Generalized Analysis of Soft-Switching DC-DC Converters

Jaber Abu-Qahouq and Issa Batarseh

Department of Electrical and Computer Engineering
University of Central Florida
Orlando, FL 32816
Email: batarseh@mail.ucf.edu

ABSTRACT

In this paper, based on the switching-cell approach, a generalized steady state analysis for families of soft-switching dc-to-dc converters will be presented. Complete generalized design equations will also be given. 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, QSW-CC, QSW-CV, ZCT-PWM, and ZVT-PWM. Also, it has been noted that all the analyzed families have one Generalized Transformation Table. The basic generalized equations will be summarized and the cell-to-cell comparison will be introduced. 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 switching-cell 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 simpler mathematical models. Such characteristic curves are used to carry out converter design and provide design information about the converter voltage and current stresses.

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 along with their switching waveforms. In Section 3, the generalized parameters and transformation table will be defined and discussed. Section 4 gives the summary of the basic generalized equations for the selected cells. The cell-to-cell comparison will be introduced in Section 5. Section 6 will include examples of other generalized equations that can be derived. A comparison between the theoretical and simulation results will be made in Section 7. Finally, Section 8 will include the conclusion.

2. THE GENERALIZED SWITCHING-CELLS

The block diagram representation for a generalized switching-cell is given in Figure (1). Figure (2) shows the six soft-switching cells for the families mentioned above in addition to the conventional cell, while Figure (3) shows the basic switching-waves for the soft switching cells. 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. Define the generalized switching-cell and the generalized parameters for it.
2. Define the generalized switching waveforms for the generalized switching-cell.
3. Analyze the switching network modes of operation.
4. Derive the time interval for each mode.
5. Use the switching network output side to derive the gain. As an example, if the output side is a diode, use the diode voltage or the diode current, whatever available and easier, to derive the gain. Or in general, find another equation that relates the cell output to the cell input.
6. Normalize and generalize the resultant equations by defining suitable normalized parameters.
7. Use the generalized analysis done in the steps from 1 to 6 to derive the stress equations and other design parameters for the analysis and design.

3. THE GENERALIZED PARAMETERS AND TRANSFORMATION TABLE

Various orientations of any of the cells in Figure (2) result in a family of converters. Using the three terminals a, b, and c in the switching-cells, generalized parameters can be defined and their values can be determined from the orientation of the cell in a specific converter. Let us define the following parameters:
Figure (1): Block Diagram Representation for the Switching-Cell

Figure (2): Switching-Cells: (a) Conventional Cell, (b) ZVS-QRC Cell, (c) ZCS-QRC Cell, (d) ZVS-QSW CV Cell, (e) ZCS-QSW CC Cell, (f) ZVT-PWM Cell, and (g) ZCT-PWM Cell

1. $M$: The overall input-to-output converter voltage gain, $M = \frac{V_o}{V_i}$.

2. $V_{\text{in}}$: The normalized cell-input voltage to the converter input voltage, $V_{\text{in}} = \frac{V_i}{V_o}$.

3. $I_{\text{out}}$: The normalized cell-output current to the converter output current, $I_{\text{out}} = \frac{I_o}{I_i}$.

4. $V_{\text{out}}$: The normalized filter capacitor ($C_f$) voltage to the converter input voltage, $V_{\text{out}} = \frac{V_f}{V_o}$. 
Figure (3): Switching-Cells Basic Waveforms: (a) ZVS-QRC Cell, (b) ZCS-QRC Cell, (c) ZVS-QSW CV Cell, (d) ZCS-QSW CC Cell, (e) ZVT-PWM Cell, and (f) ZCT-PWM Cell
5. \( V_{\text{inc}} \): The normalized cell-output voltage to the converter input voltage, \( V_{\text{inc}} = \frac{V_{\text{out}}}{V_{\text{in}}} \).

6. \( I_{\text{inc}} \): The normalized cell-current entering node \( b \) to the converter output current, \( I_{\text{inc}} = \frac{I_b}{I_o} \).

7. \( Z_a \): The characteristic impedance, \( Z_a = \frac{I_b}{V_o} \).

8. \( Q \): The normalized load, \( Q = \frac{R}{Z_o} \), where \( R \) is the converter load resistor.

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

10. \( f_s \): The resonant frequency, \( f_s = \frac{1}{2\pi\omega_s} \).

Where \( \omega_s = \frac{1}{\sqrt{LC}} \).

11. \( f_{sw} \): The normalized frequency, \( f_{sw} = \frac{f_s}{f_o} \).

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

13. \( D_i \): The duty ratio of the auxiliary switch.

14. \( \alpha, \beta, \gamma, \delta, \rho, \lambda, \sigma \): The conduction intervals for the modes of operation.

The generalized equations for each cell shown in Figure (2) will include one or more of the following previous defined normalized parameters (\( V_{\text{ng}}, I_{\text{ng}}, V_{\text{af}}, I_{\text{af}}, V_{\text{abc}}, I_{\text{abc}} \)), depending on the topology of the switching cell itself. It must be noted that all the voltages are normalized with respect to \( V_{\text{in}} \), while all the current are normalized with respect to \( I_s \).

By applying the switching cells of Figure (2) to the conventional DC-DC converters (Buck, Boost, Buck-Boost, Cuk, Zeta, and Sepic), a transformation table for each family can be generated. It is interesting to point out 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 cells given in Figure (2).

The characteristics of this table can be summarized as follows:

- As mentioned above, when two or more switching cells share the same generalized parameter, they will have the same transformation quantity for that parameter.

- \( V_{\text{ng}} = I_{\text{af}} \). This can be explained by the conservation of energy theory, the input energy is equal to the output energy, and it is for the buck converter as follows: \( E_{\text{in}} = E_{\text{o}} \Rightarrow V_{\text{ng}}I_{\text{af}} = V_oI_o \Rightarrow V_{\text{ng}} = (M)V_o \Rightarrow V_{\text{ng}}I_{\text{af}} = V_oI_o \Rightarrow V_{\text{ng}} = I_{\text{af}} \).

- \( V_{\text{af}} = I_{\text{af}} = I_{\text{abc}} = V_{\text{abc}} + V_{\text{abc}} \). This is self-explained and can be proved by applying KVL and KCL to the cells.

- As a result of the above-mentioned characteristics, the generalized parameters of the switching-cells of Figure (2) can be reduced to only two generalized parameters: \( V_{\text{ng}} \) and \( V_{\text{abc}} \).

### 4. GENERALIZED ANALYSIS RESULTS FOR THE SELECTED FAMILIES

Table (2) shows the basic generalized equations (the intervals and gain equations) for the selected soft-switching cells. Because of the simplicity of the conventional cell analysis generalization, it is not included in the table. However, it can be shown that the generalized basic gain equations for the conventional cell under the CCM (Continuous Conduction Mode) and DCM (Discontinuous Conduction Mode) operations are:

\[
\frac{V_{\text{abc}}}{V_{\text{ng}}} = -D \quad \text{CCM} \tag{1}
\]

\[
\frac{V_{\text{abc}}}{V_{\text{ng}}} = \frac{-D}{D_{\text{DCM}}} \quad \text{DCM} \tag{2}
\]

Where \( D_{\text{DCM}} \) is the ratio of the time when both the switch and the diode are OFF.

It must be noted that the generalization of the conventional cell can be extended by including the inductor at node \( c \) and analyzing the cell for both modes of operation (CCM and DCM).

The following assumption have been made when the soft-switching cells in Figure (2) are analyzed:

1. The circuit is under steady-state operation.
2. The transistors and diodes are ideal devices.
3. The reactive elements are lossless, linear, passive, time-invariant, and do not have parasitic components.
4. The filter inductor in which \( I_f \) passes through is very large so that \( I_f \) is constant (constant current source).
5. The output and filter capacitors are much larger than the resonant capacitor and can be treated as a constant voltage sources.
6. All inductors are much larger than the resonant inductor and can be treated as constant current sources.
7. The switching frequency is less than the resonant frequency.

The generalized equations of Table (2) can be validated to a specific converter by substituting for the generalized parameters from Table (1). These equations can be used to plot the characteristic curves for the design purposes.

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Table (1): Generalized Transformation Table

<table>
<thead>
<tr>
<th>Converter</th>
<th>( V_{\text{ng}}, I_{\text{af}} )</th>
<th>( V_{\text{af}}, I_{\text{af}}, I_{\text{abc}} )</th>
<th>( V_{\text{abc}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>1</td>
<td>1-M</td>
<td>-M</td>
</tr>
<tr>
<td>Boost</td>
<td>M</td>
<td>1</td>
<td>1-M</td>
</tr>
<tr>
<td>Buck-Boost, Cuk, Zeta, and Sepic</td>
<td>1+M</td>
<td>1</td>
<td>-M</td>
</tr>
<tr>
<td>CELL</td>
<td>α</td>
<td>β</td>
<td>γ</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>Quasi Resonant Converters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ZVS</strong></td>
<td>( \frac{QV_a}{MI_a} )</td>
<td>( \sin^{-1}(\frac{QV_a}{MI_a}) )</td>
<td>( \frac{MI_a}{QV_a}(1-\cos\beta) )</td>
</tr>
<tr>
<td><strong>ZCS</strong></td>
<td>( \sin^{-1}(\frac{MI_a}{QV_a}) )</td>
<td>( \frac{QV_a}{MI_a}(1-\cos\beta) )</td>
<td>( \frac{2\pi}{f_{in}} - \alpha - \beta - \gamma )</td>
</tr>
<tr>
<td><strong>Quasi Square Wave</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ZVS CV</strong></td>
<td>( \alpha = \pi - \cos^{-1}(\frac{V_{ag}}{Q}) )</td>
<td>( \frac{M(I_{ag}-I_{sw})}{V_{ag}-V_{sw}} )</td>
<td>( \pi - \cos^{-1}(\frac{V_{ag}}{V_{ag}-V_{sw}}) )</td>
</tr>
<tr>
<td><strong>ZCS CC</strong></td>
<td>( \alpha = \pi - \cos^{-1}(\frac{I_{ag}-I_{sw}}{I_{ag}}) )</td>
<td>( \frac{(I_{ag}-I_{sw})\sin\alpha}{I_{ag}} )</td>
<td>( \frac{1}{Q}\frac{V_{ag}-V_{sw}}{V_{ag}}\cos\alpha )</td>
</tr>
<tr>
<td><strong>Transition PWM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ZVS</strong></td>
<td>( \frac{MI_a}{QV_a} )</td>
<td>( \frac{\pi}{2} )</td>
<td>( \frac{2\pi}{f_{in}} D_1 - \alpha - \beta )</td>
</tr>
<tr>
<td><strong>ZCS</strong></td>
<td>( \frac{\pi}{2} + \beta_d )</td>
<td>( \pi - \alpha )</td>
<td>( \frac{2\pi}{f_{in}} [1-D]-\beta-\beta_d )</td>
</tr>
</tbody>
</table>

Where:

\[
\alpha = \sqrt{\frac{M}{Q}(I_{ag}-I_{sw})^2 + V_{ag}^2} \quad b = \sqrt{(I_{ag}-I_{sw})^2 + \left(\frac{Q}{M}V_{ag}-V_{sw}\right)^2} \quad I_{s,10} = -\frac{Q}{M}V_{ag}\delta + \frac{Q}{M}V_{ag}(V_{ag}-V_{sw})\sin\gamma + I_{sw} \\
V_{sw} = V_{ag} + \frac{M}{Q}(I_{ag}\sin\gamma - (I_{ag}-I_{sw})\delta) \quad \beta_d = \text{The time delay between turning OFF } S \text{ and } S_1 \quad I_{s,11} = I_{ag} - \frac{Q}{M}V_{ag}\sin\alpha - (I_{ag} - I_{sw})\cos\alpha
\]
Table (3): Some of the Main Switch Generalized Stress Equations

<table>
<thead>
<tr>
<th>CELL</th>
<th>( V_{\text{m,peak}} )</th>
<th>( I_{\text{m,peak}} )</th>
<th>( V_{\text{m,ave}} )</th>
<th>( I_{\text{m,ave}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi Resonant Converters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS</td>
<td>( V_{\text{m}} + \frac{M_{\text{af}}}{Q} )</td>
<td>( I_{\text{af}} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} + \frac{QV_{\text{ac}}}{M} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} )</td>
</tr>
<tr>
<td>Quasi Square Wave</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS CV</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} - I_{\text{a,l}} &gt; 2I_{\text{af}} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS CC</td>
<td>( V_{\text{m}} - V_{\text{ss}} &gt; 2V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} + \frac{f_{\text{ss}}}{\pi} \tan \beta_{\text{d}} )</td>
</tr>
<tr>
<td>Transition PWM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
<td>( V_{\text{af}} + V_{\text{ac}} )</td>
<td>( I_{\text{af}} - I_{\text{af}} )</td>
</tr>
</tbody>
</table>

Table (4): Some of the Diode Generalized Stress Equations

<table>
<thead>
<tr>
<th>CELL</th>
<th>(-V_{\text{d,peak}})</th>
<th>( I_{\text{d,peak}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi Resonant Converters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS</td>
<td>( V_{\text{m}} )</td>
<td>( 2I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS</td>
<td>( 2V_{\text{m}} )</td>
<td>( I_{\text{af}} + \frac{QV_{\text{ac}}}{M} )</td>
</tr>
<tr>
<td>Quasi Square Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS CV</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} - I_{\text{a,l}} &gt; 2I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS CC</td>
<td>( V_{\text{m}} - V_{\text{ss}} &gt; 2V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
</tr>
<tr>
<td>Transition PWM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZVS</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
</tr>
<tr>
<td>ZCS</td>
<td>( V_{\text{m}} )</td>
<td>( I_{\text{af}} )</td>
</tr>
</tbody>
</table>

Many other generalized equations can be also derived such as component stresses. The next section will include some of these equations.

5. A COMPARISON USING THE GENERALIZED EQUATIONS

The generalized equations can be used to make a cell-to-cell comparison. As an example, Table (3) shows the generalized equations for the peak and average current and voltage for the main switch, while Table (4) shows the main diode peak voltage and current for the analyzed ZVS and ZCS cells. They show how the QRC, QSW, and soft-switching transition cells voltage and current stresses on the main switch and main diode are compared. As an example, the following can be concluded from these two tables:

- The peak current stress on the main switch for the ZVS-QRC cell is high and load dependent. The higher the \( Q \), the lower the peak current stress is. For the ZCS-CC QSW cell, the peak current stress is reduced and it is load independent, but the peak voltage stress on the main switch is higher than twice of its value for the ZCS-QRC cell. In the ZCT-PWM cell, the peak switch current is high but load independent, while the switch peak voltage stress is kept low.
- The average main switch voltage is the same for all the analyzed switching cells and is equal to \( V_{\text{af}} + V_{\text{ac}} \).
- The ZVS-QSW cell causes the current stress on the diode to increase and to be load dependent by trying to reduce the voltage stress on the main switch. While the ZCS-CC QSW cell causes the voltage stress on the diode to increase and to be load dependent by trying to reduce the current stress on the main switch.
- The ZVT-PWM and the ZCT-PWM cells reduce the current and the voltage stresses on the main switch without increasing it on the diode.

6. OTHER GENERALIZED EQUATIONS FOR A SELECTED CELL (ZCT-PWM CELL)

The generalized analysis can be used to derive other characteristic equations for the generalized switching cells such as the component stresses. Some of these equations were mentioned in the previous section. However, some other equations will be derived for the ZCT-PWM as an example. These equations are:

- Generalized rms resonant inductor current (\( I_{\text{rms}} \)):
  \[
  I_{\text{rms}} = \frac{1}{T_s} \int_{t_s}^{t} i_{\text{s}}(t)dt
  \]
  \[
  = \sqrt{\frac{1}{T_s} \left[ \int_{t_s}^{t} \left( -I_{\text{f}} \cos \beta_{\text{d}} \sin \omega_0 (t-t_s) \right)^2 dt + \int_{t_s}^{t} \left( -I_{\text{f}} \cos \beta_{\text{d}} \sin \omega_0 (t-t_s) \right) dt \right]}
  \]
After normalizing by dividing the above equation by \( I_s \), the expression for the \( rms \) resonant inductor current will be:

\[
I_{L,\text{rms}} = I_{L,\text{cr}} = \frac{I_{sf}}{\cos \beta_\delta} \sqrt{\frac{f_{ms}}{4\pi} \left[ \alpha + \beta + \delta - \frac{1}{2}(\sin 2(\alpha + \beta) + \sin 2\delta) \right]}
\]

Which yields to:

\[
I_{L,\text{rms}} = I_{L,\text{cr}} = \frac{I_{sf}}{\cos \beta_\delta} \sqrt{\frac{f_{ms}}{2}}.
\]

7. DESIGN EXAMPLE AND SIMULATION RESULTS

After comparing between the cells, an appropriate cell for specific design requirements can be chosen. Here, the ZCT-PWM cell has been chosen as an example.

Design curves can be plotted using the generalized equations along with Table (1). Figure (4) shows some of these design curves for the ZCT-PWM boost converter.

A 10W ZCT-Boost DC-DC converter with \( V_o = 5 \) and \( V_i = 30 \) is to be designed here for \( f_{ms} = 0.5 \) and \( \beta_\delta = 0.427 \). The design parameters will be as follows:

- \( M = \frac{30}{5} = 6 \)
- From the gain equation in Figure (4a), \( D = 0.79 \).
- \( R_i = \frac{(30)^2}{10} = 90 \Omega \), \( I_s = \frac{30}{90} = \frac{1}{3} = 0.333 \) A
- By choosing \( f_i = 100 \text{kHz} \), \( f_o = \frac{f_i}{f_{ms}} = 200 \text{kHz} \).
- By choosing \( Q = 10.8 \), \( Z_o = \frac{90}{10.8} = 8.33 \Omega \).

Figure (4): Some characteristics curves for the ZCT-PWM Boost: (a) DC voltage conversion ratio characteristics for \( f_{ms} = 0.5 \), (b) Normalized Resonant Inductor \( rms \) Current for \( f_{ms} = 0.5 \), (c) Normalized Resonant Inductor Peak Current, and (d) Normalized Resonant Capacitor Peak Voltage for \( \beta_\delta = 0.427 \).
• Solve the following two equations $C_r$ and $L_r$:

$$Z_r = \frac{L_r}{C_r} = 8.3\Omega$$

$$f_o = \frac{1}{2\pi \sqrt{L_r C_r}} = 200\text{KHz}$$

This yields to:

$$L_r = 6.63\mu\text{H} \text{ and } C_r = 95.6\text{nF}$$

• The time interval when $D_1$ should be ON is equal to

$$\alpha + \beta_d = \frac{2\pi}{f_o} D_1 = (\pi / 2) + 0.427 \approx 2 \text{, which mean that:}$$

$$D_1 = 0.16$$

Figure (5) shows the basic waveforms from the simulation results using Pspice while Table (5) shows a comparison between some values from the theoretical results and the Pspice simulation results. This table shows the agreement between the theoretical results to the simulation results.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1.575$\mu$s</td>
<td>1.590$\mu$s</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.948$\mu$s</td>
<td>0.910$\mu$s</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.706$\mu$s</td>
<td>0.694$\mu$s</td>
</tr>
<tr>
<td>$\delta$</td>
<td>2.647$\mu$s</td>
<td>2.562$\mu$s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>4.125$\mu$s</td>
<td>4.244$\mu$s</td>
</tr>
<tr>
<td>$V_{inc}$</td>
<td>18.31V</td>
<td>18.402V</td>
</tr>
<tr>
<td>$I_{inc}$</td>
<td>2.197A</td>
<td>2.127A</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>30V</td>
<td>30.07V</td>
</tr>
<tr>
<td>$I_{dc}$</td>
<td>4.197A</td>
<td>4.127A</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>30V</td>
<td>30.09V</td>
</tr>
<tr>
<td>$I_{dc}$</td>
<td>2.00A</td>
<td>2.00A</td>
</tr>
</tbody>
</table>

**Figure (5): ZCT-PWM Boost Basic Waveforms from Pspice Simulation Results**

8. 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, QSW, and PWM converters. It is shown that a single Generalized Transformation Table for all the families exists. This leads to several advantages such as improving the computer-aided analysis and design, simplified mathematical modeling, and gives more insight into the converter-cell 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 substituting in the generalized equations. The cell-to-cell comparison was introduced and the theoretical results were compared with the simulation results.

9. REFERENCES


