IGBT Based DC/DC Converter

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ABSTRACT: This paper presents an in-depth analytical and experimental investigation of an indirect DC-DC converter. The DC-AC conversion is a full bridge based on IGBT power modules, and the AC-DC conversion is done via a high frequency AC link and a fast diode bridge. The AC link, which consists of snubbing capacitors and a variable air-gap transformer, is analytically designed to fulfill zero voltage commutation requirement. The proposed converter is simulated using PSpice and a prototype is designed, built and tested in the laboratory. PSpice simulation and experimental results are presented and compared.

Indirect DC-DC converters are increasingly becoming a viable option as Switched Mode Power Supplies (SMPS) for a variety of industrial applications (Bhat, 1991, Lo et al, 1992, Jan 1992). Their important advantages of low losses, reduced EMI and low noise, make them very suitable for high frequency, low to medium power dc-de conversion as well as low to medium power supplies of electric drives (Steigerwald, 1984, Kazimierzuk et al, 1992).

It is known that classical power supplies offer the advantages of simplicity, sturdiness and high reliability. However, for obvious reasons, they present major drawbacks whenever the size and weight of a power supply is critical. In the last decade, SMPS have offered clear solutions to these drawbacks. However, a further reduction of weight and size of SMPS calls for higher operating frequency. This means that the power switches are severely stressed and commutation losses are tremendously increased. Recently, it is believed that the exploitation of LC resonance at commutation is offering an adequate solution to the above mentioned limitations of SMPS (Severson, 1992; Bose, 1992). These new generations of DC-DC converters have gained a widespread interest and use in specialized laboratories, universities and industrial applications (Bhat, 1993; Ninomiya et al, 1991; Morrison, 1992; Bose, 1992 and Akherraz, 1992).

This paper presents an in-depth analytical and experimental investigation of an indirect dc-de converter. The technical characteristics of the proposed converter are:

i) DC input voltage 300V
ii) Adjustable dc output voltage (via the switching duty cycle ), iii) Switching frequency 24KHz, and iv) Commutation time less than 5% of the operating period.

The main features of this converter are fourfold: i) Low switching losses due to commutation at resonance ii) Clean AC link voltage and current waveforms due to the design of an air-gap transformer in the ac link, iii) High efficiency, and iv) Fast IGBT power modules as main switches.

This paper is organized in three parts. In the first part, the state variables of the switching commutation intervals are defined and solved in closed form fashion. The second part outlines the PSpice simulation results of the investigated converter. The third part presents the experimental results with discussion and comments on the performances obtained.

Switching commutation intervals

The proposed converter is shown in figure 1. T1, T2, T1′ and T2′ are IGBT power modules with anti-parallel diodes. C1, C2, C1′ and C2′ are snubbing capacitors. L1 is transformer primary leakage inductance, L2 and C are the output filter components and R is the load. The AC link transformer is a mid-point type with a variable air-gap and a unity turn-ratio.
The analysis of the commutation intervals is carried out under the following assumptions: i) IGBTs and diodes are ideal switches ii) The snubbing capacitors \( C_1, C_2, C_1', \) and \( C_2' \) are identical. Their capacitance is equal to \( C_0. \) iii) All circuit resistances are neglected, and iv) Negligible primary and secondary leakage inductances.

The obtained simplified converter's equivalent circuit, referred to the transformers primary is shown in figure 2. \( L_m \) is the magnetizing inductance. \( k_l \) symbolizes the bridge and the load (\( k = \pm 1 \)).

The initial commutation interval is assumed to be \((T_1, T_2) \) on and \( k = 1 \). Then, starting at the time when \( T_1 \) and \( T_2 \) are turned off and until \( T_1' \) and \( T_2' \) are turned on and \( k = -1 \), the commutation goes through two operating intervals.

**Interval A:** \( T_1, T_2 \) are off and \( k = 1 \). The equivalent circuit of the investigated converter, during this interval, is shown in figure 3. The corresponding voltage and current equations are as follows:

\[
V_T = L_m \frac{dl_m}{dt} \\
I_u = I_m + I_s \\
V_c + I_c > 0 \\
2V_c + V_T = E
\]

where \( V_T \) is the transformer primary voltage, \( I_u \) is the AC link current (or transformer primary current) and \( I_m \) is the transformer magnetizing current. Since the commutation energy is provided by the LC resonance, the input line current is equal to zero during commutation. Combining equations (1) to (4), the following second order differential equation is obtained:

\[
d^2l_m/dt^2 + \omega_0^2 l_m = -i \omega_0^2 l_s
\]
where $\omega_0^2 = 1/(L_m C_o)$. The initial conditions of equation (5) are $V_{c1} = V_{c2} = 0$, $V'_{c1} = V'_{c2} = E$ and $I_m = I_{m0}$. The initial magnetizing current $I_{m0}$ is determined later in this paragraph. With these initial conditions, solving for equation (5) leads to the following:

$$I_{m0} = E/(L_m \omega_0) \sin (\omega_0 t) + (I_{m0} + I_s) \cos (\omega_0 t) - I_s \tag{6}$$

$$V_T = E \cos (\omega_0 t) - L_m \omega_0 (I_{m0} + I_s) \sin (\omega_0 t) \tag{7}$$

$$I_y = E/(L_m \omega_0) \sin (\omega_0 t) + (I_{m0} + I_s) \cos (\omega_0 t) \tag{8}$$

$$V_{c1} = E/I - \cos (\omega_0 t) + I_m \omega_0 (I_{m0} + I_s) \sin (\omega_0 t) \tag{9}$$

This interval ends when $V_T$ crosses zero, i.e., $I_m$ is at maximum. This occurs at $t = t_{41}$ given by:

$$\tan (\omega_0 (t_{41})) = E/(I_m \omega_0 (I_{m0} + I_s)) \tag{10}$$

At $t = t_{41}$, all capacitor voltages are equal to $E/2$, the transformer voltage is null and the AC link current is surpassing $I_s$.

**Interval B:** $T_1, T_2$ are off and $k = 1$. The converters equivalent circuit, during this interval, is shown in figure 4. Similarly to interval A, the magnetizing current $I_m$ is given by the following differential equation:

$$d^2 I_m/dt^2 + \omega_0^2 I_m = \omega_0^2 I_s, \tag{11}$$

The initial conditions are obtained by setting $t = t_{41}$ in equations (6) to (9). The obtained solutions are as follows:

$$I_m = (I_m(t_{41}) - I_s) \cos (\omega_0 t) + I_s \tag{12}$$

$$V_T = -L_m \omega_0 (I_m(t_{41}) - I_s) \sin (\omega_0 t) \tag{13}$$

$$I_y = (I_m(t_{41}) - I_s) \cos (\omega_0 t) \tag{14}$$

$$V_{c1} = E/2 + L_m \omega_0^2 (I_m(t_{41}) - I_s) \sin (\omega_0 t) \tag{15}$$

In order to achieve the appropriate operation, i.e., commutation at zero voltage, $C_1$ ought to be charged to $E$ prior to $I_m$ reaching zero. This condition can be obtained from equation (15) by setting the magnitude of the sinusoidal term to a value greater than $E/2$, i.e.,

$$L_m \omega_0 (I_m(t_{41}) - I_s) = \lambda E \tag{16}$$

where $\lambda$ is a coefficient greater than unity. Using this coefficient as a parameter, the initial magnetizing current $I_{m0}$ is given by the following equation:

$$I_m = \text{SQRT}(\lambda E + 2 L_m \omega_0^2 - E^2)/\omega_0 + I_s \tag{17}$$

The maximum magnetizing current takes place at the end of interval A, i.e., at $t = t_{41}$, and is given by:

$$I_{m \text{max}} = \lambda E/(L_m \omega_0) + I_s \tag{18}$$
The second interval ends when $C_1$ is charged to $E$. This occurs at $t=t_{12}$ given by:

$$\sin(\omega_s t_{12}) = \frac{1}{\lambda}$$  \hspace{1cm} (19)

At $t = t_{12}$, $C_1$ is completely discharged. $T_1$ and $T_2$ can be smoothly triggered. Thus, with $T_1$ and $T_2$ conducting and $k = 1$, the commutation is over. It appears that $L_m$ and $C_o$ play a crucial role in providing adequate commutation. Therefore, they are particularly dimensioned to satisfy the following conditions: i) Appropriate commutation, i.e. $\lambda = 1$; ii) Commutation time (i.e. $t_{12}$) <= 5% switching period; and iii) Imposed maximum magnetizing current during commutation. The design of $L_m$ and $C_o$ is presented in the next paragraph.

**PSPICE Simulation**

**PSPICE Modeling:** The investigated converter is simulated using PSPICE. Each IGBT power module is represented by an n-channel enhancement type MOSFET supplying base current, through a variable resistance $R_{\text{mos}}$, to a PNP-NPN transistor connected in a gate-thyristor type circuit, as shown in figure 5. The n-channel MOSFET is modeled as an intrinsic MOSFET with series resistances with the drain and source, and shunt resistance with the drain source channel. The PNP-NPN transistors are represented by the enhanced Gummel-Pool models (Rashid, 1993). The air-gap transformer is represented by variable magnetizing inductance and an ideal transformer. The diodes are modeled with the appropriate parasitic resistance and capacitance ($R_d$ and $C_{ds}$) (Rashid, 1993).

**DESIGN OF $L_m$ AND $C_o$:** The investigated converter is PSPICE simulated for the following operating point conditions:

$E = 300V$, $I_p = 0.5 A$, $I_{\text{max}} = 1.5 A$; switching frequency $f = 24KHz$, switching period $T = 41.6 \mu\text{sec}$, and commutation time $= 5\% T$. The key equations used for designing $L_m$ and $C_o$ are derived from the equations given in the previous paragraph, in the following fashion. Given a value of $\lambda$ ($\lambda > 1$), $\omega_s$, $L_m$, $t_{11}$, $t_{12}$, $t_{1n}$ and $C_o$ are calculated, respectively, as follows:

$$\sqrt{(\lambda^2 - 1)} \cos(\omega_s t_{11}) = \frac{1}{\lambda}$$ \hspace{1cm} (20)

$$L_m = \frac{4(4\lambda^2 - 1)}{\lambda^2 - 1} - \frac{1}{\lambda}$$ \hspace{1cm} (21)

$$\sin(\omega_s t_{12}) = \frac{2}{\lambda} \frac{1}{(1 + \lambda^2 (L_m + I_p))}$$ \hspace{1cm} (22)

$$\cos(\omega_s t_{12}) = \frac{2}{\lambda} \frac{1}{(1 + \lambda^2 (L_m + I_p))}$$ \hspace{1cm} (23)

$$L_m = \frac{2}{\lambda} \frac{1}{(1 + \lambda^2 (L_m + I_p))}$$ \hspace{1cm} (24)

$$C_o = \frac{1}{L_m \omega_s}$$ \hspace{1cm} (25)

**PSPICE Simulation Results:** The investigated converter is simulated using PSPICE for the following operating point conditions:

$E = 300V$, $I_p = 0.5 A$, $I_{\text{max}} = 1.5 A$; switching frequency $f = 24KHz$, switching period $T = 41.6 \mu\text{sec}$. Commutation time $= 5\%$ of the period $T$. Variety of values of $\lambda$ are employed in order to simulate the behavior of the investigated converter during commutation. The obtained waveforms are in good agreement with the analytical predictions, especially for values of $\lambda = 1.225$. To illustrate this concordance as well as the conformity of the proposed PSPICE model, the cases of $\lambda = 1.5$ and $\lambda = 1.225$ are presented in this paragraph. Figures 6 and 7 show the capacitor voltage $V_{c1}$, the capacitor current $I_{c1}$, the transformer primary current $I_p$ and the transformer magnetizing current $I_{m}$ for $\lambda = 1.5$ and $\lambda = 1.225$, respectively. The main comments about these waveforms are threefold: i) The peak-to-peak primary current and magnetizing current are 4.4A and 3.4A, respectively, and 4.6A and 3.6A, respectively, for $\lambda = 1.5$ and $\lambda = 1.225$, ii) $I_p$ current spikes are less than 1A (i.e. 20 to 25% of the pk pk AC currents), and iii) Commutation time is within the range of 2 $\mu\text{sec}$. The obtained quantitative results are summarized in table 1.

![Figure 5. Equivalent circuit of a power IGBT module.](image)

<table>
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<tr>
<th>$\lambda$</th>
<th>$I_{c1}$ (mA)</th>
<th>$C_o$ (nF)</th>
<th>$I_m$ (A)</th>
<th>$t_{c1}$ (\mu sec)</th>
<th>$t_{m}$ (\mu sec)</th>
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<tr>
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<td>1.289</td>
<td>0.616</td>
<td>1.471</td>
</tr>
<tr>
<td>1.225</td>
<td>0.556</td>
<td>4.12</td>
<td>1.326</td>
<td>0.638</td>
<td>1.449</td>
</tr>
<tr>
<td>1.5</td>
<td>0.876</td>
<td>4.33</td>
<td>1.386</td>
<td>0.662</td>
<td>1.421</td>
</tr>
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</table>
Experimental results - Presentation and discussion

The proposed converter is designed, built and tested in the laboratory. The input voltage and switching frequency are set to 300V and 24 kHz, respectively. The characteristics of the IGBT power modules are as follows: $V_{	ext{ce}} = 1200\, \text{V}, I_{	ext{C}} = 25\, \text{A}, V_{	ext{cesat}} = 3\, \text{V}, t_{	ext{on}} = 400\, \text{ns}, t_{	ext{off}} = 500\, \text{ns}$ and $t_{\text{f}} = 200\, \text{ns}$. The IGBT's triggering circuit synoptic diagram is described in figure 8. The performance of the investigated converter are tested under variable loading conditions and variable air-gap. Salient results are presented in this paragraph. Figures 9 and 10 show the capacitor voltage $V_{	ext{cl}}$, its corresponding current $I_{	ext{cl}}$ and the $T_1$ transistor current $I_{	ext{t1}}$. They are obtained with an air gap of 0.3 mm. From figure 9, it can be seen that $C_{	ext{cl}}$ is indeed discharged, prior to the switching of $T_1$. $I_{	ext{cl}}$ spikes are drastically reduced and the commutation is improved. Figure 10 shows the commutation in more details.

The obtained commutation time is about 2 $\mu$sec, which represents 4.8% of the operating period. A further increase of the air-gap to 1.5 mm has lead to the results shown in figures 11 and 12. The commutation time is increased to 2.3 $\mu$sec (5.6% of the period) and slight commutation spikes re-appear at the capacitor current $I_{	ext{cl}}$.

The obtained waveforms are as predicted theoretically, through the state variable equations derived in the second paragraph of this paper, and by PSPICE simulation. Prior to reaching $E$, $V_{	ext{cl}}$ crosses $E/2$ at $t_{11}$, and changes slope to get to $E$ at $t_{12}$. Also, the AC-link current drops from a maximum value at $t_{31}$, and oscillates in a damped fashion until $t_{12}$, after which it continues to decrease (or increase) linearly until the next commutation.

A minor difference is observed between PSPICE and experimental results. For instance, for a switching frequency of 24kHz and a load of 1.2kW, PSPICE predicts a commutation time of 2.06$\mu$sec with a theoretical magnetizing inductance of 0.3 mH. The corresponding experimental commutation time is about 2.33$\mu$sec with an air-gap of 1.5mm and a measured magnetizing inductance of 0.47mH.
The efficiency of the proposed DC/DC converter is experimentally investigated under different air-gaps and under different loading conditions. A summary of the most relevant experimental results is presented in Table 2. The column efficiency, included in this table, indicates the maximum value observed for each air-gap and under the tested loading range.
Compromising among commutation time, switching spikes and efficiency, an empirical optimum is observed with an air-gap of about 0.9 mm. The closed form theoretical and numerical investigation of the transformer air-gap effect on the proposed converter's performance (i.e. commutation time, switching spikes and efficiency), as well as the mathematical link between $\lambda$ and the air-gap width are under investigation.

Figure 11. Voltage and current waveforms obtained with an air gap of 1.5 mm.

Figure 12. Voltage and current waveforms during commutation with a transformer air gap of 1.5 mm.
### Table 2

Summary of salient experimental results of the proposed DC/DC converter.

| Airgap (mm) | \( L_{\text{g}} \) (mH) | \( t_{\text{d}} \) (usec) | \( t_{\text{on}} \) (usec) | \( \eta \) (%) | Input voltage (V) | Input current (A) | Output voltage (V) | Output current (A) |
|-------------|----------------|----------------|----------------|-------------|----------------|----------------|----------------|----------------|----------------|
| 0.3         | 1.54           | 0.5            | 1.5            | 92          | 300            | 1.23           | 278            | 1.2            |
| 0.6         | 0.95           | 0.4            | 1.4            | 95          | 300            | 1.75           | 289            | 1.72           |
| 0.9         | 0.80           | 0.3            | 1.3            | 95          | 300            | 2.3            | 287            | 2.48           |
| 1.5         | 0.47           | 0.6            | 1.7            | 90          | 300            | 3.5            | 724            | 3.45           |

### Conclusion

The analysis and design of an indirect DC-DC converter are presented in this paper. IGBT power modules are used in the DC-AC conversion, and a variable air-gap transformer is employed in the resonant ac link. The proposed converter is built and tested in the laboratory. The obtained experimental results are in good agreement with theoretical and PSPICE simulated results.

### References


