. The system has 1 kW power rating and contains 6 voltage bus with voltage ratings of 380, 100, 60, 48, 24, and 12 V. The simulation results show that, with the proposed power balance design and control technique, the system provides good dynamic responses and stability. In addition, the proposed technique simplifies the parameter design of the PI controller and solves the basic control limitations of the DC to DC converter.

Keywords: DC distributed power supply, Power balance control, Technique average small-signal method, MATLAB/Simulink simulation

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1. INTRODUCTION

From the 1960s, semiconductor technology development started and led to the development of power electronics converters (PECs), which improved the efficiency of DC power systems. As new technologies continue to emerge, power electronic converters have been continuously improved in terms of efficiency, reliability, cost, and size, to the point where DC distribution systems now demonstrate better efficiency than AC distribution systems [1]. For this reason, many facilities nowadays are designed to be more adequate for DC distribution systems, where many organizations accepted distributed bus voltage rating is 380 Vdc attributable to high efficiency, reasonable cost, and high reliability [2]. Numerous industry standards such as eMerge Alliance, the International Electrotechnical Commission (IEC), the Society of Cable Telecommunications Engineers (SCTE), the Alliance for Telecommunications Industry Solutions (ATIS), Underwriters Laboratories (UL), the formation of the International Telegraph Union-Telecommunication Standardization Sector (ITU-T), European Telecommunications Standards Institute
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(ETSI), the National Electrical Manufacturers Association (NEMA), and the National Electrical Code (NEC) have been working on standards related to 380 Vdc and a few industry standards are under development and some have already been established. Companies such as ABB Ltd., Emerson Electric Co., Hewlett-Packard Development Company (HP), Starline Inc., Schneider Electric Company, and GVA Lighting Inc., have started manufacturing appliances that are compatible with DC distribution systems with 380 Vdc distributed power bus and gaining popularity among telecom and data centers, and could also be used for commercial or residential buildings on a larger scale in the future [3]. In such systems, the control method of the converter circuit is crucial in ensuring stability, performance, reliability, and good response. Recent works suggested that effective control design can be achieved using current mode control and voltage mode control. However, such controls have downsides in terms of stability, performance, design complexity, including limitations caused by the non-minimum phase issue [4]−[7]. To overcome these limitations, various control techniques have been researched and developed [8]−[20] however, these control techniques are complicated in design and implementation. To solve the problems, the power balance control technique and energy balance control technique, which produce simpler control design and better performance compared to the regular voltage and current mode control, have been developed [21]−[25].

This paper aims to design, analyze, and simulate the DC distribution system in all possible connection structures (i.e., parallel, cascade, source splitting, load splitting, and stack) using power and energy balance control techniques to improve the performance of systems that are connected in various voltage bus structures in DC distribution systems. The proposed system has a total power rating of 1 kW and contains 6 voltage buses with voltage ratings of 380, 100, 60, 48, 24, and 12 V. The simulation is done with MATLAB/Simulink.

2. METHOD

The proposed DC distributed system shown in Figure 1 consists of 3 main parts: flyback #1-5, buck #1-4, and a bidirectional converter. The power balance equation of the system is:

\[
\sum_{i=1}^{N} \left[ V_{in1} I_{in1} k_{in1} \right] = \left[ V_{in2} I_{in2} + V_{in2} I_{in2} \right] - P_{load} = V_{in4} \left( I_{in4} k_{in4} + I_{in4} k_{in4} \right) - P_{load} = V_{in5} \left( I_{in5} + I_{in5} \right) - P_{load} \\
= V_{in5} \left( I_{in5} k_{in5} + I_{in5} k_{in5} + I_{in5} k_{in5} \right) = \left( V_{in6} I_{in6} - P_{load} \right) + \left( V_{in7} I_{in7} - P_{load} \right) + \left( V_{in8} I_{in8} - P_{load} \right) 
\]

(1)

Figure 1. The proposed 1 kW distribution system

2.1. Design consideration

The systems with power balance control technique are shown in Figures 2 (a)-(c) shows the bidirectional converter designed to work in continuous current mode (CCM). The inductance value of buck converter is:

\[
L_{\text{min}} = \frac{(1 - D) R}{2 f_{SW}}
\]

(2)
where $L_{\text{min}}$ is the minimum inductance value, $D$ is the duty cycle, $R$ is the output impedance, $f_{\text{SW}}$ is switching frequency. $\Delta V_o$ is output voltage ripple. The capacitance value for the output capacitor of a buck converter is:

$$C = \frac{1-D}{8L(\Delta V_o / V_o)f_{\text{SW}}^2}$$

(3)

For the flyback converter, the minimum inductance is:

$$L_{\text{min}} = \left(\frac{(1-D)^2 R}{2f_{\text{SW}}}ight)^2 \left(\frac{N_1}{N_2}\right)^2$$

(4)

Figure 2. Converters with power balance control technique (a) flyback converter, (b) buck converter, and (c) bidirectional converter

The output capacitance of the flyback converter is:

$$C = \frac{D}{R \cdot f_{\text{SW}}(\frac{V_{\text{in}}}{V_{\text{out}}})}$$

(5)
The mathematical model of the modules in the system has been derived to simulate and study the dynamic response obtained from MATLAB/Simulink, as well as to analyze the compatibility for connecting the modules in all proposed connection structures in the DC distributed power supply. If $u = 1$ is the ON state of the switching, $u = 0$ is the OFF state of the switching, and $1-u = \bar{u}$, the inductor current equation of the flyback converter is:

$$i_L(s) = \frac{1}{sL} \left[ uV_o(s) - \bar{u}V_o(s) \left( \frac{N_1}{N_2} \right) \right]$$

(6)

The output capacitor voltage equation of the flyback converter is:

$$V_c(s) = \frac{1}{sC} \left[ \bar{u}I_L(s) \left( \frac{N_1}{N_2} \right) - I_R(s) \right]$$

(7)

The inductor current equation of the buck converter is:

$$I_L(s) = \frac{1}{sL} \left[ uV_o(s) - V_o(s) \right]$$

(8)

The output capacitor voltage equation of the buck converter is:

$$V_c(s) = \frac{1}{sC} \left[ I_c(s) - I_R(s) \right]$$

(9)

### 2.2. Average small signal analysis

The proposed system control technique is based on the idea of power balance, which states that the input and output power of the system is equal. Suppose that the system is lossless, thus, the average small-signal model of the power balance equations of buck and flyback converters can be obtained as follows:

For load splitting, and normal structure:

$$V_o k_B I_L = \sum_{i=1}^N V_i I_i$$

(10)

For source splitting, and paralleling:

$$\sum_{i=1}^N k_B V_i I_i = \frac{V_{load}}{N}$$

(11)

where $V_in$ is the input voltage, $V_o$ is the output voltage, $I_L$ is inductor current, $I_{load}$ is load current, $N$ is a number of output bus parallel-connected modules, and $k_B$ is the duty cycle, which is considered as loop gain.

From the power balance equations, the reference inductor current equation can be determined by the inductor current calculator. $i_{PCB}$ is the inductor current that is calculated based on load current, output voltage, input voltage, and the number of paralleled modules $N$. The peak value of $i_{PCB}$ can be derived as:

$$i_{PCB} k_B V_{in} = \frac{V_{load}}{N}$$

(12)

where $i_{ref}$ is the value of the inductor current, $i_{VR}$ is the correcting signal of the PI controller, $i_{PCB}$ is the peak value of the inductor reference current. The peak value of the inductor current is:

$$i_{ref} = i_{PCB} + i_{VR}$$

(13)

The dynamic equation of the output voltage is:
\[
\sum_{i=1}^{N} i_{Li} = C \frac{dv}{dt} + i_{\text{load}}
\]  
(14)

Performing the perturbations and small-signal approximation in (10) to (14) yields:

\[
G_{\text{in}} = \frac{k_{\text{in}} n_{\text{ref}}}{V_o}, G_{\text{L}} = \frac{k_{\text{L}} n_{\text{ref}}}{V_o}, G_{\text{L}} = \frac{I_{\text{ref}}}{V_{\text{ref}} k_{\text{L}} n_{\text{ref}}}, F_{\text{load}} = \frac{V_o}{k_{\text{L}} n_{\text{ref}}}, F_{\text{ref}} = \frac{I_{\text{load}}}{k_{\text{L}} n_{\text{ref}}}, F_{\text{in}} = \frac{V_o I_{\text{load}}}{V_o^2}
\]

The output current, the peak value of the inductor reference current, and output inductance can be expressed as:

\[
\tilde{i}_o = G_{\text{in}} \tilde{V}_{\text{in}} + G_1 \tilde{I}_{\text{ref}} - G_2 \tilde{V}_o
\]  
(15)

\[
\tilde{i}_{\text{PBC}} = F_{\text{load}} \tilde{I}_{\text{load}} - F_{\text{i}} \tilde{V}_{\text{i}} + F_{\text{v}} \tilde{V}_{\text{m}}
\]  
(16)

\[
Z_L(S) = \frac{1}{C_s} = \frac{-\tilde{V}_o}{\tilde{i}_o - i_{\text{load}}}
\]  
(17)

From (15) to (17) and the output voltage equation can be written as a block diagram as shown in Figure 3. From Figure 3, applying Mason's gain method, the output voltage loop can be shown in Figure 4. The power balance control technique consisted of an inductor current calculation block and PI controller. The output voltage will be compared with the desired reference voltage. The inductor current calculation block computes the reference input current. Then, the error signal will be compensated by the proposed PI controller. Then, the output summation signal will be compared with the input inductor current. Finally, the result command signal will be processed by pulse width modulation (PWM) or hysteresis current control, generating the signal to the gate drive circuit to control the switch. The proposed control technique can be simply implemented by analog and digital circuits.

Figure 3. Block diagram of a converter in the proposed system with power balance control technique

Figure 4. Block diagram of the output voltage loop

Where \( G_{k_b} \) is the PI controller and \( k_{fb} \) is the feedback gain, the output voltage can be expressed as:

\[
\frac{\tilde{V}_o}{V_{\text{ref}}} = \frac{G_{k_b} k_{fb} n_{\text{ref}}}{V_o CS + G_{k_b} k_{fb} n_{\text{ref}} k_{fb}}
\]  
(18)

The open-loop transfer function (OLTF) of the output voltage can be expressed as:
\[ \text{OLTF} = \frac{V_c K_p}{V_{CS}} \] (19)

### 2.3. Control strategy

The control strategy requires a feedback compensation process to regulate the output voltage over the output load variation and input voltage. The frequency gain and location of the zero must be selected for the compensation network, the steady-state error of the output voltage should also be as small as possible. From the proposed system output voltage transfer functions can investigate using Bode diagrams to get the desired frequency and phase shift. The equation of PI controller for voltage regulation is:

\[ G_{ir}(s) = K_c + \frac{\omega_z}{s} \] (20)

Figures 5 and 6 show the Bode diagrams of the proposed system’s output voltage, the PI controllers, and open-loop transfer functions. Each part has about 85-90 degrees of phase margin, enough to stabilize the system.

![Figure 5. Bode diagrams of the proposed systems (380 Vdc bus)](image)

![Figure 6. Bode diagrams of the proposed systems (100, 60, 48, 24, and 12 Vdc bus)](image)
3. RESULTS AND DISCUSSION

Figure 7 shows the simulation results of the proposed system. The transient response effectiveness of the system is investigated by MATLAB/Simulink to verify the control algorithm and evaluate the performance of the system, using the calculated specification shown in Table 1. Figure 7 (a) shows the responses of bus voltage and load current at the 380 V, 100 V, 60 V, 48 V, 24 V, and 12 V bus. Figure 7 (b) shows the state of charge, current, and voltage of the battery. From 0-0.1s, the system initialization starts and has full load at 100% as designed. At 0.1s, a sudden step down of the system’s load from 100% (1 kW) to 10% (100 W) occurs. At 0.2s, a sudden step up of the system’s load from 10% (100 W) to 100% (1 kW) occurs. Then, at 0.3s, a sudden cut off of the system main sources occurs, then the bidirectional converter with energy balance control technique connected to the battery maintains the stability of the voltage at the 24 V and 12 V bus. Then, at 0.4s and 0.5s are sudden step down from 100% (400 W) to 10% (40 W) and step up from 10% (40 W) to 100% (400 W) of the load. The simulation results demonstrated the stability, reliability, and fast dynamic responses of the systems with the proposed control technique.

![Figure 7](image_url)

Figure 7. Simulation results (a) bus voltage and current and (b) battery state of charge (SOC), current, and voltage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flyback#1</th>
<th>Flyback#2</th>
<th>Flyback#3</th>
<th>Flyback#4-5</th>
<th>Buck#1</th>
<th>Buck#2</th>
<th>Buck#3</th>
<th>Buck#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage, $V_{in}$</td>
<td>60 V</td>
<td>50 V</td>
<td>311 V</td>
<td>380 V</td>
<td>100 V</td>
<td>24 V</td>
<td>100 V</td>
<td>100 V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>200 V</td>
<td>180 V</td>
<td>380 V</td>
<td>100 V</td>
<td>24 V</td>
<td>12 V</td>
<td>48 V</td>
<td>60 V</td>
</tr>
<tr>
<td>Inductance</td>
<td>666 µH</td>
<td>479 µH</td>
<td>9.14 mH</td>
<td>195.90 µH</td>
<td>136.80 µH</td>
<td>25.5 µH</td>
<td>3.8 mH</td>
<td>4.5 mH</td>
</tr>
<tr>
<td>Output capacitance</td>
<td>480 µF</td>
<td>600 µF</td>
<td>150 µF</td>
<td>1600 µF</td>
<td>800 µF</td>
<td>1200 µF</td>
<td>1300 µF</td>
<td>800 µF</td>
</tr>
<tr>
<td>Output voltage ripple</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Total output power</td>
<td>200 W</td>
<td>300 W</td>
<td>500 W</td>
<td>850 W</td>
<td>400 W</td>
<td>300 W</td>
<td>150 W</td>
<td>150 W</td>
</tr>
</tbody>
</table>

$K_e$, $K_I$ of the PI controller | 8,800 | 8,800 | 8,800 | 4,400 | 50,500 | 10,2000 | 4,400 | 4,400
4. CONCLUSION

This work presents the design and simulation of distributed power supply in DC architecture with power and energy balance control technique for the proposed 1 kW distribution system that contains 6 voltage bus with voltage ratings of 380, 100, 60, 48, 24, and 12 V, consisted of 5 connection structures. The proposed average small-signal analysis and control technique is able to simplify the parameters design of the PI controller and solve the basic control limitations of the DC-to-DC converters. The system has been simulated by MATLAB/Simulink in various scenarios including normal operation with full load, operation with sudden load change including step down from 100% to 10% at 0.1s and 0.4s. Step up from 10% to 100% at 0.2s and 0.5s. And in the event that the main sources stopped supplying power to the system at 0.3s, the battery started to supply the energy to maintain the 24 V and 12 Vdc bus voltage with the energy balance control technique. The simulation results demonstrate stable system stability and dynamic response. The proposed technique can also reduce the size of the output capacitor due to the reduction of output voltage ripple in the steady state, resulting in the increase of the power density of the system. The results from this work can be applied to DC distribution systems that are likely to become prevalent in the future.

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