Design of LLC Resonant Type Full-Bridge DC-DC Converter

Hou Lei¹, Niu Lida¹, Nie Xiangxin¹ and Ma Huizhuo¹

¹ State Grid Hebei Electric Power Co., Ltd. Xiong an New Area Power Supply Company, Baoding, China
² XJ Group Corporation, Xuchang, China

xiaooufan@126.com

Abstract. In order to develop and utilize renewable energy reasonably, the problems such as the increasingly intensive power load, insufficient power supply capacity and short power supply radius in major cities should be overcome. In this paper, a LLC resonant DC-DC converter is proposed for low voltage distribution network. Firstly, the energy transmission model and mathematical model of DC-DC converter under different modes are analysed. Secondly, the parameters of the resonator are designed. Finally, the simulation platform is built, and the simulation and experiment of DC-DC converter under different working conditions are carried out to verify the correctness of the proposed scheme.

1. Introduction

In recent years, with the rapid development of power electronic converter technology and control technology, smart grid has been applied and promoted all over the world. Especially, after the change of energy supply and demand mode, industry, agriculture and life have put forward higher requirements for electricity demand, power quality and power supply reliability. Therefore, the current AC distribution network is faced with challenges such as the vigorous access of distributed new energy, the diversification of user-side demands, the quality, efficiency and reliability of power supply[1-2].

There is a kind of distribution network -DC distribution network eliminates the AC-DC conversion link, which is more convenient for the access of distributed generation, energy storage and frequency conversion speed regulation devices. Compared with the traditional AC power network, it will be more efficient. As the main part of dc power distribution network of dual active bridge converter is also known as power electronic transformer, through the original and deputy while introducing power electronic converter on the primary side and secondary side voltage amplitude and phase of the real-time digital control, compared with traditional power transformer, power electronic transformer can be more precise, flexible, stable and reliable to adjust output terminal. The advantages and characteristics of power electronic transformers can be applied to many difficult problems in many environments. Figure 1 shows a typical medium and low-voltage distribution network topology [3].
It can be seen from figure 1 that it mainly includes 10kV distribution network, AD/DC Converter, DC/AC Converter, DC bus, DC/DC Converter, all kinds of loads, etc. AD/DC Converter and DC/AC Converter use MMC (Modular Multilevel Converter, MMC) Converter [4-8].

Under the application condition of low-voltage DC distribution network, the traditional full-bridge DC/DC converter is generally controlled by phase shift. Although it can achieve soft switch, namely zero voltage on (ZVS), the output cannot be adjusted in a large range due to the limited range of phase shift Angle, and it can only be adjusted by buck. In this case, the resonant type DC/DC converter arises at the right moment. By adding a resonant cavity in the primary side of the high frequency transformer, adding several resonant capacitors $C_r$ and resonant inductors $L_r$, through their different impedance at different frequencies, the purpose of variable voltage output is achieved. Because the resonator is sensitive or capacitive at a specific frequency, the voltage flowing through the switch tube leads or lags the current, thus achieving the effect of zero voltage on (ZVS) or zero current off (ZCS). In the aspect of voltage regulation, it can simultaneously boost and buck regulation, which can realize a large range of voltage regulation in the full power range. Among many types of resonant converters, LLC resonant topology has obvious advantages and has become the focus of research by scholars at home and abroad.

2. Analysis of LLC resonant DC-DC converter operation model

Figure 2 shows the LLC resonant DC-DC topology of the full bridge
Figure 2 shows the full bridge LLC resonant DC-DC converter topology. Where, DC is the DC input bus voltage, $C_0$ is the output capacitor; $Q_1$-$Q_4$ is the primary side power switch, $D_1$-$D_4$ represents the reverse connected parallel diode of the switch, and $C_1$-$C_4$ corresponds to the parasitic junction capacitance of the power switch. $LR$ is a resonant inductor, which can be used as a part of the resonant inductor. $C_r$ is the resonant capacitance of the resonant cavity; $T_1$ is a high-frequency transformer; $L_{m1}$ is the excitation inductance of the HF transformer; $D_5$ and $D_6$ are output rectifier diodes; $R_{out}$ is the load resistor.

The resonant system consists of a resonant cavity of LLC resonant converter with two resonant frequencies, $f_1$ and $f_2$. When only the resonant inductor $L_r$ resonates with the resonant capacitor $C_r$ in the resonant cavity, the resonant frequency is the first resonant frequency $f_1$. When the excitation inductance $L_{m1}$ resonates with $L_r$ and $C_r$, the resonance frequency at this time is the second resonance frequency $f_2$. The expressions of the first resonant frequency $f_1$ and the second resonant frequency $f_2$ are as follows:

$$\begin{align*}
  f_1 &= \frac{1}{2\pi\sqrt{L_r C_r}} \\
  f_2 &= \frac{1}{2\pi\sqrt{(L_r + L_{m1}) C_r}}
\end{align*}$$

The DC gain characteristic curve of LLC resonant DC/DC converter is shown in Figure 3, where $Q$ is the quality factor of the circuit topology. $f_n$ is the working frequency of the power switch, and the expression is as follows:

$$f_n = \frac{f_x}{f_t}$$

The working interval of the LLC converter is divided into three regions as shown in figure 3 in the DC gain characteristic curve: region 3 resonator capacitances in which the actual switching operating frequency is less than the fixed resonant frequency; When the LLC resonant converter operates in region 1 and region 2, the resonant cavity is overall sensible and the switch tube can achieve zero voltage on (ZVS). The gain $M$ of region 2 is greater than 1 and not less than off; The gain $M$ in region 1 is less than 1, so it is not greater than off. The LLC resonant DC intermediate C topology is usually designed in regions 1 and 2 due to the small loss when the switch tube operates at zero voltage on (ZVS). The following will discuss the working state of the resonant converter in the region and the region respectively.
2.1. Operating modes under region 1

Figure 4 shows the working waveform of the primary side current in Region 1, where \( i_r \) is the resonant current flowing through the resonant inductor. \( i_m \) is the excitation current flowing through the excitation inductor. Region 1 can be divided into three modes:

Mode 1: At the time of \( t_0 \), switch Q2 is turned off, and the resonant current is less than zero. The diode reverse connected to Q1 clamps the voltage at both ends of Q1 drain source to zero, creating conditions for the next phase of switch Q1's zero voltage on zero switch (ZVS). Resonant current \( i_r \) changes sinusoidally to zero. During this period, the secondary side D6 of the transformer is turned on, and the output voltage is clamping the excitation inductor through the transformer. Therefore, the excitation inductor \( L_m \) increases linearly under the action of the primary side voltage in the D5 conduction stage and does not participate in resonance. The resonant circuit of the resonant cavity consists only of the resonant inductor \( L_r \) and the resonant capacitor \( C_r \).

Mode 2: \( t_2 > t > t_1 \), during this period, within the cavity resonance current \( i_r \) continues with sine law of change, excitation current under the action of \( i_m \) clamping voltage at the edge of the original linear continue to rise, the resonant inductor \( L_r \) and resonant capacitance \( C_r \) continue in resonance, \( t_2 \) time, switch tube Q1 shut off, the transformer rectifier diodes D5, on the edge of vice conduction, excitation inductance is clamping don't participate in resonance.

Mode 3: The lower half period of the resonator system operating in region 1 is similar to the upper half period and will not be described in detail here.

The resonant system works in region 1, and the operating frequency \( f_s \) of the switch tube is greater than the first resonant frequency \( f_1 \). Moreover, the excitation inductor \( L_m \) has been clamped and does not participate in the resonance of the resonant inductor LR and the resonant capacitor \( C_r \).

2.2. Operating modes in region 2

The operating waveform of LLC resonant DC/DC converter in Region 2 is shown in figure 5 The LLC converter has four modes in Region 2:

Mode 1: At the time of \( t_0 \), switch Q2 is turned off, and the resonant current is less than zero. The diode reverse connected to Q1 clamps the voltage at both ends of Q1 drain source to zero, creating conditions for the next phase of switch Q1's zero voltage on zero switch (ZVS). Resonant current \( i_r \) changes sinusoidally to zero. During this period, the secondary side D6 of the transformer is turned on, and the output voltage is clamping the excitation inductor through the transformer. Therefore, the excitation inductor \( L_m \) increases linearly under the action of the primary side voltage in the D5 conduction stage and does not participate in resonance. The resonant circuit of the resonant cavity consists only of the resonant inductor \( L_r \) and the resonant capacitor \( C_r \).

Mode 2: \( t_2 > t > t_1 \), during this period, within the cavity resonance current \( i_r \) continues with sine law of change, excitation current under the action of \( i_m \) clamping voltage at the edge of the original linear continue to rise, the resonant inductor \( L_r \) and resonant capacitance \( C_r \) continue in resonance, \( t_2 \) time, switch tube Q1 shut off, the transformer rectifier diodes D5, on the edge of vice conduction, excitation inductance is clamping don't participate in resonance.

Mode 3: The lower half period of the resonator system operating in region 1 is similar to the upper half period and will not be described in detail here.

The resonant system works in region 1, and the operating frequency \( f_s \) of the switch tube is greater than the first resonant frequency \( f_1 \). Moreover, the excitation inductor \( L_m \) has been clamped and does not participate in the resonance of the resonant inductor LR and the resonant capacitor \( C_r \).
Mode 1: $t_2 > t > t_0$. The working process of the topology at this stage is the same as that of the mode in Region 1.

Mode 2: $t_2 > t > t_1$. Before $t_1$, the current flowing through diode $D_5$ on the auxiliary side of the transformer decreases linearly, but it is still on. Therefore, the excitation inductor is clamped and does not participate in resonance. The resonance current of the resonator cavity changes in accordance with sinusoidal law, and the excitation current increases linearly. $t_2$ time through the rectifier diodes $D_5$ reduce to zero, the output voltage cannot through the transformer secondary side of a lateral excitation inductance clamping, harmonic current $i_r$ was forcibly equals the excitation current of $i_m$, participate in resonant excitation inductance, resonance frequency for the second resonance frequency $f_2$, because a larger than resonant inductance excitation inductance value, makes the second resonance frequency $f_2$ is far less than the first resonance frequency $f_0$.

Mode 3: $t_3 > t > t_2$. During this period of time, the excitation inductor is engaged in resonance, and the variation period of the primary resonant current increases greatly, and the resonant current is almost unchanged in a very short time. At the moment $t_3$, $Q_1$ is turned off, and the existence of resonant current $i_r$ creates conditions for the zero voltage switching on (ZVS) of $Q_2$.

In this mode, the excitation current $i_m$ is equal to the resonant current $i_r$, and the current that makes $Q_2$ zero voltage turn on in the next stage is also the excitation current $i_m$. Therefore, the resonant current can be reduced as far as possible through the reasonable design of the high-frequency transformer, so as to reduce the switching loss.

Mode 4: The second half of the cycle is similar to the first half of the cycle and will not be described in detail here.

The resonant system works in region 2, and the switching tube's working frequency $f_s$ is greater than the first resonant frequency $f_1$ and less than the second resonant frequency $f_2$. In each working cycle of the switching tube, the excitation inductor only resonates in part of the time.

3. LLC resonant DC-DC converter gain and load adaptation characteristics

The selection of the variable voltage ratio $M$ of LLC resonant converter has a great influence on the performance and working area of the converter. The voltage variation characteristic of the main circuit is mainly reflected by the voltage variation ratio $M$, and its expression is as follows:

$$M = n \frac{V_0}{V_{in}} = \frac{1}{\sqrt{\left(1 + \frac{L_r}{L_m} \frac{f_1}{f_2}\right)^2 + \frac{L_r}{C_r} \frac{1}{R_{out}} \left(\frac{f_s}{f_1} - \frac{f_1}{f_s}\right)^2}} \quad (3)$$

where, $L_r$ is the resonant inductor, $L_m$ is the excitation inductor, $f_s$ is the actual switching operating frequency, $f_1$ is the first resonant frequency composed of the resonant inductor and the resonant capacitor, $C_r$ is the resonant capacitor in the resonant cavity, and $R_{out}$ is the equivalent load.

In order to (2), parameter $m$ is defined as:

$$m = \frac{L_r}{L_m} \quad (4)$$

The equivalent circuit diagram's quality factor $Q$ is expressed as follows:

$$Q = \frac{L_r}{\sqrt{C_r R_{ac}}} = \frac{n^2}{8n^2 R_{out}} \frac{L_r}{C_r} \quad (5)$$

Combine the switching tube operating frequency, $f$ with the first resonant frequency. The stone is normalized

$$f_n = \frac{f_s}{f_1} \quad (6)$$
After normalization, the gain $M$ of the main circuit of LLC resonant DC/DC topology can be expressed as follows:

$$M = \frac{1}{\sqrt{\left(1 + \frac{m}{f_n^2} - m\right)^2 + Q^2 \left(f_n - \frac{1}{f_n}\right)^2}}$$

(7)

In addition to the variable ratio $M$ of LLC converter and the working frequency of the converter, parameter $m$ and the value of the quality factor $Q$ of the main circuit will also have a great impact on the variable ratio $M$ of LLC resonant converter. In order to more intuitively reflect the influence of prime factor $Q$, normalized frequency $f_n$ and parameter $m$ on system gain $m$, different values of $m$ and $Q$ in (6) are taken to fit the function curve in Matlab. According to the different values of parameters $m$ and $Q$, figure 5 is obtained.

For all $m$ and $Q$ values, LLC resonant type DC/DC topology of main circuit of variable pressure characteristics for the first resonance frequency $f_1$ world, when the working frequency close is greater than the frequency, gain $M$, less than 1 converter in a step-down mode, when the working frequency $f_s$ is lower than the first resonance frequency $f_1$, system gain greater than 1, the converter is in booster mode.

![Figure 6. Gain curves at fixed Q and different m values](image)

![Figure 7. Gain curves at fixed m values and different Q values](image)
When the system work on the first resonance frequency of the first cavity $f_1$, the system of variable than $M$ value is 1, the cavity resonant inductor $L_r$ and resonant capacitance $C_r$ in the resonance state, so in the first resonance frequency, the resonant inductor $L_r$ and resonant capacitor equivalent series resistance of $C_r$ is zero, has nothing to do with $m$ and $Q$ value, so the work in this mode, the system of variable pressure characteristics has nothing to do with the size of the load, the output characteristic of the converter is best.

As shown in Figure 6, when $m$ is the same, for the same operating frequency $f_s$, the larger the $Q$ value is, the smaller the value of the LLC converter's transformation ratio $M$ is.

As shown in Figure 7, when $Q$ values are the same and for the same operating frequency, the larger $m$ is, the steeper the curve of gain $M$ will be. In addition, in the step-down mode region of LLC converter, the same operating frequency is different. Under the condition of the same $Q$ value, the larger the value of $m$ is, the smaller the value of the variable voltage ratio $M$ is. This shows that in the LLC resonant DC/DC topology, the larger the value of $m$ is, the better the buck performance of the converter will be. When the operating frequency is the same, compared with other load conditions, the LLC resonant converter gains the maximum $M$ under no-load condition. No-load belongs to the limit state of light load, and the no-load condition $Q=0$. Substitute in (7) to obtain the no-load transformer ratio of the converter. The expression of $M_{LOW}$ is as follows:

$$M_{LOW} = \frac{1}{1 + m - \frac{m}{f_n^2}}$$

According to (8), when the operating frequency of the converter is infinite, the expression of the limiting voltage variation ratio $M_{LOW}$ under the no-load condition of the system is as follows:

$$M_{LOW} = \frac{1}{1 + m}$$

By (9) can be obtained: the LLC resonant converter under no-load condition system gain $M$ limit value and $m$ values only and has nothing to do with the size of the other parameters, so, when the working frequency of LLC resonant converter is close range is determined, can by adjusting the value of $m$, namely cavity resonant inductor $L_r$ and high-frequency transformer excitation inductance $L_m$ under light load condition to meet the size of the converter performance requirements. As long as the limit value of the LLC converter's no-load variable ratio $M$ meets the specific requirements, the variable voltage characteristics of the resonant converter's light-load state will also be naturally applicable to the design requirements.

### 4. LLC resonant type DC-DC converter resonator parameter design

The design process of LLC resonant DC/DC converter needs to check the parameters of the resonant cavity calculated according to the initial setting requirements to check whether it meets the prese requirements. If it does not meet the design requirements, it needs to be re-designed. The resonant cavity parameters after calibration are in good agreement with each other. The following is to design it in detail.

#### 4.1. The rated working point of the resonator is determined

In the design of resonant cavity parameters, designers need to roughly determine the converter's working frequency range, according to the design experience to initially select the value of the first resonant frequency point $f_1$, and then roughly determine the maximum normalized working frequency of $f_{n\text{-max}}$, and the minimum normalized working frequency of $f_{n\text{min}}$.

According to the characteristic conclusion of the LLC resonant DC/DC converter's ratio $M$, a more reasonable working range can be obtained as follows: the rated working point of the converter is set at the first resonant frequency $f_1$, and the working range under frequency conversion control includes most of the voltage boost area and a small part of the voltage drop area. Transformer ratio is:
\[ n = \frac{V_m}{V_0} \]  

where, \( V_m \) is the DC input voltage of the converter, and \( V_0 \) is the output voltage. After the variable ratio \( n \) is obtained, the maximum gain of the whole converter system, \( M_{\text{max}} \), and the minimum gain, \( M_{\text{min}} \), are expressed as follows:

\[ M_{\text{max}} = n \frac{V_{0,\text{max}}}{V_{\text{in}}} \]  \[ M_{\text{min}} = \frac{V_{0,\text{min}}}{V_{\text{in}}} \]  

where, \( V_{0,\text{max}} \) is the maximum value of the output voltage, and \( V_{0,\text{min}} \) is the minimum value of the output voltage.

### 4.2. Parameter \( m \) value calculation

According to the previous discussion, the value of parameter \( m \) has a great impact on the performance of LLC resonant converter. When designing the value of parameter \( m \), the main consideration is that the converter can work normally under light load conditions. In other words, in the limit state, when the system gain \( M \) is not greater than \( M_{\text{max}} \), the maximum system gain can be obtained by sorting out (8), the corresponding parameter \( M \) is as follows:

\[ m = \frac{f_{n,\text{min}}^2}{f_{n,\text{max}}^2 - 1} \cdot \frac{1 - M_{\text{max}}}{M_{\text{max}}} \]  

### 4.3. Determine the \( Q \) value of quality factor

In order to ensure that the LLC resonant converter works in the safe inductive region at full power, it is very important to determine the reasonable quality factor \( Q \) value. According to the requirements, the maximum output voltage \( V_{0,\text{max}} \), \( Q_{\text{max,1}} \) in the case of no load and the minimum output voltage \( V_{0,\text{min}} \), the corresponding quality factor \( Q_{\text{max,2}} \) in the case of full load are calculated. The expression of the quality factor in these two extreme working modes is as follows:

\[ Q_{\text{max,1}} = \frac{m}{M_{\text{max}}} \sqrt{\frac{M_{\text{max}}^2}{M_{\text{max}}^2 - 1} + \frac{1}{m}} \]  

\[ Q_{\text{max,2}} = \frac{2T_D}{\pi (1 + k) f_n - \frac{1}{f_n}} \frac{1}{C_{\text{osr}} R_{\text{ac}}} \]

Among them, \( T_D \) is the driving dead interval required by the design. During this time, the resonant current in the resonant topology needs to complete the charging and discharging process of the junction capacitance of the power switch tube of the upper and lower bridge arms. \( C_{\text{osr}} \) is the equivalent output capacitance of the power switch in the resonant topology. In the design process, a certain safety margin needs to be set aside for the system, so the final determined maximum quality factor \( Q_{\text{max}} \) of the system is expressed as follows:

\[ Q_{\text{max}} \leq 0.90 \sim 95 \min \{Q_{\text{max,1}}, Q_{\text{max,2}}\} \]
4.4. Determine the resonance element parameter value

After the maximum quality factor \( Q_{\text{max}} \) of the system is determined, the resonant inductance \( L_r \), resonant capacitor \( C_r \) and the excitation inductance \( L_m \) of the resonant cavity are expressed as follows:

\[
Z_r = Q_{\text{max}} R_{\text{ac}} \\
C_r = \frac{1}{2\pi f_r Z_r} \\
L_r = \frac{Z_r}{2\pi f_r} \\
L_m = \frac{L_r}{m} \tag{17}
\]

Wherein, \( Z_r \) is the characteristic impedance of the main circuit of the resonant topology.

4.5. LLC resonant DC/DC topology primary edge realizes ZVS condition

Power switch MOSFET and IGBT in DC/DC converters used in high-power occasions all have equivalent output capacitance and zero voltage switching mode, which is more conducive to saving loss of this kind of switch. This project takes N-channel power tube MOSFET as an example to discuss the necessary conditions for it to work in ZVS environment.

![Simplified model of MOSFET](image)

Figure 8. Simplified model of MOSFET

Figure 8 shows the simplified model inside MOSFET. When the LLC main circuit is working, the resonant current completes the discharge of the equivalent output capacitor \( C_{\text{oss}} \) of the switch tube to be switched on in the next stage within the driving dead interval \( TD \). At the same time, the equivalent output capacitor \( C_{\text{oss}} \) of the power switch MOSFET which has been turned off is charged accordingly. After the charge-discharge action is completed, the reverse parallel diode of the power tube to be opened is switched on, and the voltage of the drain and source of the MOSFET is clamped to zero, thus completing the zero-voltage conduction (ZVS). The equivalent input capacitance \( C_{\text{iss}} \), equivalent output capacitance \( C_{\text{oss}} \), and reverse capacitance \( C_{\text{rs}} \) are expressed as follows:

\[
C_{\text{iss}} = C_{gd} + C_{gs} \\
C_{\text{oss}} = C_{ds} + C_{gd} \\
C_{\text{rs}} = C_{gd} \tag{18}
\]

Therefore, in order to achieve zero voltage switching on, it is necessary to ensure that the resonant current \( i_r \) in the resonant cavity is greater than the minimum current \( I_{\text{c-min}} \) required to complete the charging and discharging of the junction capacitors of the upper and lower leg switches in the dead time \( TD \). The expression is as follows:
where, $V_{sw}$ is the voltage at both ends of drain and source when each switch is in the dead time, and $C_{oss}$ is the sum of junction capacitance and distributed capacitance of each power switch. Therefore, the resonant current $i$, in the dead zone should meet the following requirements:

$$I_{r} \left( \frac{kT}{2} \right) > I_{c-min} = \frac{V_{sw}}{T_{D} \sqrt{2}} C_{oss}$$

where $k$ is a positive integer.

In the actual design process, the maximum output voltage, no-load mode and the minimum output voltage, full load mode are usually guaranteed in the two extreme environments. If the primary side switch works in the zero voltage on mode (ZVS), it can guarantee the soft switch in the full power range.

LLC resonant topology, under the condition of the maximum output voltage $V_{0-max}$, the main circuit variable voltage ratio reaches the maximum value $M_{max}$. At the same gain $M$, the larger the load, the larger the quality factor $Q$, and the smaller the switching frequency required. Therefore, under the condition of maximum output voltage and full load, the maximum gain of the system is $M_{max}$, and the maximum quality factor $Q_{max}$ corresponds to the minimum switching frequency $f_{min}$. $Q_{max}$ satisfies (14).

When the output voltage is the minimum, the gain of the system reaches the minimum value $P_{min}$, and the system must work in the inductive interval. In this mode, it is only necessary to ensure that the resonant current $i$, meets the minimum current required by the soft switching. Under no-load conditions, the switching frequency reaches a maximum of several $f_{max}$ and the input impedance reaches a maximum of $Z_{in-max}$. At this time, the resonant current is the minimum value and the output current is zero. Therefore, the input impedance is pure inductive. At this point, the expression of $Z_{in-max}$ is as follows:

$$Z_{in-max} = jZ_{r} \left[ C_{r} \left( \frac{1 + \frac{1}{m}}{f_{n} - f_{n-max}} \right) \right]$$

In order to meet the minimum current required by the charging and discharging of junction capacitance and parasitic capacitance, the resonant current shall meet the following conditions:

$$\frac{T_{D} \sqrt{2} V_{in-max}}{Z_{in-max}} > V_{sw} C_{oss}$$

Then

$$\frac{Z_{r}}{T_{D}} < \frac{2}{\pi C_{oss} R_{ac} \left[ (1 + \frac{1}{m}) f_{n} - f_{n-max} \right]}$$

$$Q_{max} < \frac{2 T_{D}}{\pi C_{oss} R_{ac} \left[ (1 + \frac{1}{m}) f_{n} - f_{n-max} \right]}$$

The expressions for $Z_{r}$ and $Q$ are as follows.
5. Simulation analysis of LLC resonant DC-DC converter
A 5.2kW LLC resonant DC/DC converter is designed, and the specific parameters are shown in Table 1. Finally, the inductance ratio $m=0.3$ and the quality factor $Q=0.7$ were selected, and the gain characteristic curve of normalized frequency was fitted, as shown in Figure 9.

![Figure 9. Gain characteristic curve](image)

**Table 1. LLC resonant DC-DC converter system parameters**

| Parameters             | Value    | Parameters         | Value    |
|------------------------|----------|--------------------|----------|
| Input voltage          | 500V     | Resonant capacitance | 62.28nF  |
| Output voltage         | 350-600V | Excitation inductance | 138.2uH  |
| Frequency              | 80-105kHz| Resonance frequency | 100kHz   |
| System gain            | 0.7-1.2  | MOSFET             | HMS47N65A|
| Inductance ratio       | 0.3      | Ron                | 0.08Ω    |
| Q                      | 0.7      | Cs                 | 150pF    |
| Rated power            | 5.2kW    | VDs                | 650V     |
| Efficiency             | 95%      | ID$s$              | 47A      |
| Resonance inductance   | 40.68uH  | VDR                | 1200V    |

Figure 10 shows the output voltage and driving voltage waveform at rated power. Figure 11 shows the driving voltage frequency control value and output current waveform under rated load.
As shown in Figure 10(a), the average output voltage is 500V. Because there is a certain static difference in the system under PI control, the output voltage is 494.5V, which meets the design conditions. Figure 10(b) shows the driving signal of the power switch in steady state, and the switching operating frequency is 95kHz at the first resonant frequency.

As shown in Figure 11(a), is the frequency control value of the modulated driving voltage. The larger the value is, the smaller the modulated signal frequency will be. As shown in Figure 11(b), for the output voltage of 500v when the high-frequency transformer primary side harmonic current waveform, current waveform is sine signal, because the system voltage gain M to 1, in the boundary zone 1 and zone 2, deputy side rectifier diode is in the critical conduction mode, so the excitation inductance of high frequency transformer resonance will not be involved.

As shown in Figure 12 for the load resistance is 38.5 Ω, output voltage and harmonic current waveform. It can be concluded from Figure 12 (a) that the average output voltage is 448V, within the reasonable allowable range of static difference. At this time, the diode on the secondary side of the transformer
works in continuous conduction mode, the system works in region 1, and the resonance current on the primary side is sinusoidal.

![Graphs showing output voltage and current](image1.png)

**Figure 12.** The load resistance is 38.5 Ω output voltage and output current

As shown in Figure 13 when the load resistance is 69.2 Ω output voltage and harmonic current. The theoretical output voltage under this condition is 600V, and the average value of the output voltage is 605.5V, which is within the allowable error range, as shown in Figure 13. At this time, the secondary diode of the transformer works in discontinuous conduction mode, and the excitation inductor resonates for a period of time.

![Graphs showing output voltage and resonant current](image2.png)

**Figure 13.** The load resistance is 69.2 Ω output voltage and output current

6. Conclusion
In this paper, the working principle, mode and parameter calculation of LLC resonant DC-DC converter are designed and analyzed. A 5.2kW LLC resonant DC-DC converter is designed and simulated, and the following conclusions are obtained:
(1) LLC resonant DC-DC converter is more suitable for voltage boost regulation. The frequency range required under buck regulation is large, which brings difficulties to the design of magnetic components, especially the design of high-frequency transformers.

(2) In order to achieve a wide range of voltage regulation under full power, frequency conversion control can be used to control the voltage boost interval and a small part of the step-down interval, and the remaining step-down interval can be realized by phase-shift control mode.

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Acknowledgements
This research was supported by the kjcb-2020-34 program through the State Grid Hebei Electric Power Co., Ltd project.