Design of driving power supply with high isolation and small coupling capacitance based on current transformer

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Abstract. General drive power supply can not meet the requirements of high-voltage isolation under high-voltage and high-frequency (HV-HF) conditions, and the larger coupling capacitance of general power supply will bring common-mode noise. In this paper, a 10kV isolation power supply with 1.55pF low coupling capacitance and multiple output is designed. The power supply adopts LCL-T resonant circuit to produce a 100kHz current source. The current transformer is used to isolate the power supply, which realizes high voltage isolation and small coupling capacitance. The number of output circuits is changed by increasing or decreasing the magnetic core.

1. Introduction
In recent years, breakthroughs in SiC, GaN materials and manufacturing have promoted the development of HV-HF power devices. MOSFETs of SiC and GaN are more used in high-power, HV-HF power electronic devices. However, in the case of HV-HF, the general grid-driven power supply can not meet the isolation requirements, and the power supply with large coupling capacitance will produce large common-mode noise at high frequency, which will reduce the performance of the power supply.

At present, in order to solve the problem of high voltage isolation, the high isolation driving power supply usually uses magnetic cores to isolate primary and secondary windings, increase insulation distance and maintain sufficient creepage distance[1]. In [2], the current source is obtained by buck circuit, and the current is inverted by bridge circuit. Then resonance is added to improve the current waveform, and the secondary side is charged from the primary side by the magnetic ring. Both mentioned methods achieve high voltage isolation, but the circuit volume increases and the power density decreases. In order to reduce the coupling capacitance, two back-to-back current transformers form an isolation transformer[3]. Although the coupling capacitance is very small, it needs two cores to drive each switch device, so it is difficult to achieve multi-output. Isolation transformer uses a transformer structure similar to current sensor to realize 1.05pF coupling capacitance[4], but the switching frequency of the system is low, and no more detailed design information such as the main circuit topology of the power supply is given.

In this paper, to solve the above problems, a driving power supply with high isolation and small coupling capacitance is designed as shown in Figure 1. The half-bridge inverter circuit is combined with LCL-T resonance. The resonance output current passes through the magnetic ring by the high-voltage cable. The output circuit is powered by the current magnetic ring. The stable DC voltage is obtained by rectifying and stabilizing the output circuit.
2. Principle and design of LCL-T resonant converter

2.1 Principle of resonance
The resonance is equivalent by AC analysis method[5]. The equivalent circuit is shown in Figure 2. $U_{peak}$ is the peak value of the fundamental component of voltage square wave which is the output of half-bridge inverter. $R_e$ is the load resistance equivalent to the resistance of the primary side.

$U_{peak}$ is the peak value of voltage of $R_e$; $F$ is the ratio of switching frequency $f_s$ to resonant frequency $f_0$; $\alpha$ is the ratio of inductance $L_k$ to $L_r$; $n$ is the ratio of primary and secondary turns of transformer and $Z_n$ and $Q$ are characteristic impedance and quality factor.

In equation (2), only $Q$ is related to load $R$. When $F=1$, the output current is independent of load.

So at the resonant point, the output current of the resonance is independent of the load, and the output gets the property of a constant current source.

The output current of the inverter is the current through the inductor $L_r$:

$$I_{tr} = \frac{U_f}{Z_n} = \frac{2/\pi U_j}{\omega_j L_r 8/\pi^2} = \frac{Q(1-\alpha F^2) + j F 8/\pi}{(1-F^2) + j \frac{\pi^2}{8} Q[(1+\alpha)F - \alpha F^3]}$$  

The phase angle of the input voltage $U_i$ is set at $\theta_i=0^\circ$. When $F=1$, the phase difference between the output current and the voltage of the inverter is as follows:

$$\theta = \theta_i - \theta_e = \arctan \frac{8/\pi^2}{Q(1-\alpha)} - 90^\circ = \arctan \frac{Q(1-\alpha)}{8/\pi^2}$$
In the converter, when the phase of current lags behind the phase of voltage, the switch can realize ZVS. When the converter works in constant current mode, ZVS can be realized by making $a<1$. So, $L_k$ is slightly smaller than $L_r$.

### 2.2 Parameter design of converter

When the converter is in constant current mode, the current gain is given by equation (3), and the parameters of the components are as follows:

$$I_o = H \cdot \frac{U_i}{2Z_n} - \frac{4U_i}{n\pi^2 Q R_o}$$

(6)

According to equation (6), the ratio of transformer is:

$$n = \frac{4U_i}{\pi^2 Q R_r I_o}$$

(7)

According to the characteristic impedance and quality factor of the circuit, $L_r$ and $C_r$ can be calculated by the following equation:

$$\begin{align*}
L_r &= n^4 Q R_r / (2\pi f) \\
C_r &= 1 / (2n^2 \pi^2 Q R_r)
\end{align*}$$

(8)

According to equations (7) and (8), the values of $n$, $L_r$ and $C_r$ are determined by $Q$ at a certain frequency. On the basis of subsection 1.1, the resonance is provided with a constant current characteristic only at the resonant point. However, in practical circuits, the operating frequency of the circuit will deviate from the resonant frequency due to the dispersion of component parameters. Equation (2) shows that the larger the $Q$ is, the larger the range of current gain varies with the change of $F$, and the stronger the current adjustability when the frequency deviation occurs. On the other hand, when the frequency has been offset, which means the $F$ is unchanged, the larger the $Q$ is, the smaller the gap between $H$. Therefore, at the same operating frequency, the larger the $Q$ is, the better the constant current performance.

In constant current mode, $L_k$ current can be obtained from equation (4):

$$I_{k} = I_{k0} \cdot \frac{Z_{C_0}}{Z_{C_0} + R_r + Z_{k1k}} = \frac{\pi U_i}{4\omega_k L_r} \cdot \frac{Q}{(1-F^2) + j\frac{\pi^2}{8}Q[(1+\alpha)F-\alpha F^3]}$$

(9)

Equations (4) and (9) show that when the $Q$ is larger, the current of $L_r$ and $L_k$ is larger, the loss and volume of inductor will be negatively affected by the current, which is not conducive to the design of converter.

Therefore, when choosing $Q$, the balance between constant current characteristic, volume and efficiency of the converter should be taken into account. On the premise of volume and efficiency, the performance of the converter is better by choosing the maximum $Q$.

### 3. Transformer design and coupled capacitance model

#### 3.1 Implementation of high voltage isolation and multiplex output

In order to achieve 10kV high voltage isolation, the requirements of creepage distance of 200mm and electrical clearance of 125mm are met simultaneously. Compared with conventional voltage transformer (VT), the way to increase creepage distance without increasing volume is to add gap to PCB. As shown in figure 3, this method requires a large enough core to meet the requirement of high voltage isolation. However, figure 4 show that the current-mode transformer (CT) scheme adopted separates the high-voltage side from the low-voltage side on two boards and connects them by a single-turn winding transformer. The design does not need to change the size of the magnetic core, epoxy coating of core need not, and design requirements of the creepage and clearance can be satisfied by changing the interface distance between the high-voltage side and the low-voltage side.
Usually, voltage transformers need to increase windings to achieve multi-output. When the load is unbalanced, the coupling between windings will affect each other, which makes the control of the system more complex. With current transformer, only the number of transformer cores need to be increased or decreased to change the number of outputs, which makes the power supply more flexible and has more application scenarios. In summary, the single-turn winding transformer is used in the design.

3.2 Modeling of coupled capacitance of transformer

The structure of current-mode transformer is shown in figure 5. The coupling capacitance $C_{io}$ can be calculated by using the stored energy method\cite{6}\cite{7}. The coupling capacitance $C_{io}$ is mainly affected by the following six parts: P1 and S1, P1 and S2, P2 and S1, P2 and S2, P3 and S3, P4 and S4. Assuming that the voltage distribution of the transformer is linear, the static capacitance of each part can be calculated by equation (10), and the stored electric energy of each part can also be calculated. Then, the total energy storage $E_{total}$ is obtained by summing up the energy storage of each part. The coupling capacitance $C_{io}$ of the transformer is given by equation (11):

$$C = \frac{\varepsilon S}{4\pi kd} \quad (10)$$

$$E_{total} = \frac{1}{2} C_{io} (V_p - V_s)^2 \quad (11)$$

Figure 6. Calculations and measurements of the coupled capacitance.

Four transformer cores are used to verify the model. The comparison error is shown in figure 6. The results of measurement and calculation coincide with each other, which verifies the model.
4. Experimental results
In this paper, a prototype of isolated DC/DC power supply with 48W power, 24V input and two output voltages and 100kHz rated switching frequency is designed. The parameters of each element as follows: according to the analysis of subsection 2.2, the simulation results under different Q are compared. It is more appropriate to select \( Q = \frac{16}{\pi^2} \). Then, \( n = \frac{1}{4}, \ L_s = 3.9 \mu H \) and \( C_r = 0.65 \mu F \) can be calculated, inductance \( L_k \) is slightly smaller than \( L_s \), \( L_k = 3.7 \mu H \). Current transformer adopts core #2 in subsection 3.2 to realize coupling capacitance of 1.55pF and isolation voltage of 10kV (creepage distance greater than 200 mm, clearance greater than 125 mm).

![Figure 7. Switch waveform of drain-source voltage and gate signal.](image)

Experiments are carried out on a prototype. Figure 7 shows the experimental waveforms of drain-source voltage (\( V_{ds} \)) and gate signal (\( V_{gs} \)) for a single load of the circuit. Before \( V_{gs} \) became a high-level signal, \( V_{ds} \) had dropped to zero voltage, and the switch realized ZVS.

When the circuit is single load, the output current of the resonance is shown in figure 8 and 9. The current clamp is used to measure the current flowing through the primary side. The square wave has been sinusoidal after adding the resonance, which reduces the harmonics, and the current amplitude and frequency have not changed significantly when the load changes, thus realizing the constant current source.

![Figure 8. Resonance output current at \( R=12\Omega \).](image)

![Figure 9. Resonance output current at \( R=24\Omega \).](image)

![Figure 10. Output voltage and current of the two outputs.](image)
In the case of multiple output of power supply and rated load of both outputs, the output voltage and current are shown in figure 10. The input power is 48W and the efficiency of the prototype is 87.89% calculated according to the measurements. The power supply has better fault-tolerant performance. As shown in figure 11, when one of the two output, \( V_{o1} \), is shorted, the \( V_{o1} \) decreases to zero, and the \( V_{o2} \) can keep stable without being affected by the short-circuit fault of the output1. When the short-circuit fault of output1 is cleared, the \( V_{o1} \) is completely recovered.

![Figure 11. Output voltage waveform in output circuit short and recovery](image)

5. Summary and conclusion
In this paper, a power supply is designed to drive multiple SiC and GaN metal oxide semiconductor field effect transistors (MOSFET) modules. The LCL-T resonant circuit is added behind the inverting circuit in design. Then the characteristic of resonance becoming constant current source when the resonance is at resonant point is used, and current source is the input of the current transformer. The adopted scheme simplifies the circuit structure, reduces harmonics, and realizes ZVS of switches to reduce loss. Using current transformer as isolation transformer, the high voltage isolation of power supply and 1.55pF low coupling capacitance are realized, easy to achieve multi-output, and the output circuit has a certain fault-tolerant ability for short-circuit fault. Finally, the feasibility of power supply structure design is verified by the prototype experiment.

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