Design and simulation of series resonant push-pull 3KV DC high voltage power supply

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Abstract: In order to meet high efficiency and small size of neutron tube ion source power supply, a technical solution of series resonant push-pull converter is proposed. This converter utilizes the parasitic parameters of mosfet to eliminate oscillation of the circuit, and uses the first capacitor of capacitor-doide voltage multipliers as resonant component to achieve ZVCS of the switch to reduce loss. First Harmonic Approximation is used to establish voltage gain mathematical model to reflect the influence of quality factor on voltage gain. Parameter design method for push-pull LC resonant voltage multipliers is given. A prototype was simulated by saber software to verify the correctness of theoretical analysis.

1. Introduction
In order to satisfy the demand of oil well logging in using neutron generator, it is imperative to design DC high power supply with a small volume, high efficiency, and high stability. Having high requirements for circuit efficiency, especially circuits are powered by battery in oil wells[1-3]. Traditional PWM hard-switch exists cross losses when switches is turned on and turned off. The appearance of parasitic inductance and capacitance would generate largely inrush currents and highly peak voltage when the power mosfet is driven by high frequency square waves, which increases switching losses and limits switching frequency[4-6].Therefore, it is difficult to achieve miniaturization and high efficiency. The resonant conversion technology is adopted to realize the zero-voltage turn-on and the zero-current turned off of the push-pull converter. Meantime, the capacitor-doide voltage multipliers can greatly reduce the transformer step-up times and volume so this circuit is an ideal topology form.

2. The overall working principle
Neutron tube 3kv DC high voltage power supply resonant conversion circuit principle is shown in Figure 1.
The push-pull transformer secondary side achieves 3kv output by 6 times voltage-doubling rectifier. VD1 and VD2 are switch body diodes, CS1 and CS2 are the sum of parasitic capacitor of mosfet and external parallel capacitors. Besides, CS1=CS2, C1=C2=C3=C4=C5. Lr, Lr1 and Lr2 are leakage inductance of transformer, Cr is the first capacitor of capacitor-dioide voltage multipliers, and RL is the actual load.

3. Research on characteristics of converter

Steigerwald proposed an analytical method, which is suitable for any kind of resonant converter[7]. The fundamental wave of Fourier series of the voltage and current are used to replace the input square wave of the converter, abbreviated as First Harmonic Approximation. The AC analysis method was used to analyze the steady-state of the topology. For ease of analysis, power mosfets are ideal switches and all passive components are linear components.

The switches Q1 and Q2 are alternately conducted. The primary input DC voltage of the transformer is a square wave whose amplitude equals Ui. Fundamental wave of primary-side voltage in one cycle:

$$u_p(t) = \frac{4}{\pi} U_i \sin(w_i t)$$

$$w_i = 2\pi f_s$$, fs is switching frequency of the mosfet. From the formula (1), the primary input current $i_p(t)$ is also a sine wave:

$$i_p(t) = \sqrt{2} I_p \sin(w_i t)$$

Ip is root mean square of current. The input current $I_{i,dc}$ of DC voltage source can be regarded as average value of $i_p(t)$ flowing through the Q1 switch in one cycle.

$$I_{i,dc} = \frac{2}{T_i} \int_0^{T_i/2} i_p(t) dt = \frac{2\sqrt{2}}{\pi} I_p \cos \theta$$

The input voltage of the transformer secondary resonant circuit in one cycle is a square wave with amplitude $U_s$. Its fundamental wave component can be expressed as:

$$u_s(t) = \frac{4N U_o}{\pi} \sin(w_s t) = \frac{4U_o}{\pi} \sin(w_s t)$$

After the LC resonant converter, output voltage of the resonant network and capacitor-dioide voltage multipliers input voltage are a square wave with an amplitude of $U_o/6$. Their fundamental wave equal:

$$u_d(t) = \frac{2}{3\pi} U_o \sin(w_o t - \varphi)$$

Input current of capacitor-dioide voltage multipliers and output current of resonant network can be expressed as:

$$i_d(t) = \sqrt{2} I_d \sin(w_o t - \varphi)$$

Id is RMS of output current of the resonant network. $\varphi$ is input impedance angle. In order to facilitate analyzing output characteristics of resonant network, the capacitor-dioide voltage multipliers is equivalent to a rectifier circuit whose voltage multiplier is 6. The UR and Id are in same phase. With respect to LC resonant network, the capacitor-dioide voltage multipliers can be equivalent to a resistor:
The high frequency components of \( I_d \) are filtered by capacitors so that \( I_o \) have only DC components flowing through the load \( R_L \). According to the power equal principle, \( I_o \) can be inferred:

\[
I_o = \frac{12}{T_s} \int_0^T |i_o(t)| = \frac{12\sqrt{2}}{\pi} I_d = \frac{P_o}{U_o} = \frac{U_o}{R_L}
\]

(8)

\( P_o \) is power when the output resistance is \( R_L \). From (8) and (7), \( R_e \) can be given:

\[
R_e = \frac{8}{\pi} R_L
\]

(9)

Known by Kirchhoff’s voltage law, \( C_r \) of the resonant network has the same voltage polarity and amplitude, when mosfets are turned on and turned off[8]. The circuit model is equivalent when the power mosfets are turned on alternately. FHA circuit model is shown in figure 3.

\[
\frac{\sqrt{2}}{\pi} I_s \cos \theta \quad \text{and} \quad a_s(t) = \frac{4}{\pi} U_s \sin(w_s t)
\]

(10)

After it is normalized, DC voltage gain equals:

\[
M = \frac{1}{2\pi f_s f} = \frac{1}{2\pi \sqrt{f_s f}}
\]

(11)

\( f = f_s/f_r \), \( f_s \) is the circuit switching frequency. resonant frequency: \( f_r = 1/2\pi \sqrt{I_c/C_r} \), quality factor:

\[
Q = Z_r / R_c \quad \text{and} \quad Z_r = \sqrt{L_r/C_r} = 2\pi f_r L_r = 1/2\pi f_r C_r
\]

When \( f \) and \( Q \) are selected differently, the curve of voltage gain \( M \) vs frequency \( f \) is drawn by using matlab. It is shown in figure 5.
As shown in figure 4, we can conclude that simulation curves will go through an independent load point for different Q. Besides, the increment of Q narrows the frequency adjustment range, and the voltage gain decreases as the impedance increases. In practical engineering applications, it is necessary to choose different Q according to actual situations.

4. Circuit parameter selection principle
This paper select efficiency optimization as a parameter design principle. Considering power efficiency is relative to many factors, here we use normalization method to obtain efficiency curve of the resonant converter topology[9,10]. The physical values in the circuit are expressed by using a normalized value: 
\[ U_B = 2\sqrt{2}U_c/\pi, \quad Z_B = Z_r = \sqrt{I_c/C_r}, \quad I_B = U_B/Z_B, \quad f_B = f_r. \]

After the physical values are normalized, standard load output current equals: 
\[ f = 6N/I_B, \quad \text{voltage gain is:} \quad M = U_c/U_B. \]

The efficiency can be expressed as:
\[ \eta = \frac{P_o}{P_i} = \frac{Mf}{M^2Q}. \] (12)

As shown in fig 7, the curve of efficiency vs voltage gain is obtained by selecting different f, which can provide important reference for circuit parameter selection.

When designing a circuit actually, we can choose the maximum efficiency operating point according to efficiency vs voltage gain plots.

\[ P_o = U_o I_o = \frac{M^2 U_B^2}{Z_B} \] (13)

\[ Z_B = \sqrt{\frac{I_c}{C_r}} \]

\[ f = \frac{w_r}{w_c} = \frac{2\pi f_c}{w_c}, \quad w_r = \frac{1}{\sqrt{L_c C_r}} = \frac{2\pi f_c}{f} \]. According to the above two formulas, we can get:
Using $L_r$, $C_r$ equations and efficiency vs voltage gain diagram, component parameters can be chosen.

5. Circuit design and parameter selection
Power working parameters are designed as follows: switching frequency $f_s=100\text{KHz}$; input voltage, ratio of winding: $N=9$; full load power is 50W; mosfet is IRF640. Switching period of the series resonant soft-switching of push-pull circuit is equal to the sum of the resonant period and the dead time. To achieve soft switching better, $f_s<fr$, $f=0.8$. From Figure 5, we can see that efficiency is maximum and $fr$ equals 125kHz, when the gain $M$ is equal to 0.72. According to figure 4, $Q=3$, then $J = 2.16$. Substituting the above parameters, we can get $Cr=(Pof)/(MJUB22\pi f)=11.9\text{nF}$, $Lr=(MJUB2f)/(Po2\pi f)=135.5\text{uH}$.

6. Simulation results
The rationality of parameter design is verified by using simulation software saber. $CS1=CS2=25\text{nF}$, $Cr=12\text{nF}$, $Lr1=Lr2=25\text{uH}$, $Lr=135\text{uH}$. Simulation schematic diagram is shown in figure 1. The simulation results are shown in the figure below.

As shown in figure 7, power supply achieves 3kv output. Besides, switches Q1 and Q2 achieve zero voltage turn-on and zero current turn-off, which can help power improve efficiency and reduce power consumption.
7. conclusion
Based series resonant push-pull converter, 3kv DC high voltage power supply is designed and simulated for neutron tube ion source power. After studying and analyzing the characteristics of its resonant converter, voltage gain vs efficiency curve of the resonant converter has important value for designing resonant parameters of the converter. At the same time, using capacitor-diode voltage multipliers can reduce voltage multiplier of transformer, the volume and weight of neutron ion source power supply, which is convenient for oil well logging and portable applications.

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