Abstract—In this paper, a new zero-voltage switching (ZVS) buck converter with a tapped-inductor is proposed. This converter improves the conventional tapped inductor critical conduction mode (CRM) buck converters that have the ZVS operation range determined by the tapped-inductor turn ratios. It includes another soft switching range extension method, the current injection (CI) method, which gives an additional design freedom for the selection of the turn-ratios and enables the optimal design of the winding ratio of the tapped-inductor so that both the switching loss and the conduction loss may be minimized. This soft-switching buck converter is suitable for extremely low step-down ratio applications. The principle of the proposed scheme, analysis of the operation, and design guidelines are included. Finally, the experimental result of the 100W prototype DC/DC converter is given for hardware verification.

I. INTRODUCTION
Recently, newly-emerging power electronics applications such as renewable energy conversion systems, telecommunication power systems and high-frequency ballast systems require extreme step-down (or step-up) voltage conversion ratios [1]. This extreme conversion ratio causes the duty cycle to be extremely high or low as well. The operation with small duty cycle in buck converter cases influences both steady state and transient state performance. This small duty cycle degrades the power efficiency and the transient dynamics with the effect of the minimum pulse width of MOSFET gate drivers [2, 3]. In order to remove these problems, the duty cycle is increased by employment of a transformer. The utilization of transformer has some benefits in that the duty cycle of the converter can be adjusted to a desirable value in order to prevent the extreme duty cycle at the high step-up or low step-down ratio through the proper selection of the winding ratio [4]. This extra degree of freedom enables the switches to avoid high-peak current, and contributes to a reduction of the switching loss and conduction loss of the converters. However, the isolation type converters keep a low efficiency level due to the transformer loss itself and the bulky size with an increasing number of extra components to reset the transformer. To obtain both the extreme voltage conversion and high efficiency, the application of a tapped-inductor has been considered as one of the effective alternatives in previous researches [5-8] since the tapped inductor operates as an autotransformer without the need a reset circuit. Furthermore, less copper can be used with an autotransformer than with an isolation-type transformer [9]. However, there are some difficulties in applying the tapped-inductor to converters because the ringing between the leakage inductance of the inductor and the parasitic capacitances leads to higher voltage stress across switching devices and more EMI. These problems prevent the tapped inductor from being the optimal solution for extreme conversion ratio applications. In order to remove these problems, it is necessary to apply the soft-switching technique to tapped-inductor applications.

In this paper, a new zero-voltage switching (ZVS) buck converter with the tapped-inductor is proposed. The proposed converter improves the conventional critical conduction mode (CRM) buck converter that has a ZVS operation range extended by the tapped-inductor turn ratios [10]. The proposed one includes another soft switching range extension method (named as the current injection (CI) method in this paper) which gives another design freedom for the selection of the turn-ratios and enables the optimal design of the tapped-inductor so that both the switching loss and the conduction loss may be minimized. This soft-switching converter is suitable for applications with wide input ranges leading to extremely low step-down ratios. The following sections explain the principle of the proposed scheme, analyze the operation, and suggest design guidelines. Finally, the results of the 100W prototype dc-dc converter will be given for hardware verification.

II. OPERATION PRINCIPLES OF PROPOSED TAPPED-INDUCTOR SOFT-SWITCHING CONVERTERS
The soft switching operation is so meaningful to the converter employing a tapped inductor, which has a leakage inductance causing severe ringing at the switching moment. This is important not only for efficiency, but also in the EMI viewpoint, because the parasitic leakage inductance causes serious performance degradation. The soft-switching technique is able to attenuate these problems by enabling the use of a loss-less capacitive snubber without paying for efficiency reduction and additional parts, with the exception of a capacitor [11]. This snubber absorbs the ringing energy of the leakage inductor and significantly reduces the switching-off loss by adapting the switching speed to an optimal level. The following sections introduce a conventional soft switching approach as well as the one proposed in this research. The proposed approach applies an additional soft-switching technique to the conventional approach, which gives one more design freedom for obtaining the soft-switching operation over the entire operation range.

The conventional critical conduction mode (CRM) soft-switching tapped-inductor buck converter is shown in Fig. 1. For the analysis, it is assumed that the tapped-inductor is completely coupled and the output capacitor is a complete voltage sink. There are 3 operation modes in CRM operation – MOSFET conduction mode, diode conduction mode, and resonant mode between the tapped-inductor and the parasitic capacitors of the switches, as shown in the shadowed area in Fig. 2(a) and 2(b). The equivalent circuit of the resonant mode is shown in Fig. 2(c). In the figure, the resonant capacitor, \( C_r \), represents the parallel equivalents of \( C_{d1} \) and the reflected \( C_{d2} \) in Fig. 1, and \( L_o \) refers to the inductance of \( N_2 \). When the initial condition is the un-energized state of \( L_o \) and \( C_r \) (i.e. \( V_c(0) = 0 \), \( I_L(0) = 0 \)), then the resonant voltage \( V_c \) reaches up to \( 2V_o \). Since the resonant voltage of the untapped CRM converter \((N_1=N_2)\), \( V_s \) of Fig. 2(a), cannot exceed \( 2V_o \), the soft switching range of the untapped CRM buck is limited where the input-output voltage conversion ratio is higher than 0.5. However, if the filter inductor is replaced with a tapped inductor as in Fig. 1, the soft-switching is achieved as shown in Fig. 2(b), in spite of the conversion ratio less than 0.5, because the tapped inductor increases the resonant voltage, \( V_s \), up to the input voltage, \( V_{in} \), as an auto-transformer. In order to obtain ZVS operation in all operating ranges, the winding ratio \( N \) of the tapped-inductor which steps up the secondary voltage, \( V_C \) \((V_{d1} \text{ in fig. } 1)\), to the primary voltage, \( V_s \), must satisfy the following condition:

\[
V_s(t) = V_o - N \cdot V_o \cos \omega t \geq V_o,
\]

where \( N = N_1/N_2 \).

Thus, the extended soft switching condition expressed with voltage gain \( M \) and turn ratio \( N \) is established as:

\[
N \geq \frac{1}{M} - 1.
\]

(2)

B. Proposed Tapped-Inductor Soft-switching Converter

As shown in the previous section, the conventional strategy utilizes a tapped-inductor in order to obtain soft-switching operation even for extremely low voltage gain by the enhancement of the resonant voltages. However, when the application has wide input ranges starting from un-extreme transfer ratio to extreme ones, a tapped-inductor is not advantageous because the soft switching requires an extremely high turn-ratio of the inductor in order to satisfy the ZVS condition, which leads to the increase of free-wheeling current and voltage stress and finally, to the degradation of performance such as the decrease of overall efficiency, especially in the un-extreme conversion area. In this paper, in order to remove this problem, an additional soft-switching technique, named current injection (CI) is introduced into the conventional tapped-inductor soft-switching converter by replacing the freewheeling diode with an active switch (synchronous rectifier), as shown in Fig. 3. The proposed soft-switching technique is a hybrid type which combines the tapped-inductor (voltage-enhancement type) soft-switching technique with the CI technique. This hybrid type soft-switching converter has very similar circuit operation with the conventional CRM converter. However, the current injection method extends the soft-switching region by not passively depending on the parasitic resonance, but actively storing current in the filter inductor for the resonance of the subinterval. The principle of the CI method has been proposed as a soft-switching technique for some applications in previous researches [11, 12]. This CI method is also a good alternative for wide input range applications although it is not suitable for extreme gain applications.

Figure 4 shows the key waveforms (gating signals, \( V_S \), and \( I_L \) in Fig. 3) of the proposed tapped-inductor soft-switching buck converter with the CI method. There also exist three kinds of operation modes like the conventional tapped-inductor scheme – switch conduction mode (DT period in Fig. 4), diode (synchronous rectifier) conduction mode ((1-D)Ts - Tr), and resonant mode (Tr) from the resonance between parasitic capacitances of the switching devices and the filter inductor. However, in this proposed scheme, the synchronous rectifier maintains turn-off until the freewheeling inductor current turns into negative (\( I_L \) of synchronous rectifier ON period in Fig. 4). Then, when the rectifier turns off, the current, \( I_{L,off} \), is released to enhance the resonant voltage by charging switch output capacitors, \( C_{d1} \) and \( C_{d2} \), shown in Fig. 3. Peak of the enhanced voltage...
(\(V_{C,\text{peak}}\)) is derived from: 
\[
\frac{1}{2}C_r \cdot V_{C,\text{peak}}^2 = \frac{1}{2}L_r \cdot I_{L,\text{off}}^2,
\]
thus the higher the inductor current is, the higher the peak of the resonant voltage is. And this voltage (\(V_{\text{sync}}\) in Fig. 3) is enhanced by tapped-inductor once more (\(V_s\) in Fig. 3). Thus, the extreme voltage boost for soft-switching of the main switch is achieved. This approach uses a filter inductor instead of the parasitic inductance for the resonant action and the switching current (\(I_{L,\text{off}}\)) required to satisfy the soft-switching is small. Thus, the CI method influences a very small portion of the main operation for factors such as device stress and switching frequency. This method has an advantage of achieving the extension of the soft-switching range without depending on the extreme turn ratio of the tapped-inductor even for the extreme step-down condition.

For the detailed descriptions of the subinterval, the equivalent circuit of the resonant mode, shown in Fig. 2(c), is considered. The differences from the conventional operation are the initial conditions. The moment the resonance subinterval begins, the inductor has initial current stored by the synchronous rectifier. The initial conditions are:

\[
V_c(0) = 0, \quad I_c(0) = I_0,
\]
where \(V_c\) in Fig. 5 corresponds to \(V_{\text{sync}}\) in Fig. 3, and \(I_0\) is the current through the winding \(N_2\). From this condition, the boosted capacitor voltage \(V_c(t)\) is derived as follows:

\[
V_c(t) = V_o - \sqrt{V_o^2 + (I_0 \cdot Z_n)^2} \cdot \cos(\omega t + \theta),
\]
where \(Z_n = \frac{L_0}{\sqrt{C_r}}, \quad \omega_n = -\frac{1}{\sqrt{L_r \cdot C_r}}\).

For the ZVS operation, the turn ratio \(N\) of the tapped-inductor which is another boosting source of the resonance voltage, stepping up \(V_c\) into primary voltage \(V_S\) in Fig. 3, must satisfy the following condition:

\[
V_S(t) = V_o - N \cdot \sqrt{V_o^2 + (I_0 \cdot Z_n)^2} \cdot \cos(\omega t + \theta),
\]
where \(\theta\) is the phase angle presented in Fig. 5(b), the state-plane trajectory between \(V_c\) and \(I_0\). Thus, the soft-switching condition is satisfied when the peak value of \(V_S\) is higher than input voltage \(V_{in}\), which is established as:

\[
\frac{I_0 Z_n}{V_{in}} \geq \frac{\sqrt{1 - 2M + (1 - N^2)M^2}}{N}
\]

This equation shows that the proposed soft-switching method does not require extremely high value of \(N\) for the ZVS operation due to the initial inductor current \(I_0\). Also, this result shows that the ZVS condition is not dependent on the load condition.

\[\text{Fig. 3. Proposed ZVS tapped-inductor buck converter with the current injection(CI) method}\]

\[\text{Fig. 4. Key waveforms (gating signals, main switch voltage } V_S \text{, and inductor current } I_L \text{) of the proposed scheme}\]

\[\text{Fig. 5. The state plane trajectory between } V_c \text{ and } I_0\]

### III. OPERATION PARAMETER ANALYSIS

For the design-oriented operation analysis, an objective function is introduced in this section. The conventional and proposed tapped-inductor topologies have simple structures and the performances are dominantly affected by the utilization efficiency of the switching device. For example, a power processing parameter \(U_{SW}\) (named device utilization factor) for the main switch, is introduced as:

\[
U_{SW} = \frac{V_o \cdot P_{LOAD}}{V_{in} \cdot I_{on,on}}.
\]

\(U_{SW}\) has a reciprocal relationship with the power stress of the main switch that is proportional to voltage stress and current stress. High \(U_{SW}\) means that the switching device processes reduced power for a given output and the device obtains alleviation not only of conduction and switching loss, but
also of thermal stress, ESR loss, EMI noise, packaging size, etc [13]. Therefore, this parameter is appropriate to the estimation of the converter performance in the viewpoint of power stress and efficiency as a whole.

In order to derive the objective function, the voltage gain M is derived in (8) with the assumption that the inductor current flowing negatively through the synchronous rectifier is small enough to be negligible and \( \delta M \) (period of the subinterval) is kept constant as \( \pi/\omega_n \), which means the resonant subinterval terminates at the mid-point of the resonant period.

\[
M = \frac{D}{D + (1 - D)N - \delta M} \quad (N \geq 1)
\]  
(8)

where \( \delta M, \delta N \) is derived in (8) with the assumption that the inductor current flowing negatively through the synchronous rectifier is small enough to be negligible and \( \delta M \) (period of the subinterval) is kept constant as \( \pi/\omega_n \), which means the resonant subinterval terminates at the mid-point of the resonant period.

The switching frequency equation is implicitly established as:

\[
f_s = \frac{(1 - M)^2}{(MN - M + 1)^2} \left( 1 - \frac{\pi}{\omega_n} \cdot f_s \right) + \frac{1}{\omega_n},
\]
(9)

where \( \omega_n = \frac{R_1}{2L_s} \).

The switching current (turn-off) of the main switch is:

\[
I_{\text{sw,off}} = 2 \cdot \left( I_{\text{load}} + \frac{V_o}{Z_o} \cdot \delta M \right) \left( 1 - \frac{M + \frac{MN}{N - M}}{M + N - M} \right) \left( \frac{1}{1 - \delta M} \right)
\]
(10)

For the analysis of the tapped-inductor effect, the previous parameter is normalized by the untapped inductor case (N=1). The normalized switching current is:

\[
I_{\text{sw,off},N} = \frac{M(1 - M + N \cdot M)}{N} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(11)

The square of the RMS current of the main switch is:

\[
I_{\text{rms,sw},N}^2 = \frac{D \cdot I_{\text{sw,off},N}^2}{3}
\]

\[
= \frac{M(1 - M + N \cdot M)}{N} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(12)

The normalized main switch current is:

\[
I_{\text{rms,sw},N}^2 = \frac{M(1 + M \cdot N)}{N} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(13)

In the same way, the RMS current stress of the synchronous rectifier is:

\[
I_{\text{rms,off},N}^2 = \frac{D \cdot I_{\text{sw,off},N}^2}{3}
\]

\[
= \frac{M(1 - M + N \cdot M)}{N} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(14)

The normalized current stress is:

\[
I_{\text{rms,off},N}^2 = \frac{(1 - M + M \cdot N - \delta M)^3}{3} \left( 1 - \frac{\delta M}{1 - \delta M} \right)
\]
(15)

The normalized synchronous rectifier voltage stress is [10]:

\[
V_{\text{SYNC,N}} = M \cdot \frac{1}{(1 - M)}
\]
(16)

The normalized main switch voltage stress is [10]:

\[
V_{\text{SW,N}} = 1 + N \cdot M - M
\]
(17)

Finally, the normalized main switch utilization factor is:

\[
U_{\text{SW,N}} = \frac{1}{I_{\text{rms,sw},N} \cdot V_{\text{SYNC,N}}}
\]

\[
= \frac{N}{(1 - M + M \cdot N)} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(18)

And, the normalized rectifier utilization factor is:

\[
U_{\text{sync,N}} = \frac{1}{I_{\text{rms,off},N} \cdot V_{\text{SYNC,N}}}
\]

\[
= \frac{N}{(1 - M + M \cdot N)} \left( 1 - \frac{\delta M}{1 - \delta M} \right) \left( 1 + \frac{2}{\pi} \cdot \frac{R_1}{Z_o} \cdot \delta M \right)
\]
(19)

Figure 6 shows the normalized main switch and synchronous rectifier utilization factor of the tapped-inductor converter. The contours of \( U_{\text{SYNC,N}} \) and \( U_{\text{SYNC,N}} \) in Fig. 6(a) and 6(b) are used to design N for the optimization of the objective function. The x-axis represents the voltage conversion ratio M and the y-axis represents the turn ratio N. Each line in the contour represents the same utilization factor. The region bounded by the solid line with "o" represents the soft-switching condition of the conventional tapped/untapped inductor converter (without CI method), which is presented in eq. (2). In order to obtain high efficiency in the overall operation area, all operating points should be in the ZVS operation area in Fig. 6. The figure shows that a higher N results in a greater utilization factor in the extremely small M region (\( \leq 0.2 \)). However, as M increases, the utilization factor of high N decreases rapidly. Thus, for the wide-input and extreme step-down design, it is difficult to find an optimal solution for the conventional tapped-inductor.

As a design example, the solid line between points C and D marked with "X" (0.15 \( \leq M \leq 0.48 \)) in the figure represents the conventional tapped-inductor converter design result for the spec. of a 100W DC/DC converter hardware prototype in chapter IV. The parameter N is high (\( \geq 6 \)) due to the ZVS region of the conventional tapped-inductor converter. The proposed converter, however, is allowed to set N as a lower value (\( \geq 3 \)) such as C' and D' because of both the tapped-inductor and the current injection soft-switching methods (eq. (6)). This optimized N design has higher \( U_{\text{SYNC,N}} \) and \( U_{\text{SYNC,N}} \) than both the conventional tapped inductor and untapped inductor (N=1) designs in most input ranges of the prototype.
The results of analysis and design are verified by the prototype hardware test of a 100W tele-communication equipment power supply. The input voltage range is 100V ~ 320V<sub>DC</sub> and the output voltage is 48V<sub>DC</sub>. The conversion ratio is from 0.15 to 0.48. TABLE I presents the major components used for the conventional and proposed hardware prototypes.

Figure 7 shows the experimental results. In Fig. 7(a), it is shown that the ZVS operation is achieved in the main switch of the proposed scheme. In Fig. 7(b), the previous tapped or untapped CRM shows the efficiency to be below 93%, while the proposed tapped converter employing the CI method maintains an efficiency level above 93% through the overall operating range.

IV. EXPERIMENTAL RESULTS

![Image](image_url)

(a) Major waveforms of the proposed (N=3) converter (Ch1: gating signal of main switch, Ch2: gating signal of synchronous rectifier, Ch3: inductor current, Ch4: voltage of the main switch))

![Image](image_url)

(b) Measured efficiency comparison between the proposed (N=3) and conventional (N=1, N=6) converters

Fig. 7. Major waveforms of the hardware prototype and measured efficiency comparison between the proposed ZVS Tapped CI converter and the previous ZVS Tapped and untapped soft-switching converters.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>MAJOR COMPONENTS USED FOR THE CONVENTIONAL AND PROPOSED CIRCUIT PROTOTYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>Parameters</td>
</tr>
<tr>
<td>Tapped L</td>
<td>EI28, N = 1, L = 140uH</td>
</tr>
<tr>
<td>Main Switch</td>
<td>IRF740 (400V, 10A)</td>
</tr>
<tr>
<td>Synchronous Rect.</td>
<td>IRF740 (400V, 10A)</td>
</tr>
<tr>
<td>(a) Conventional untapped-inductor CRM converter with CI method</td>
<td></td>
</tr>
<tr>
<td>Components</td>
<td>Parameters</td>
</tr>
<tr>
<td>Tapped L</td>
<td>EI28, N = 3, L&lt;sub&gt;1&lt;/sub&gt; = 310uH, L&lt;sub&gt;2&lt;/sub&gt; = 35uH</td>
</tr>
<tr>
<td>Main Switch</td>
<td>IRFB18N50 (500V, 18A)</td>
</tr>
<tr>
<td>Synchronous Rect.</td>
<td>IRF640 (200V, 18A)</td>
</tr>
<tr>
<td>(b) Proposed tapped-inductor CRM converter with CI method</td>
<td></td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

In this paper, a new ZVS buck converter employing a tapped-inductor is proposed. In order to obtain the soft-switching operation in wide-input extreme step-down applications without a tapped-inductor with a high turn-ratio, the proposed converter utilizes not only the resonant voltage enhancement by the tapped-inductor, but also the current injection (CI) method that enhances the resonant voltage by the initial inductor current. This voltage enhancement method gives another design freedom to select the turn ratio, and thus it is possible to obtain a more optimal design than the conventional tapped-inductor or the CI only method. The operation principle and the design-oriented analysis of the proposed converter have been presented. The experimental result with a 100W hardware prototype is also included to show that the proposed converter has a higher efficiency than the conventional tapped/untapped buck converters.

REFERENCES


