Dynamics of magnetic pulse compression circuit of metal vapor laser

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Abstract: Solid-state pulse power supply uses magnetic pulse compression circuit (MPC) to reduce the rise time of the voltage pulse applied across the Metal vapor Laser (MVL). In MPC, the nonlinear characteristics of ferromagnetic material is leveraged, to obtain large change in its inductance. These inductors get saturated during application of desired voltages and offer low impedance, which acts like a closed switch. It is desirable to fix the operating point in the B-H curve for smooth functioning of the switch, hence a current is applied to the magnetic switch to reposition the operating point on B-H curve from positive saturation flux to negative before appearance of next pulse. In MVL proper reset becomes extremely important because of small tolerance in the timing, for obtaining low jitter requirement.

At low repetition rate, resetting of magnetic switch is easy as the oscillation in L-C circuit in MPC dies out before the next pulse. However, as the repetition rate increases there is very little time for reset dynamics to take place before the next pulse. In this paper we are presenting detailed dynamics of 9 kHz pulse repetition rate MPC for MVL. B-H curve have been derived using voltage, current waveform and Jiles Atherton equation in simulation model. We have shown how MPC oscillation affects the B-H curve of the magnetic switch. An experimentally validated simulation model is developed for detailed analysis of dynamics of MPC and to observe other implications like effect of reset on jitter in output of MPC.

Keywords: Magnetic Pulse Compression; Core reset; Pulse Power Supply; Magnetic Switch; Copper Vapor Laser.

1. INTRODUCTION

In order to increase the population in upper laser level of copper atomic transition i.e., population inversion, electrical discharge is applied across the laser head. As the upper energy level has very short life time in the range of 500 ns, the pulse discharge needs to have sharp rise time of less than 100ns [1, 2]. This requirement of low-rise time voltage pulse is accomplished using magnetic pulse compression circuit. MPC is an L-C circuit with capacitor used for storing energy and saturable inductor acts as switch [3]. The switching operation is realized in inductor by virtue of variation in inductance due to non-linear B-H characteristics of ferromagnetic core of the inductor. During unsaturated state it acts like an open switch and in saturation state it acts like a closed switch [3,4]. In MPC stages, capacitor value is fixed in each stage and inductance value is reduced to reduce the rise time with maximum power transfer in successive stages. At high repetition rate understanding of MPC dynamics becomes important for parameter optimization to get desired performance from MPC. Reset is used in magnetic switches to ensure constant ΔB variation in each pulse and quickly die out the oscillations set inside the
MPC [4, 5]. In this paper we have presented that how load variation causes flux swing variation (ΔB) in the magnetic switch, leading to jitter in the output current. As laser is a dynamic load without proper reset there will be ΔB variation due to load variation. CVL is generally operated in MOPA configuration, which makes jitter constraint even tighter [1]. Therefore, understanding of reset dynamics and then application of proper reset current becomes crucial. In this paper a detailed analysis of the reset dynamics has been studied. Behavior of magnetic switches due to oscillation in MPC is presented using derived B-H curve with hysteresis. An experimentally validated simulation model of pulse power supply is used to support the analysis.

2. DESCRIPTION OF LASER POWER SUPPLY

The electrical circuit diagram of pulse generating unit is shown in fig 1. It basically consists of DC power supply (400V, 20 A), pulse-transformer (1:32), magnetic switches to reduce the rise time to less than 100ns and a laser head as a dynamic load. The repetition rate of power supply is 9 kHz and the impedance offered by load is 25 ohms. The required power for population inversion through discharge in laser, is provided by Switch mode power supply. The resonant circuit is used to double the voltage across the capacitor ‘C’. This doubled voltage is fed to pulse transformer to amplify it and subsequently rise time of amplified voltage is reduced by MPC stages. The MPC stages reduces the rise time from 1.5μs to 80ns. The final output voltage is 13 kV with 80 ns rise time. Detailed description of pulse power supply and CVL is presented in the reference 6 and 7.

![Circuit diagram of Pulse power supply](image1)

When a voltage pulse propagates though magnetic switch, its core gets biased to positive saturation flux. Before appearance of next pulse, the core must be reset to negative saturation flux. To accomplish this at high repetition rate a dc current is supplied to winding to reset it in negative(opposite) direction.

3. DYNAMICS OF MPC

![Simulated circuit of pulse power supply](image2)
The Fig 2 shows the simulated model of pulse power supply. The details of simulation model are presented in reference 7. The DC voltage in simulated model is 390V. The simulated voltage waveform at the output of pulse transformer and the three stages of MPC is compared with the experimental waveform as shown in fig 3. It can be seen that the simulated waveform closely resembles the experimental waveform. Three Ni-Zn ferrite cores of dimension 150/100/15 mm are used for each switch with primary and secondary turns of 48/4, 13/4 and 4/4 respectively for S1, S2 and S3 [7]. The saturated leakage inductance of all three magnetic switches is calculated and found to be 14.7 μH, 4 μH, 1.15 μH for magnetic switches S1, S2, S3 respectively [7]. From ferrite datasheet, the unsaturated permeability of Ni-Zn (CMD5005) ferrite core is 1000 times the saturated permeability. Maximum flux swing available for the core is 0.37 T. In simulation model losses are neglected and ideal components are assumed for modelling.

**Fig 3.** Simulated and experimental waveforms at various stages in pulse power supply

The figure 4 shows the simulated voltage waveform on capacitor (VC, blue), voltage across Switches (Vs, Red), current through switches (Is, Black), Magnetic field intensity (Bs, brown). In simulation study we have used constant resistive load of 25 ohm. For analysis of MPC dynamics, the polarity as
shown in the fig 5 is considered positive. During operation of the MPC, voltage on the capacitor develops in the direction of positive polarity as indicated and the current in the switches flows from + terminal to – terminal.

Fig 4.1 First Stage of MPC (\(V_{c1}, V_{s1}, I_{s1}, B_{s1}\))

Fig 4.2 Second Stage of MPC (\(V_{c2}, V_{s2}, I_{s2}, B_{s2}\))

Fig 4.3 Third stage of MPC (\(V_{c3}, V_{s3}, I_{s3}, B_{s3}\))

Fig 5 Reverse voltage charging of capacitor
When C1 is charged through transformer a voltage appears across S. Switch, S1, offers high inductance until it gets saturated. On saturation of L1 voltage is transferred from C1 to C2. Before transfer of voltage fully from C1 to C2 a net negative voltage appears across S1, which brings it out of saturation and S1 regains its high inductance and current through it reduces to ~2A. A residual voltage of ~2kV is left on capacitor C1. Then S2 gets saturated and voltage is transferred from C2 to C3. A reverse voltage appears across S2 and it comes out of saturation. A residual voltage is left on C2. After this S3 gets saturated and voltage is transferred from C3 to C4. The voltage pulse is compressed and current is amplified. By the time full voltage is transferred from C3 to C4 a significant current develops through inductor S3 which causes C3 to be charged in slight negative voltage. C4 starts discharging into resistive load and net reverse voltage across switch S3 starts reducing. Meanwhile C3 dumps its energy to C2 as S2 still favors current in positive direction.

Oscillating circuit is formed between C2 and C3. By the time current reduces in S2 to zero, C3 is charged to positive voltage and C2 to negative voltage. Oscillating circuit is formed between C3 and C4 as saturation value for Inductor S3 is very small. When the voltage across C2 becomes negative, a net negative voltage appears across S1 and it offers high inductance till it gets saturated and transfers voltage left on C1 to C2. C2 again becomes positive and a net negative voltage appears across inductor S1 and again it offers higher inductance. By this time C2 transfers its voltage to C3 by saturating S2, meanwhile voltage on C1 is dissipated through leakage current.

Now C1 and C2 starts charging in reverse direction through the path as shown in the figure 5. After saturation of all the switches, positive direction of current as shown in fig 5 is favored by each switch. C1 charges through R-S3-S2-S1 and the time period of oscillation is given by eq 1.

$$T = 2\pi \sqrt{\frac{L}{C}}$$  \hspace{1cm} (1)

Where L= Sum of inductance of Switch S1, S2 and S3. The calculated time period of 39.43 μs matches with simulation result. Similarly, the time period for C2 comes out to be 20.17μs and matches with the simulation result. This charging of voltage in positive direction causes appearance of reverse voltage across inductor and causes its B-H curve point to move towards negative saturation. Higher the value of inductance and higher the voltage on capacitor, the deeper the point will move towards negative saturation in B-H curve as shown in the figure 4. As saturation value of switch S3 is small, the voltage of C3 and C4 forms an oscillating circuit of time period 6.28μs. The figure 5 shows the current path while resetting of switches S1, S2 and S3 happens. Red color shows the reverse charging path for C1, green for C2. Blue and orange represents the high frequency oscillations between C3 and C4. This concludes that even with fixed load there are oscillation in the MPC stages due to inherent nature of L-C circuit used in MPC. When the load is dynamic then voltage on capacitor, oscillation frequency and even flux swing variation in inductor is variable due to reflections from the variable load. This further complicates the proper resetting of MPC switches.

The B-H curve of the switches is simulated using equation 2 and Jiles Atherton model parameters [6,7,8].

$$B = \frac{\int V dt}{NAe} \text{ and } H = \frac{IN}{le}$$  \hspace{1cm} (2)

Where V is the voltage across inductor(switch), I is the current through the inductor, N is the number of winding turns, Ae is the effective cross-section area that is the actual area of the magnetic material in the core excluding the area of the insulation and le is average magnetic path length. The B and H value calculated using simulated voltage and current waveform is fed to x-y graph block to draw B-H curve. The purpose of adding hysteresis in the B-H curve is to see the effect of MPC dynamics on B-H curve. Hysteresis is added using Jiles Atherton method for nonlinear inductor in simulation model with the parameters value as shown in Table 1.
Table 1. Jiles Atherton parameter for Hysteresis simulation

| Parameter                              | S1       | S2       | S3       |
|----------------------------------------|----------|----------|----------|
| Number of primary / reset turns        | 48/4     | 13/4     | 4/4      |
| Effective length                       | .471m    | .471m    | .471m    |
| Effective cross-sectional area         | .002250m²| .002250m²| .002250m²|
| Anhysteric B-H gradient                | 0.003mT/A| 0.003mT/A| 0.003mT/A|
| Flux density point on Anhysteric B-H curve (Tesla) | 0.2      | 0.2      | 0.2      |
| Corresponding field strength           | 150      | 100      | 100      |
| Coefficient for reverse magnetization  | 0.5      | 0.4      | 0.2      |
| Bulk Coupling Coefficient             | 15       | 15       | 20       |
| Inter domain coupling factor           | 1e-9     | 1e-9     | 1e-9     |

As mentioned earlier, due to high frequency oscillation formed between C3 and C4, current and voltage oscillates with high frequency which is reflected in the B-H curve of S3. Whereas there is roughly no oscillation in the B-H curve of S1. In switch S2, few oscillations are observed due to oscillating voltage on C3. The hysteresis loss is a function of frequency. Since the reflection from the load is dynamic in both amplitude and shape, so losses due to each reflected pulse will be different. The amplitude of voltage on capacitor in MPC stages due to propagated reflected voltage will be different for each pulse. So, it can be concluded that the dynamicity of load adds voltage variation (ΔV) and the flux swing variation (ΔB).

4. MAXIMUM FLUX SWING IN SWITCH

As can be seen from the simulated waveform in fig 4 that S1 gets saturated in reverse direction at the time when voltage across C1 builds in reverse direction. The voltage difference between C1 and C2 appears across S1. The voltage across Inductor in a C-L-C circuit is given by

\[ V = -N \frac{d\phi}{dt} \]

\[ \int vdt = N\Delta \phi \]

\[ \int vdt = N\Delta BA \]
Where $\omega = \frac{1}{\sqrt{LC}}$ during reverse charging of $C_1$, $L =$ Inductance of $(S1+S2+S3) = 19.85 \text{mH}$, $C = C_1 = 2 \text{nF}$, $N = 48$ for $S1$, Area of core cross section $= 2.25 \times 10^{-3} \text{ m}^2$ and peak voltage on inductor $= 3200 \text{V}$ (Simulation result).

\[
\int_0^\pi V \cos(\omega t) \, dt = N \Delta BA
\]
\[
\frac{2V}{\omega} = N \Delta BA
\]
\[
\Delta B = 0.37 \text{ Tesla}
\]
\[
B_{ss} - (-B_{ss}) = 0.37
\]

(Negative saturation) $B_{ss} = 0.17 \text{ Tesla}$ (matches the simulation result)

Whereas for third switch due to high frequency oscillation between $C3$ and $C4$, the $B$ field also oscillates. But due to transfer of voltage from $C2$ to $C3$ through $S2$, develops a net negative voltage of $160 \text{V}$ across $S3$ along with oscillating voltage due to $LC$ oscillations ($C3-S3-C4$) which contributes to zero flux over an integer multiple of time period. So, flux swing available at $S3$ can be calculated

\[
\int v \, dt = N \Delta BA
\]

Where $V=160 \text{ volts}$ (Simulated waveform), $t=19.74 \mu\text{s}$ (Simulated waveform), $N=4$, $A= 2250 \times 10^{-6} \text{ m}^2$. So $\Delta B$ comes out to be $0.350 \text{ tesla}$ and $B_{ss} = 0.15 \text{Tesla}$. Similarly, for $S2$ $B_{ss} = 0.17 \text{ Tesla}$ which can be verified from the B-H graph shown in the Fig 6. Thus, it can be concluded that the core is not fully utilized, as flux swing used in the MPC is much less than available flux swing in the core. If full available flux swing is used, the size of MPC can be reduced. However, that will affect the cooling of MPC stages.

5. RESET IN MPC SWITCHES

As we have seen that the dynamics of the MPC involves load impedance. So varying load impedance will change the dynamics of the MPC. We have plotted $B$ field as a function of time for different load impedance of $15/25/35/45 \text{ ohm}$, as shown in fig 7. It can be seen there is significant variation in simulated $B$ field for third stage switch due to load variation. Copper vapor laser is a dynamic load, its impedance varies with time. So, it can be deciphered that the load variation will lead to jitter in the system as per the equation 3.

\[
\frac{1}{2} V t = N A \Delta B
\]

(3)

Where $t$ is the saturation time of magnetic switch, $N$ is number of turns, $A$ is core area, $\Delta B$ is flux density swing and $V$ is voltage applied. As it has been shown that load variation causes variation in $B$ w.r.t time. So $\Delta B$ variation available for different pulse will be different and hence it will contribute to jitter. It has been shown in section 3 that load dynamicity causes both voltage and the flux swing variation. Thus, as per eq 3, voltage and flux swing variation cause jitter in the output pulse.
Reset becomes important for MPC stage used in pulse power supply of dynamic loads like CVL. We have simulated the B field variation of switch, S1, with time for different values of reset current of 0/0.5/1/1.5.

It can be seen in fig 8, that with high reset current, B-s (negative saturation) is quickly reached. As the oscillation in B field quickly damps out, so B-s remains at same value before appearance of next pulse.
We have plotted variation of settling time with reset current for all the three magnetic switches as shown in fig 9. It can be seen that reset current plays major impact on the dynamics of S3 as compared to S1 and S2. Since field associated with S3 experience high frequency oscillation as mentioned in the previous paragraph, so using reset in S3 will be more useful.

6. RESET CALCULATIONS

Now let us calculate the reset parameters for first stage MPC. The voltage across C1, causes the S1 to saturate. The voltage on reset side will depend upon reset winding to primary winding ratio. During initial stage when S1 is getting saturated, we can calculate the peak current in the reset winding. Due to saturation of S1, inductance offered by it is very small and hence in the reset winding whole voltage appears across blocking inductor as shown in fig 8. Thus, we can write –

$$V(1 - \cos(\omega t)) = \frac{L_{isolation}}{L_{isolation}} \frac{di}{dt}$$

$$\frac{\int_{t_{sat}}^{t_{res}} V(1 - \cos(\omega t))dt}{L_{isolation}} = \int_{I_0}^{I_{pk}} di$$

Where $\omega = 1/\sqrt{LC}$ ($L=14.7$ mH, $C=1$ nF), $t_{sat} = \pi/\sqrt{LC}$ $L_{isolation} = 1.6$ mH, Suppose $I_0$ (reset current) = 2A. Then solving above equation $I_{pk} = 3.35$ A (Matches with the simulation results). Now as we have discussed the current path while resetting and the peak current in the reset winding, so we can calculate settling time for a reset current.

$$\int_0^{t_{reset}} Vdt = L \int_{I_0}^{I_{pk}} di$$

$$I = I_{pk} \cos \omega t$$

$$V_{t_{reset}} = L_{pk}(\cos \omega t_{reset} - 1)$$

$$t_{reset} = \frac{1}{\omega} \cos^{-1}\left(\frac{V_{t_{reset}}}{L_{pk}}\right)$$

(4)

Where $\omega$ is decided by path taken during reseting of core as shown in the fig 5, so $\omega = 1/\sqrt{LC}$, $L = 19.85$ mH and $C = 2$ nF. $V_{t_{reset}} (400 \times 10^{-6}$ Weber) is the saturation flux of magnetic switch S1, obtained using experimental voltage current waveform across S1. And inductance is the sum of primary and primary referred inductance of reset winding. Solving eq 4, $t_{reset}$ comes out to be $19.7 \mu s$ (matches simulation result). Thus the reset current should be so chosen that the switch gets reset before appearance of next pulse and the reset current of 2 A is sufficient to reset the core of switch S1.

7. CONCLUSION

A detailed analysis of reset dynamics of MPC is presented. It is shown that load plays a significant role
in reset dynamics and influences the MPC parameters. Proper resetting of each switch is important to avoid flux swing variation leading to jitter. As S3 experiences high frequency oscillations its resetting becomes crucial.

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