High step-up isolated DC-DC converter based on resonant network for DC offshore wind farms

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Abstract. At present, the use of DC convergence and DC transmission (abbreviated as all DC) is recognized as the most effective technical solution and inevitable trend to solve the flexible access of large-scale new energy generation. However, the high-voltage and large-capacity DC-DC converters used in the DC convergence of the full DC system are still in the preliminary research stage. This paper presents a high voltage and large capacity isolated DC-DC converter topology, which is composed of three-stage boost circuit. The simulation results show that the topology can increase the output voltage of wind turbine from 1kV to 320kV, effectively improve the boost ratio of converter, and provide a theoretical basis for the realization of full DC offshore wind power system.

1. Introduction

At present, DC-DC converter topology of DC offshore wind farm can be divided into isolated type and non-isolated type. Non-isolated type mainly includes resonant converter based on thyristor[1], DC-DC converter based on modular multilevel converter[2] and so on. Although the non-isolated type saves the isolation transformer and reduces the volume, it also loses the electrical isolation capacity, and requires additional fault isolation circuit. The isolation type mainly includes traditional full bridge converter[3] and MMC isolation converter[4]. The isolated full bridge converter mainly uses multi module cascading and transformer ratio to improve the output voltage. When it is used in DC wind farm, it needs more sub module cascading. The resonant circuit is only used to achieve soft switching and improve the conversion efficiency. MMC isolated converter can realize high power and high voltage DC-DC conversion, but it also needs more sub modules cascaded. For the parallel DC convergence mode, the first stage boost mode has the advantages of efficiency and easy realization of converter capacity, but the voltage boost ratio is required to be tens or hundreds of times. If the existing cascaded bidirectional active bridge or isolated MMC topology is adopted, the number of cascaded modules will be huge and the high cost will be difficult to bear.

The existing topology of high boost ratio DC-DC converter basically uses a large number of low-voltage modules to increase the voltage. This article intends to introduce multi-stage boost units, and propose an ultra-high boost ratio isolated DC-DC topology composed of three-stage boost circuits. The topology consists of low-voltage DC-AC converter, isolation transformer, resonant network and rectifier (voltage doubling). The total boost ratio is the product of the boost ratio of three boost units,
which can effectively improve the boost ratio of the converter and meet the requirements of high-voltage and large capacity converter for offshore DC wind power system.

2. The proposed circuit model

2.1. Boost topology
At present, the output AC voltage of wind turbines mainly includes 690V and 3.3kV, and the outlet DC voltage is about 1kV~5.2kV. The maximum DC bus voltage of existing wind power projects is ±320kV. Therefore, the first stage boost mode is selected, and the DC boost ratio is about 320 to 65. The topology of the three-stage boost converter which can meet the super high voltage rise ratio is shown in figure 1. This topology uses the LC resonant network to achieve the second-stage boost, and effectively improves the converter boost ratio on the basis of the transformer. \( L_r \) is the resonant inductance, \( C_r \) is the resonant capacitor, and \( L_f \) is the filter inductance.

![High boost ratio isolated DC-DC converter topology.](image)

2.2. Converter’s Operating Principles
Figure 2 shows the main working waveform of the converter when the resonant network works in the inductive region. \( S_1 \) and \( S_4 \) turn on and off at the same time, \( S_2 \) and \( S_3 \) turn on and off at the same time. There is a certain dead time between the two groups of switching devices, and there are ten switching modes in a switching cycle. Before the analysis, the following assumptions are made: 1) All switches, diodes, inductors and capacitors are ideal devices; 2) The output filter capacitors \( C_1 \) and \( C_2 \) are equal and large enough, the filter capacitor voltage is half of the output voltage and \( V_o \) is a constant voltage.

The waveform shown in the figure is analysed as follows:

- \([t_0<t<t_1]\): Trigger pulses are applied to primary switches \( S_1 \) and \( S_4 \) at \( t_0 \) to turn them on. The resonant inductor \( L_r \) and the resonant capacitor \( C_r \) resonate, the filter inductor \( L_f \) does not participate in the resonance.
- \([t_1<t<t_2]\): The resonant inductor current \( i_{L_r} \) starts to be larger than the resonant capacitor current \( i_{C_r} \), the filter inductor \( L_f \) participates in the resonance. The diode on the rectifier side turns on to charge the capacitor on the high voltage side. Due to the intermittent current of the filter inductor, the rectifier diode can realize zero current switching (ZCS).
- \([t_2<t<t_3]\): At \( t_2 \) time, switches \( S_1 \) and \( S_4 \) turn off, all switches are not conductive, they are in the dead time stage. The primary resonant current \( i_p \) of the transformer charges the parasitic capacitors \( C_1 \) and \( C_4 \) until the voltage reaches \( V_o \) and discharges the parasitic capacitors \( C_2 \) and \( C_3 \) until the voltage drops to zero.
- \([t_3<t<t_4]\): The charging and discharging process of parasitic capacitance is completed at \( t_3 \) time. Since no switch is triggered to turn on, the primary resonant current \( i_p \) is freewheeling through the parasitic diodes \( D_2 \) and \( D_3 \), and the filter inductance still participates in resonance.
- \([t_4<t<t_5]\): At \( t_4 \), trigger pulses are sent to \( S_2 \) and \( S_3 \) to make them turn on. Because the voltage at both ends of \( S_2 \) and \( S_3 \) has dropped to zero before the switch is turned on, \( S_2 \) and \( S_3 \) realize zero voltage switching (ZVS). At \( t_5 \), \( L_f \) no longer participates in the resonance, and the diode on the rectifier side is turned off.
After the end of the working stage, the first half of the working cycle ends and the second half of the working cycle begins. Because the working principle of the second half cycle is the same as that of the first half cycle, it will not be repeated here.

3. Topology analysis

3.1. Equivalent model

Because the proposed converter only works at the resonance point, the fundamental harmonic approximation (FHA) method is used to analyse the resonant circuit. And the steady state equivalent model of the converter can be obtained as figure 4.

The input voltage $v_g$ of resonant circuit is written in Fourier series form:

$$v_g = \frac{4nV_i}{\pi} \sum_{i=1,3,5, \ldots} \frac{1}{i} \sin(i \cdot \omega t)$$  \hspace{1cm} (1)

The Fourier series form of the output voltage $v_{co}$ of the resonant circuit is:
\[ v_{co} = \frac{1}{2} \frac{4}{\pi} V_o \sum_{i=1,3,5,...} \frac{1}{\sin(i \cdot \omega t - \varphi)} \]  

(2)

Where \( \varphi \) is the phase angle of the input impedance of the resonant circuit.

Assuming that the fundamental effective value of \( v_g \) and \( v_{co} \) is \( V_{gl} \) and \( V_{col} \)

\[ V_{gl} = \frac{2\sqrt{2}}{\pi} nV_s \]  

(3)

\[ V_{col} = \frac{\sqrt{2}}{\pi} V_o \]  

(4)

The fundamental power consumed on \( R_{eq} \) is approximately equal to the output power:

\[ R_{eq} = \frac{V_{eq}^2}{V_o^2} R_o = \frac{2}{\pi^2} R_o \]  

(5)

### 3.2. Voltage gain analysis

The steady state model of the resonant network can be obtained from the converter topology, the transfer function can be obtained by the fundamental harmonic approximation method as follows:

\[ H(j\omega) = \frac{V_{col}}{V_g} = \frac{R_{eq}}{j\omega C_i} \left( j\omega L_r + R_e \right) \left( j\omega C_i \right)^{-1} \]

\[ \left( j\omega L_r + R_e \right) \left( j\omega C_i \right)^{-1} \]

(6)

The DC gain \( M \) is equal to the modulus of the transfer function, which can be obtained:

\[ M = |H(j\omega)| = \left| \left( \frac{1}{\omega^2} + \frac{\omega^2}{Q^2 \omega_i^2} \left( 1 + k - \frac{k}{\omega_i^2} \right) \right)^{\frac{1}{2}} \right| \]  

(7)

In the above formula, \( R_e \) is the equivalent load, the first resonant frequency \( \omega_1 = \sqrt{L_i C_i} \), and the second resonant frequency \( \omega_2 = \sqrt{L_i C_i} \), \( k = L_i / L_o \) is the characteristic impedance, and \( Q = R_e / Z_r \) is the quality factor, \( Z_r = \sqrt{L_i / C_i} \) is the characteristic impedance.

It can be seen from formula (7) that the maximum voltage boost ratio of resonant network is:

\[ M|_{\omega=\omega_0} = \frac{V_o}{V_i} \mid_{\omega=\omega_0} = Q \]  

(8)

Assuming that \( f \) is the operating frequency of the switch and \( f_i \) is the resonant frequency, the normalized frequency is \( f_u = f / f_i \), take the quality factor \( Q \) as the variation, \( k \) as 0.2. The horizontal axis as the normalized frequency \( f_u \), and the vertical axis as the voltage gain \( M \), the DC gain curve family of the resonant network shown in figure 5. It can be seen that the DC gain reaches the maximum at the first resonant frequency. Therefore, it is the best choice to control the working frequency near \( f_i \) in the simulation.

### 3.3. Control strategy

Because the proposed converter mainly uses the resonant circuit to boost the voltage, the general LLC resonant converter control method can be used for output control. This paper uses the voltage mode control loop as shown in figure 6, the output voltage is used as the only control signal for loop control. As can be seen from the figure above, the loop control mode is as follows: the error amplifier generates the feedback signal \( V_i \) from the output voltage \( V \) and the reference voltage \( V_{ref} \), and then through the PI regulator, the voltage controlled oscillator (VCO) generates the square wave signal \( f_i \).
with the corresponding frequency according to the size of the input signal to drive the primary switch network of the converter. The control block diagram is shown in figure 7, which is mainly composed of voltage to frequency transfer function $G_o(s)$, regulator transfer function $G_R(s)$ and voltage controlled oscillator transfer function $G_{VCO}(s)$. The transfer function of VCO can be regarded as a fixed value: $G_o(s) = kG_o(s)$, The transfer function of the regulator is as follows:

$$G_R(s) = k + \frac{k}{s}$$  \tag{9}$$

From Fig. 7 and formula (9), the total open-loop transfer function of the system can be obtained as:

$$G(s) = kG_R(s)G_o(s) = k \left( k + \frac{k}{s} \right) G_o(s)$$  \tag{10}$$

By using the extended function description method, the small signal model of the system can be established, and the voltage to frequency transfer function $G_o(s)$ can be obtained.

4. Analysis of simulation results

The following is a specific example to design the parameters of the circuit. The DC bus voltage at low voltage end is 2kV, the DC voltage at high voltage end is 320kV, the transformation ratio of high frequency isolation transformer is 8, and the transmission power is 1MW (DC load impedance is $102.4\, \Omega$), then the boost ratio of resonant network is 10.

It can be seen from the second section of this paper that the boost ratio and transmission power of the resonant network are directly related to its quality factor, characteristic impedance and resonant frequency. Therefore, reasonable selection of resonance parameters can meet the requirements of boost ratio and transmission power. Assuming that the first resonant frequency is 10kH and the filter inductance is 5mH, considering the intermittent current of filter inductance, according to formula, $L_r$ and $C_r$ can be calculated. Table I summarizes the specifications of the system and the converter circuit parameters.

In PSIM software, the low-voltage side power supply is DC power supply, and two groups of switches are controlled to make the DC-AC converter output square wave voltage with a dead time of 1μs. The simulation results are shown in figure 8.
Table 1. System specifications in simulation.

| Specification         | Value       |
|-----------------------|-------------|
| Output voltage (Vo)   | 320kV       |
| Working frequency     | 10kHz       |
| Load resistance       | 102.4kΩ     |
| Lr                    | 27.2mH      |
| Cr                    | 9.79nF      |
| Lf                    | 5mH         |
| Transformer ratio     | 1:8         |

The simulation results show that when the resonant network works in the inductive region, that is, the square wave frequency is greater than the first resonant frequency. It can be seen that zero voltage switching (ZVS) is realized in the primary side converter, and zero current switching (ZCS) realized by rectifier diode, which reduces the switching loss of the converter. The output voltage of HVDC can reach 320kV, which verifies that the topology can meet the requirements of high voltage ratio when transmitting megawatt power.

5. Conclusion
In this paper, a topology of high voltage and large capacity isolated DC-DC converter based on resonant network with ultra-high voltage boost ratio is proposed, and its switching mode is analyzed. Furthermore, the relationship between the gain of input and output voltage of the resonant network and the switching frequency and quality factor is derived according to the equivalent circuit model. The simulation results show that the topology can meet the requirements of high voltage rise ratio, and can realize ZCS of diode at rectifier end and ZVS of power switch at low voltage end. Compared with other existing topologies, this topology reduces the cost under the condition of the same boost ratio and makes the realization of ultra-high boost ratio converter possible. It provides a theoretical basis for the construction of offshore wind power full DC system. The next research will be based on the existing control mode, using a more stable control loop, so that the working frequency can achieve tracking control.
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