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Simulation of 3-Staged MPC Using Custom Characteristics of Magnetic Cores

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ABSTRACT
A low inductance circuit has been fabricated in order to obtain shorter time to saturation during core unsaturation and current pulses with shorter widths during core saturation. B-H curves have been derived from the measured voltage and current waveforms. Characteristics of the magnetic core for pulsed-power generators have been investigated and the Electromagnetic Transient Program (EMTP) simulation has been carried out in order to determine the effects of leakage current on the energy efficiency of a 3-staged magnetic pulse compressor (MPC). As results, the derived B-H curves show the following characteristics: a high ratio of unsaturated to saturated permeability ($\mu_{\text{un}}/\mu_{\text{sat}}$), a maximum flux swing of about 2.55 T, a high ratio of remanent flux density to saturation magnetic flux density ($B_r/B_s$) and low core loss. And, it is found that $\mu_{\text{un}}$ increases with time to saturation and that $\mu_{\text{sat}}$ is strongly influenced by the stray inductions of the core. By applying custom characteristics to each stage in EMTP simulation, more practical energy transfer in MPC is obtained.

Index Terms — B-H curve, leakage current, magnetic core, MPC, EMTP.

1 INTRODUCTION

RECENT developments in ferromagnetic materials [1], [2] and semiconductor switches have allowed high repetitive operation of magnetic switches (MS) [3-7] with very low losses, and have made it possible to use repetitive pulsed power generated by magnetic pulse compressors (MPC) in practical industrial applications such as laser exciters, decomposition of hazardous gases, removal of volatile toxic compounds and water treatment [8-15]. The magnetic switch used in pulsed-power applications is superior in its high repetition rate, high stability, and long lifetime to electrical discharge switches that have unstable switching and short lifetimes due to electrode deterioration. The saturable inductor (SI) works as a switch by blocking current with a high inductance during the unsaturated state and passing current with a low inductance during the saturated state. Eligible magnetic materials for repetitive pulsed-power applications must have the following characteristics: a high ratio of unsaturated to saturated permeability ($\mu_{\text{un}}/\mu_{\text{sat}}$), a high flux swing, a high saturation flux density ($B_s$) and remnant flux density ($B_r$), and low core loss.

The dc and ac characteristics of magnetic materials have been well known and easy to obtain from manufacturers. As the use of magnetic cores has become popular in pulsed-power applications, there have been several studies of the pulse magnetic characteristics that are critical for a multi-stage MPC [16-20]. However, there are still some necessities for the users of the magnetic cores to measure the pulse characteristics for more efficient MPC design. As the number of stages in an MPC increases, the efficiency of the energy transfer that is one of the dominant measures for overall performance becomes poor.

In this paper, a low inductance circuit fabricated to obtain shorter time to saturation during core unsaturation and current pulses with shorter pulse widths during core saturation is described. Also, the characteristics of the magnetic core for pulsed-power applications are described using the B-H curves derived from the measured voltage and current waveforms. Finally the Electromagnetic Transient Program (EMTP) simulation is carried out in order to determine the effects of leakage current on the energy efficiency of a typical 3-staged MPC.

2 EXPERIMENTAL SETUP AND PROCEDURES

Figure 1 describes the schematic diagram of the low inductance circuit for measuring dynamic properties of the magnetic core. The discharge circuit has a coaxial geometry to reduce the stray inductance of the circuit. The total inductance around the main current loop during saturation of the core has been calculated to be as low as about 85 nH using equation (3). A reset circuit is used to obtain a maximum flux swing. The magnetic core used in this study is a FINEMET core (FT-1H, Hitachi Metal Corp., Japan),
which has a 60 mm inner diameter, 130 mm outer diameter and is 25.4 mm in height.

In Figure 1, a dc voltage source (E) is used to charge a capacitor (C) through a high resistance (R). On closure of the triggered spark gap switch (SGS), the SI begins to saturate after time to saturation, $\tau_1$. The applied voltage across the SI, $v_{SI}$ and the discharge current, $i_{SI}$ have been measured using a voltage divider (EP-50K, Pulse Electronic Engineering Co., Japan) and a current monitor (Model 110A, Pearson Electronics, USA), respectively. An oscilloscope (TDS3054B, 500 MHz, Tektronix) recorded the single-shot signals from the measurement devices.

Figure 2 illustrates the derivation method for the $B$-$H$ curves from the measured voltage and current waveforms.

\[
B = \frac{\int v_{SI} dt}{N \cdot A_e} \quad \text{(1)}
\]

where $N$ is the number of winding turns and $A_e$ is the effective cross-section area that is the actual area of the magnetic material in the core excluding the area of the inter-laminar insulation.

\[
H = \frac{i_{SI} \cdot N}{l_e} \quad \text{(2)}
\]

where $l_e$ is average magnetic path length.

Time to saturation, $\tau_1$, and current pulse width $\tau_2$ can be used in deriving several physical quantities. However, it is very difficult to exactly determine the boundary line of the two terms in Figure 2 because the current pulse at earlier times is distorted by the saturation of the core. Therefore, $\tau_1$ and $\tau_2$ are determined by the following iterative procedure in this study. First, the current pulse width, $\tau_2$, is roughly determined from the measured current waveform. $\tau_1$ is then calculated from the voltage and current waveforms. In order to verify these values, the circuit inductance at SI saturation $L_{sat}$ is obtained from:

\[
L_{sat} = \left( \frac{\tau_2}{\pi} \right)^2 \frac{C}{2} \quad \text{(3)}
\]

and the voltage at $\tau_1$ is obtained from [17]:

\[
v_{\tau_1} = \frac{1}{C} \cdot \sqrt{\frac{L_{sat}}{C}} \quad \text{(4)}
\]

where $I_{max}$ and $C$ are the maximum current value and capacitance, respectively. $\tau_1$ can then be determined in accordance with $v_{\tau_1}$ from the voltage waveform. Finally, this $\tau_1$ is compared with the roughly determined one. If there is a significant difference between them, a new value of $\tau_2$ is taken. The procedure is repeated until the values are equal to each other. The results are shown in Table I with the experimental parameters. $L_{sat}$ of 100 nF is larger than those of others because of the different geometry of the capacitor. The reset current was chosen as 0.5 A or 1.0 A in order to get a more coercive force than the 0.6 A/m that is recommended by the manufacturer. The frequency of the current pulse during saturation can be determined from:

\[
f_{sat} = \frac{1}{2 \tau_2} \quad \text{(5)}
\]
3 RESULTS AND DISCUSSION

3.1 DERIVATION OF B-H CURVES

Figure 3 shows the typical voltage and current waveforms (top) and derived \( B-H \) curves (bottom) for the case of one single core and reset current of 1.0 A. In the voltage and current waveforms, on closure of the triggered SGS at 0 ns, most of the charge voltage is applied across the SI. It is observed that the leakage current increases as time increases and that \( \tau \) increases with decreasing voltage because the product of voltage and time is constant. After \( \tau \), the SI reaches saturation and operates as a closing magnetic switch. The trend of the maximum current can be explained by equation (4).

The \( B-H \) curves are derived from the measured voltage and current waveforms using equations (1) and (2). From the hysteresis loops, it can be seen that: (1) the ratio of unsaturated to saturated permeability \( (\mu_{uns}/\mu_{sat}) \) is very large, which means very good switching performance, (2) the maximum flux swing over 2.5 T is obtained by applying a reset current greater than a current value corresponding to the coercive force \( H_c \) of the magnetic core, which means that this core can contribute to the compact pulsed-power generators, (3) the ratio of remnant flux density to saturation magnetic flux density \( (B_r/B_s) \) is close to 1, which means good switching performance and (4) low core loss is expected from the narrow area of the hysteresis loop, which means that repetitive operation is possible.

Dependence of unsaturated relative permeability \( (\mu_{uns}) \) on time to saturation \( (\tau) \) is shown in Figure 4. It can be seen that \( \mu_{uns} \) increases with \( \tau \) for a fixed product of voltage and time. This is because \( \mu_{uns} \) increases with decreasing \( dB/dt \), that is, decreasing voltage [16]. From these results, it is considered that the last stage in MPC will show worse switching performance because it has a shorter \( \tau \) and a larger leakage current. Also, it is observed that the permeability of two cores is higher than that of one core due to the fact that \( dB/dt \) has been halved by keeping the voltage constant while doubling the number of cores. It is thought that the switching performance of the magnetic core in MPC can be improved as the number of cores increases for the same voltage at the cost of other factors.

Dependence of saturated relative permeability \( (\mu_{sat}) \) on frequency is described in Figure 5. It can be seen that \( \mu_{sat} \) is almost independent of frequency for a fixed charge energy because the magnetic core behaves as an air core during the saturated state. Also, it is observed that the permeability of two cores is lower than that of one single core. This is because \( L_{sat} \) is constant in the saturated state while the core cross section area has doubled. In fact, \( \mu_{sat} \) does not indicate the relative permeability of the magnetic core but rather the stray inductance of the core holder divided by the cross section area. Also, it is observed that \( \mu_{sat} \) does not decrease to 1 due to the stray inductance of the core holder. The stray
Figure 4. Dependence of unsaturated relative permeability ($\mu_r$) on time to saturation.

Figure 5. Dependence of saturated relative permeability ($\mu_r$) on frequency.

The inductance calculated from the geometry of the core holder can be determined from [7]:

$$L_{\text{holder}} = \mu_0 \frac{N^2 \cdot h}{2\pi} \ln \frac{b}{a}$$  \hspace{1cm} (6)

and is about 20 nH where $h$, $a$, and $b$ are the height, the outer radius, and the inner radius of the core holder, respectively.

The saturated inductance calculated from $\mu_r$ in Figure 6 using the relation [17]:

$$L_{\text{sat}} = \mu_0 \mu_r \frac{N^2 \cdot A}{l_e}$$  \hspace{1cm} (7)

is also about 20 nH. These same results indicate that the stray inductance of the core holder directly influences the slope of the $B$-$H$ curve in the saturated state and that the inherent $\mu_r$ of the magnetic core is nearly unity. From these results, it is evident that the maximum current and effective energy transfer in the saturated state of a real MPC circuit strongly depend on the stray inductances of the circuit.

3.2 EMTP SIMULATION WITH CUSTOM AND IDENTICAL B-H CURVES FOR EACH MPC STAGE

In this study, EMTP [21, 22] has been used to carry out the comparison studies between an MPC (MPC 1 hereafter) with custom $B$-$H$ curves and the other MPC (MPC 2 hereafter) with identical $B$-$H$ curves for each MPC stage. The $B$-$H$ curves of the different permeability characteristics derived in the last section and a $B$-$H$ curve reported by the manufacturer in [2] have been utilized for the magnetic cores of MPC 1 and MPC 2, respectively.

Figure 6 shows the schematic diagram of the EMTP simulation circuit for a typical 3-staged MPC. The simulation circuit has a foremost stage for pulse generation and three subsequent stages for pulse compression, and consists of capacitors ($C_0$, $C_1$, $C_2$ and $C_3$), saturable inductors ($S_{L0}$, $S_{L1}$, $S_{L2}$ and $S_{L3}$), stray inductances ($S_{L0}$, $S_{L1}$, $S_{L2}$ and $S_{L3}$), a switch (SW), a pulse transformer (PT) and a matched load. The capacitances of $C_0$, $C_1$, $C_2$ and $C_3$ are 2.3 µF, 16 nF, 16 nF, and 16 nF, respectively. The charge voltage on $C_0$ is 2.6 kV. Stray inductances used for each stage are shown in Table 2. These values are based on a real MPC [23]. PT has a function of an ideal step-up transformer with the voltage gain of 12. A 2.3 Ω resistor is used as the matched load.
Table 2. Stray inductances used in the EMTP simulation circuit.

<table>
<thead>
<tr>
<th>SL₀</th>
<th>SL₁</th>
<th>SL₂</th>
<th>SL₃</th>
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<tr>
<td>0.847 µH</td>
<td>0.6 µH</td>
<td>0.276 µH</td>
<td>0.06 µH</td>
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Table 3. Calculated Inductances of the magnetic cores of MPC 1.

<table>
<thead>
<tr>
<th>SI₀</th>
<th>SI₁</th>
<th>SI₂</th>
<th>SI₃</th>
</tr>
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<tbody>
<tr>
<td>Lu</td>
<td>Ls</td>
<td>Lu/Ls</td>
<td></td>
</tr>
<tr>
<td>0.125 mH</td>
<td>0.024 µH</td>
<td>5200</td>
<td>1.34 µH</td>
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Table 4. Calculated Inductances of the magnetic cores of MPC 2

<table>
<thead>
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<th>SI₀</th>
<th>SI₁</th>
<th>SI₂</th>
<th>SI₃</th>
</tr>
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<tbody>
<tr>
<td>Lu</td>
<td>Ls</td>
<td>Lu/Ls</td>
<td></td>
</tr>
<tr>
<td>0.105 mH</td>
<td>0.024 µH</td>
<td>4370</td>
<td>5.98 mH</td>
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Table 5. Calculated current pulse widths on each stage of MPC 1

<table>
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<th>Stage</th>
<th>PW (ns)</th>
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<tr>
<td>0</td>
<td>3140</td>
</tr>
<tr>
<td>1</td>
<td>391</td>
</tr>
<tr>
<td>2</td>
<td>164</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
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Figure 7 shows the custom B-H curves for SI₀, SI₁, SI₂ and SI₃ of MPC 1, and the identical B-H curve for SI₀, SI₁, SI₂ and SI₃ of MPC 2, respectively. The custom B-H curves for SI₀, SI₁, SI₂ and SI₃ of MPC 1 were derived from Case 3, Case 6, Case 2 and Case 1 in Table 1, respectively. All the curves show different slopes (that is, μro) during the unsaturated state due to the leakage current characteristics of the magnetic core, and same slopes (that is, μrs) during the saturated state due to the transition of the core from the magnetic material to the air.

Figure 8 shows the flux and current relationships for SI₀s, SI₁s, SI₂s and SI₃s of MPC 1 and MPC 2, respectively. The curves were derived from the B-H curves shown in Figure 7 using the following relationships:

\[ \Phi = N \cdot B \cdot A_c \]  
\[ I = H \cdot I_e / N \]

where \( \Phi \) is flux [Wb-T], \( I \) is current [A]. The numbers of winding turns for SI₀, SI₁, SI₂ and SI₃ of MPC 1 and MPC 2 are 3, 16, 4 and 2 respectively, and the numbers of cores for SI₀, SI₁, SI₂ and SI₃ are 1, 2, 1 and 1, respectively.

From the derived flux-current curves, it is possible to calculate the unsaturated and the saturated inductances of the magnetic switches. The results are shown in Table 3 and 4. The ratios of the unsaturated to the saturated inductance (Lu/Ls) for SI₀, SI₁, SI₂ and SI₃ of MPC 1 are 5300, 11200, 2200 and 1360, respectively, whereas the ratios of the unsaturated to the saturated inductance for SI₀, SI₁, SI₂ and SI₃ of MPC 2 are consistently about 4400. It can be expected that the overall performance of MPC 1 decreases as the number of stages increases, whereas that of MPC 2 remains unchanged. Also, it should be noted that this big difference in the ratios plays an important role as a switch in the MPC circuit.

Figure 9 shows the typical voltage and current waveforms on each stage of MPC 1. On switch closure in the pulse generation stage, the magnetic assist by the SI₀ follows the switching of the SW for 1.85 \( \mu s \). Magnetic assist has the effect of reducing the switching loss [4]. Thus, an MPC that consists of the magnetic switch and the solid state switch can be operated with higher repetition rate, longer lifetime and higher reliability than conventional ones.

In Figure 9a, the charge energy in \( C_n \) is transferred to \( C_{n+1} \) by C-L-C resonance as SI₀ saturates with the following relation [23]:

\[ \int V(t)dt = \frac{V_{stn} \cdot \tau_n}{2} \geq N \cdot \Delta R_m \cdot A_e \]

If the leakage current in SI₀ is ignored, the voltage \( V_n(t) \) on \( C_n \) of the n-th stage is given by

\[ V_n(t) = V_{n-1} \frac{C_{n-1}}{C_{n-1} + C_n} (1 - \cos \omega t) = \frac{V_{n-1}}{2} (1 - \cos \omega t) \]

where \( n = 1, 2 \) and 3, \( \omega = \frac{1}{\sqrt{L_T C_T}} \), \( L_T = L_{SI_{n-1}} + SL_{n-1} \),

\[ C_T = \frac{C_{n-1} C_n}{C_{n-1} + C_n} \]

The voltage waveforms are compressed as the number of stages increases because \( L_T \) is designed to decreases with the number of stages in the following way.

\[ V \cdot t \] for SI₀ not to saturate for \( \tau_{n-1} \) is obtained by
The calculated current pulse widths on each stage of MPC 1 are shown in Table 5. This results show a good agreement with Figure 9b.

Figure 10 shows the voltage waveforms on each stage of MPC 1 and MPC 2. The charge voltage on C1 of MPC 2 is lower than that of MPC 1 because SI1 of MPC 2 has a higher leakage current from Figure 7 than that of MPC 1. Also it is seen that the charge voltage on C1 of MPC 2 is lagged to that of MPC 2 because equation (10) must be satisfied. The situation is reversed in C2. The charge voltage on C2 of MPC 2 becomes higher than that of MPC 1 because SI2 of MPC 2 has a lower leakage current than that of MPC 1. The phase of voltage waveforms in C2 remains unchanged because V·t of SI1 is significantly higher that of SI2. The difference of the charge voltages between MPC 1 and MPC 2 becomes larger in the last stage due to the larger leakage current. The energy transfer rate on each stage of the pulse compression part is shown in Figure 11. It should be noted that the transfer rate of MPC 1 decreases exponentially, whereas that of MPC 2 decreases linearly, which indicates that a significant difference can be brought about between custom and identical B-H curves for each MPC stage.
4 CONCLUSION

The following critical characteristics for the repetitive pulsed-power operation of MPC have been observed from the derived B-H curves for a magnetic core: a high ratio of unsaturated to saturated permeability ($\mu_{\text{uns}}/\mu_{\text{sat}}$), a maximum flux swing of about 2.55 T, a high ratio of remanent flux density to saturation magnetic flux density ($B_r/B_s$) and low core loss.

The unsaturated relative permeability increases with time to saturation and decreasing voltage. The stray inductance of the core holder directly influences the slope of the B-H curve in the saturated state.

Comparison studies between MPCs with custom B-H curves and identical B-H curves for each MPC stage have been carried out using EMTP simulation. The energy transfer rate of the MPC with custom characteristics decreases exponentially, whereas that with identical characteristics decreases linearly.

Based on the present study, it is believed that it is possible to design an MPC with a higher accuracy by using the custom characteristics for the magnetic core of each MPC stage.

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REFERENCES


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