ABSTRACT

The analysis for a given Soft-Switching DC-DC converter family can be generalized using the switching-cell of that family leading to a number of generalized equations with a Transformation Table. In this paper, the concept of generalization and step by step procedure for the generalized process are discussed and applied to selected soft-switching families such as ZVS-QRC, ZCS-QRC, ZCS-CC QSW, ZVS-CV QSW, ZCT-PWM, and ZVT-PWM. Also, it has been noted that all the analyzed families have one Generalized Transformation Table. It will be shown that the Generalized Analysis leads to several advantages.

1. INTRODUCTION

Over the last ten years, many soft-switching dc-dc converter families were introduced in the open literature [2-7]. The objectives of many of these topologies are to develop high switching converters with high power density and high efficiency. This was accomplished by adding additional components to the power stage to either limit the resonant period and/or to utilize power device parasitic components. As a result of adding an additional auxiliary circuitry (additional resonant components and auxiliary switches and diodes), the steady-state analysis of soft-switching topologies tend to be cumbersome time consuming, and provided little insight into the converter operation.

In this paper, it will be shown that the analyses of the soft-switching dc-dc converters can be generalized for a given switching network family. As a result, instead of analyzing each converter topology in a given family separately, only one switching network for each family is needed to be analyzed. By using generalized parameters, it is possible to generate a single transformation table from which the voltage converter ratios and other important design parameters for each converter can be obtained directly. The derivation of the model is obtained from studying the switching network modes of operation and by expressing the switching intervals in terms of the converter design parameters such as gain, normalized frequency, and normalized load. Using the proposed generalized analysis, it is possible to analyze a complete dc-dc converter family as simple as analyzing one converter topology. Moreover, re-design of converter family is made much easier due to the flexibility in generalized parameter variation. Finally, since the parameters are generalized, it is much easier to obtain steady-state design curves using such simpler mathematical models. Such characteristic curves are used to carry out converter design and provide design information about the converter voltage and current characteristics.

In this paper, generalized switching cells are derived for selected dc-dc soft-switching PWM families including the conventional hard-switching PWM topologies. The generalized cells were derived for the following well-known families: 1) Zero-Voltage-Switching (ZVS) and Zero-Current-Switching (ZCS) – Quasi-Resonant Converter (QRC) families [2], 2) ZVS-Clamped Voltage (CV) Quasi-Square-Wave (QSW) family [3,4], 3) ZCS-Clamped-Current (CC) QSW family [5], and 4) Zero-Voltage-Transition (ZVT) and Zero-Current-Transition (ZCT) PWM families [6,7].

The concept and the process of generalized cells will be discussed in Section 2. Specific two examples of a soft switching ZVT-PWM and ZVS-QRC families will be presented in Section 3 to illustrate how the generalized analysis is carried out. Finally, the conclusion will be given in Section 4.

2. GENERALIZED SWITCHING-CELLS AND THEIR TRANSFORMATION TABLE

Figure (1) shows the switching-cells for the seven families mentioned above. Since each family uses the same switching network (same modes of operation) and the same waveform shapes, the analysis can be generalized. The following steps can be used in the analysis generalization process:

1. Analyze the switching network modes of operation.
2. Derive the interval times for each mode.
3. Use the switching network output side to derive the gain. As an example, if the output side is a diode, use the diode average voltage or the diode average current, whatever available and easier, to derive the gain.
4. Normalize and Generalize the resultant equations by defining suitable normalized parameters.
5. Form the Transformation Table.
6. Use the generalized analysis done in steps 1 to 4 to derive the stresses equations and other design parameters for the analysis and design.

3. GENERALIZED ANALYSIS FOR TWO SELECTED FAMILIES

Because of the space limitation, the complete analysis for the seven families that mentioned in Section 1 could not be included here. So, part of the generalization analysis results for the ZVT-PWM and ZVS-QRC families will be given here as an example.

Let us define the following parameters:

1. \( M \) : The over all output-to-input converter voltage gain,
   \[ M = \frac{V_o}{V_i} \]
2. \( V_{nf} \) : The normalized cell-input voltage to the converter input voltage,
   \[ V_{nf} = \frac{V_i}{V_m} \]
3. \( I_{nf} \) : The normalized cell-output current to the converter output current,
   \[ I_{nf} = \frac{I_f}{I_o} \]
4. \( V_{nf} \) : The normalized constant filter capacitor \( C_f \) voltage to the converter input voltage,
   \[ V_{nf} = \frac{V_f}{V_m} \]
5. \( I_{nf} \) : The normalized constant filter inductor \( L_f \) current to the converter output current,
   \[ I_{nf} = \frac{I_f}{I_o} \]

\( V_m, I_m, nFV, nFI, nT, nFIV, nTIV, nFI, IV, TIV, I, F, o, III-507 \)
6. \( Z_0 \): The characteristic impedance, \( Z_0 = \sqrt{L_0/C_0} \).

7. \( Q \): The normalized load, \( Q = \frac{R}{Z_0} \). Where \( R \) is the converter load resistor.

8. \( f_s \): The switching frequency, \( f_s = \frac{1}{T_s} \). Where \( T_s \) is the switching period.

9. \( f_n \): The natural frequency, \( f_n = \frac{1}{2\pi \omega_n} \). Where

\[ \omega_n = \frac{1}{\sqrt{L C}}. \]

10. \( f_m \): The normalized frequency, \( f_m = \frac{f_m}{f_n} \).

11. \( D \): The duty ratio of the main switch.

12. \( D_1 \): The duty ratio of the auxiliary switch.

13. \( \alpha, \beta, \gamma, and \ \delta \): The intervals for the modes of operation.

The generalized equations for each family shown in Figure (1) will include one or more of the following previous defined normalized parameters (\( V_{ng}, I_{nf}, V_{ng}, I_{nf}, V_{nd}, I_{nf} \)), depending on the topology of the switching cell itself.

By applying the switching cells of Figure (1) to the conventional DC-DC converters (Buck, Boost, Buck-Boost, Cuk, Zeta, and Sepic), a transformation table for each family can be generated. It has been noted that when two or more switching cells share the same normalized parameter, they will have the same transformation quantity for that parameter. So, one transformation table can be generalized for all the families and only the parameter that is applicable for specific family generalized equations can be used. It can be shown that the single transformation table given in Table (1) is complete and applies to all the families given in Section I.

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>( V_{ng} )</th>
<th>( V_{nf} ) or ( I_{nf} )</th>
<th>( V_{nd} )</th>
<th>( I_{nf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>1</td>
<td>1-M</td>
<td>-M</td>
<td>1</td>
</tr>
<tr>
<td>Boost</td>
<td>M</td>
<td>1</td>
<td>1-M</td>
<td>M</td>
</tr>
<tr>
<td>Buck-Boost, CUK, Zeta, and Sepic</td>
<td>1+M</td>
<td>1</td>
<td>-M</td>
<td>1+M</td>
</tr>
</tbody>
</table>

3.1 Generalized Analysis Results for the ZVT-PWM Family:

Figure (1f) shows the switching network for this family. The switching waveforms of the modes of operation are shown in Figure (2). The generalized analyses for the switching-cell yields to the following generalized equations:
\[ \alpha = \omega_o (t_1 - t_2) = \frac{MI_{nF}}{QV_{ng}} \quad \text{(Mode 1)} \]  

\[ \beta = \omega_o (t_2 - t_1) = \frac{\pi}{2} \quad \text{(Mode 2)} \]  

\[ \gamma = \omega_o (t_6 - t_5) = \frac{QV_{ng}}{MI_{nF}} \quad \text{(Mode 3)} \]  

\[ \frac{V_{Dh}}{V_{ng}} = -(D + D_1) + \frac{f_{ns}}{2\pi} (1 + \alpha - \frac{\gamma}{2}) \quad \text{(Gain Equation)} \]  

The equations for a specific converter can be easily obtained using Table (1). The generalized equations were plugged in the MathCad software to obtain the switching cell properties for design purposes. Figure (3) shows the control characteristic curves of the ZVT-PWM Buck, Boost, Buck-Boost, Cuk, Zeta, and Sepic.

Other properties can be also obtained from the generalized analysis such as switches and component stresses and the range for the soft-switching conditions. As an example, the generalized equation for the soft-switching condition for the ZVT-PWM switching cell is given by:

\[ D_1 \geq \frac{f_{ns}}{2\pi} \left( \alpha + \frac{\pi}{2} \right) \]  

Also, the normalized average main switch voltage is given by:

\[ V_{n,avg} = \frac{V_{n,avg}}{V_{in}} = \frac{f_{ns}}{2\pi} V_s \left[ 1 + \alpha + \frac{\gamma}{2} + \frac{2\pi}{f_{ex}} \left( 1 - D - D_1 - \frac{f_{ns}}{2\pi} \gamma \right) \right] \]  

3.2 Generalized Analysis of the ZCS-QRC Family:

Figure (1c) shows the switching network for this family. The switching waveforms of the modes of operation are shown in...
The generalized analyses for the switching-cell yields to the following five generalized equations:

\[ \alpha = \alpha_1 (t_1 - t_0) = \frac{M_{sf}}{QV_{ng}} \] (Mode 1) \hfill (7)

\[ \beta = \alpha_1 (t_2 - t_1) = \sin^{-1} \left( -\frac{M_{sf}}{QV_{ng}} \right) \] (Mode 2) \hfill (8)

\[ \gamma = \alpha_1 (t_3 - t_2) = \frac{QV_{ng}}{M_{sf}} (1 - \cos \beta) \] (Mode 3) \hfill (9)

\[ \delta = \alpha_1 ((t_0 + T_s) - t_3) = \frac{2\pi}{f_{ns}} - \alpha - \beta - \gamma \] (Mode 4) \hfill (10)

\[ V_{nd} = \frac{f_{ns}}{2\pi} \left[ \frac{M_{sf}}{2Q} \gamma^2 - V_{ng} (\beta + \gamma - \sin \beta - \gamma \cos \beta) \right] \] (Gain Equation) \hfill (11)

The equations for a specific converter can be easily obtained using Table (1). From the previous generalized equations, other advanced properties can be also generalized such as switch stresses and conversion conditions. As an example, the generalized switch peak current \( I_{n,Sp} = \frac{I_{n,Sp}}{I_{o}} \) is:

\[ I_{n,Sp} = I_{n,Sp} + \frac{QV_{ng}}{M} \] (12)

The generalized equations were plugged in the MathCad software to obtain the switching cell properties for design purposes as was done in Section (3.1). By choosing the ZCS-QRC Boost converter here as an example, the normalized control characteristics for the ZCS-QRC boost converter is obtained as shown in Figure (5).

4. CONCLUSION

A generalized analysis method for families of soft-switching dc-dc converters was proposed in this paper. The generalization technique is applied to several well-known switching families including QRC, QSC, and PWM converters. It is shown that a single Generalized Transformation Table for all the families is exist. This leads to several advantages such as improving the computer-aided analysis and design and simplified mathematical modeling and more insight into the converter operation. The generalized equations for each family can be easily used in the analysis of any new converter that uses the same switching cell. This is done by finding the generalized parameters for the new converter and then substitute in the generalized equations. Two examples were given for illustration purposes.

5. REFERENCES