Design and Implementation of the Isolated Bidirectional DC-DC Converter

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Abstract. With the development of intelligent distribution networks and the increasing demand for new energy access, the isolated bidirectional dc-dc converter has become a key link in modern energy transformation systems. In order to realize the functions of electrical transformation and electrical isolation of dc voltage, this paper proposes a structure of isolated bidirectional dc-dc converter, and analyzes it in detail. The proposed isolated bidirectional dc-dc converter can not only realize voltage transformation, but also have voltage regulation and fault isolation functions. Finally, based on the MATLAB/Simulink simulation platform, the proposed isolated bidirectional dc-dc converter topology is built and verified by simulation. The structure of isolated bidirectional dc-dc converter not only has the functions of voltage transformation and electrical isolation, but also has fault isolation, power flow control and other functions.

1. Introduction

In recent years, with the continuous development of science and technology, electronic equipment has gradually entered people's daily life. It has gradually brought its advantages into play in human production and life, helping mankind get rid of the shackles of life. While the electronic industry is booming, the converter is also constantly innovating. Among them, DC-DC converter, as an indispensable component of all kinds of equipment, has attracted more and more researchers to improve it. DC-DC converter is a voltage converter that can effectively output a fixed voltage after changing the input voltage. It is divided into boost type, step-down type and voltage rise and fall type. Because a large number of electronic devices need a variety of voltage supply, DC-DC converter has become an essential part [1-2]. DC-DC converters are widely used in computer, data center, remote power transmission, office automation equipment, military and other fields, involving all walks of life of the national economy. Therefore, if the DC-DC converter is made more intelligent and digital, the efficiency of information processing will be greatly improved. As a research hotspot in recent years, intelligent control, including many excellent control algorithms such as neural network and fuzzy control, has achieved good results in the control of DC-DC converter. Moreover, with the gradual deepening of energy-saving concept in various fields and the gradual improvement of the performance of digital controller, people also began to pay attention to the digital control of DC-DC converter. Compared with traditional control, digital control has great advantages. Digital control can realize the relevant intelligent control that can not be realized by analog circuit, and improve the overall efficiency and stability. Nowadays, many cutting-edge researchers are committed to the all digital control of DC-DC converter. Due to the increasing global demand for various large electrical appliances, digital control will have a wide application prospect in high-power DC-DC converters. While meeting the steady-state and dynamic performance indexes, it has gradually become the goal of
designers to reduce the energy loss of DC-DC converter in the working process as much as possible by improving the control strategy, so as to improve its working efficiency [3-4].

2. Research status at home and abroad

The converter originated in the 1950s [5]. In the 1980s, researchers put forward the idea of reducing the volume of DC-DC converter and increasing the switching frequency at the same time. However, these two aspects cannot achieve win-win results. Subsequently, various technical modes gradually developed. In literature [6], neural network control was used to improve the control effect of DC-DC converter, and combined with traditional PID control to achieve high adaptability. In this paper, the online data are used to train and optimize the parameters of neural network. In reference [7], aiming at the faster switching frequency of DC-DC converter to meet the requirements of miniaturization and power efficiency, a reference modification method based on neural network predictor is proposed.

Nowadays, the main research direction is digital DC-DC converter, but its response characteristics are poor. There are two research directions. One is to improve the PID algorithm and adjust it by using the characteristics of proportional, differential and integral branches [8]. The second is nonlinear control algorithm. Now the common research includes nonlinear gain, adaptive control, sliding mode control, fuzzy control, neural network control, charge balance control algorithm and so on. However, the digital DC-DC converter studied in China is still far from practicability. The core technology depends on foreign products and can not realize product performance upgrading and application expansion.

3. Closed-loop control

Isolated DC-DC converter aims to convert one form of DC into another and connect with each other through transformer. And it conforms to the basic transformation law of AC power system. As shown in the figure 1:

Assume that the power plant voltage on the right is $V_s$, and the phase is the initial value 0, i.e. $\overline{V_s}=V_s e^{j0} = V_s$. Similarly, assume that the point pressure of the power plant on the left is $V_i$, and phase lead $\theta$, i.e. $\overline{V_i}=V_i e^{j\theta}$. Therefore, the current $i_s$ in the circuit can be written as $i_s = \frac{\overline{V_i}-\overline{V_s}}{j\omega L}$. And then according to Euler's formula $e^{j\theta} = \cos \theta + j \sin \theta$, $i_s$ can be expanded to $\frac{V_i \sin \theta - j(V_i \cos \theta - V_s)}{\omega L}$. And because $i_s = I_p + I_Q$, it follows that $I_p = \frac{V_i \sin \theta}{\omega L}, I_Q = \frac{V_s - V_i \cos \theta}{\omega L}$, so $P_s = V_s I_p = \frac{V_s V_i \sin \theta}{\omega L}, Q_s = -V_s I_Q = \frac{V_s V_i \cos \theta - V_s^2}{\omega L}$. The principle of DC-DC converter is similar. As shown in the figure 2:
Figure 2. DC-DC converter model

Figure 3. Variation diagram of each variable with time

The left and right sides are DC power supply, which is composed of two sections of "H" bridge and isolation transformer in the middle. The "H" bridge is composed of four switching tubes. The polarity of the power transmission is changed by conducting the tubes. The "H" bridge is composed of four switching tubes. The polarity of the power supply is changed by conducting the tubes. If the switching tubes $Q_1$ and $Q_4$ are connected, the converter will input $V_1$ voltage. If the switching tubes $Q_2$ and $Q_3$ are connected, the converter will input $-V_1$ voltage; If the switching tube $S_1$ and $S_4$ are connected, the $NV_2$ voltage will be output. If the switching tube $S_2$ and $S_3$ are connected, the $-NV_2$ voltage will be output. Therefore, the input voltage and output voltage form two square waves with a phase difference of $\theta$. According to the phase difference, the variation curve of current $i_{L_1}$ with time $t$ can be drawn. Therefore, by changing the phase difference between the input voltage and the output.
voltage, a current is formed to realize the flow of power. The converter can convert DC to AC and then AC to DC. This method needs to manually change the phase angle to output the corresponding voltage value, so it has some limitations.

![Relationship between power and angle](image)

Figure 4. Relationship between power and angle

However, it is found from the above formula that if the voltage at both ends of the converter is sinusoidal, the power \( P \) and phase \( \theta \) show a sinusoidal correlation curve. But when the two ends of the converter are square wave voltage, the relationship between power \( P \) and phase \( \theta \) is

\[
P = \frac{\theta (\pi - |\theta|) NV_1 V_2 T}{2 \pi^2 L_i}.
\]

The illustration shows that when \( \theta \) at 0 ∼ 180°, the power is forward transmission, when \( \theta \) at 180 ∼ 0°. The power is reverse transmission. Between 0 ∼ 90°, \( \theta \) increases with the increase of \( P \). Between 90 ∼ 180°, \( \theta \) decreases with the increase of \( P \). So make the output voltage \( U_0 \) increases, \( P \) must be increased, \( \theta \) shall also be controlled within a certain range, taking into account the energy loss, i.e. reactive power \( |Q_s| \) should be small, so value range of \( \theta \) is 0 ∼ 90°. Therefore, the introduction of integral controller can effectively solve the above problems. By inputting the desired voltage value, the system can automatically match the corresponding phase angle to realize the closed-loop control of DC-DC converter.

4. Proportional integral controller

![Schematic diagram of proportional integral controller](image)

Figure 5. Schematic diagram of proportional integral controller

The proportional integral controller is composed of proportional controller and integral controller, and its formula is

\[
u(t) = K_p e(t) + K_i \int e(t) dt,
\]

\( K_p \) and \( K_i \) are parameters, \( e(t) \) is the input
deviation, it can be obtained by the difference between the reference value $U_{\text{ref}}$ and the actual value $U_0$. The output variation of the proportional controller is directly proportional to the input deviation.

The larger the parameter $K_p$, the larger the output. Therefore, $K_p$ is a parameter to measure the strength of proportional effect. The biggest advantage of proportional control is that it has fast dynamic response speed and reduces the error. Only by modifying the parameters, the corresponding output value will be greatly improved, but at the same time, it has the disadvantage that the error cannot be eliminated. However, due to the detection error of each system, there will be residual error in the proportional control result. Therefore, the integral controller solves this problem well. The deviation of the integral regulator is the integration of the deviation with time. As long as there is a deviation in the system, the regulator output will change continuously until the deviation is 0. The size of the output signal of the controller is not only related to the size of the deviation, but also depends on the length of time the deviation exists. Therefore, when time is very small, the regulator output is also very small and the control effect is relatively weak. Therefore, the integral controller is generally not used alone, but in combination with the proportional controller. Therefore, under the action of proportional integral controller, the output of the system can achieve the effect of high efficiency and high precision.

5. **Proportional integral controller based on power model**

In order to improve the output voltage efficiency of DC-DC converter, the combination of power model and proportional integral controller is often introduced. The relationship between power $P$ and phase $\theta$ is

$$ P = \frac{\theta(180 - |\theta|) NV^2 T}{64800 L_i} $$

And power can also be expressed as

$$ P = \frac{U_o^*}{R} , \quad U_o^* $$

is the voltage reference value. However, because the load resistance $R$ changes constantly during operation, the load resistance $R$ can be converted into

$$ R = \frac{U_o}{i_o} , \quad U_o $$

is voltage sampling value, $i_o$ is the current sampling value. Supposing $a = \frac{64800 L_i P}{NV^2 T}$, thus it can be simplified to

$$ \theta^2 - 180\theta + a = 0 , \quad \theta = 90 \pm \sqrt{90^2 - a} . $$

But the angle $\theta$ needs to be taken $0 \sim 90^\circ$, so

$$ \theta = 90 - \sqrt{90^2 - a} . $$

The figure 6 shows the V-T image of input voltage 1000V and load resistance $10\Omega$ under proportional integral control based on power model.
Figure 6. 1000V voltage steady state response

Figure 7. Output voltage response without proportional integral controller (left) and with proportional integral controller (right)
In order to better understand the role of power model, step response can be adopted. As shown in the figure 7 above, the left figure is the dynamic response diagram under the control of traditional proportional integral controller, and the right figure is the dynamic response diagram under the control of proportional integral controller based on power model. It can be seen from the figure that when the output is stepped from 1000V to 800V in 0.3s, the dynamic characteristics of proportional integral control based on power model are faster, which is 0.05s faster than the traditional proportional integral control.

![Figure 8. Input voltage response without proportional integral controller (left) and with proportional integral controller(right)](image)

The above figure 9 shows the time variation of the actual output voltage of the two controls when the input voltage steps from 800V to 1000V in 0.3s. It can be seen from the figure that under the traditional mode, the dynamic response time is about 0.2S, while under the action of the power model, the stability time is about 0.4s.

However, when the proportional coefficient and integral coefficient are not set properly, the dynamic response of the system will also be affected:

Case 1: When the proportional coefficient and integral coefficient are too large, although the reference value can be reached quickly, the system will oscillate violently.
Case 2: When the proportional coefficient is too large and the integral coefficient is too small, the system will oscillate, and the integral effect is not obvious, and the residual error elimination is very slow.

Case 3: When the proportional coefficient is too small and the integral coefficient is too large, the oscillation of the transition process is violent and the stability is reduced.
Case 4: When the proportional coefficient and integral coefficient are too small, the whole proportional integral cycle is very long and the effect is poor.

6. Conclusion
In order to realize the voltage transformation of the simultaneous DC port to facilitate the access of renewable energy systems, the isolated bidirectional dc-dc converter is proposed. The structure of isolated bidirectional dc-dc converter proposed in this paper is analyzed in detail. Finally, the simulation of the isolated bidirectional dc-dc converter is built and verified. The theoretical analysis and results give that:

(1) The structure of isolated bidirectional dc-dc converter proposed in this paper can transform with both voltage transformation and electrical isolation functions.

(2) The structure of isolated bidirectional dc-dc converter proposed in this paper is convenient for the access of renewable energy systems.
(3) The structure of isolated bidirectional dc-dc converter proposed in this paper has the ability to shut down the fault.

References
[1] Sabahi M, Hosseini S H, Sharifian M B, et al. Zero-voltage switching bi-directional SST[J]. IET Power Electronics, 2010, 3(5): 818-828.
[2] Bifaretti S, Zanchetta P, Watson A, et al. Advanced power electronic conversion and control system for universal and flexible power management[J]. IEEE Transactions on Smart Grid, 2011, 2(2): 231-243.
[3] She Xu, Huang A Q, Wang Gangyao. 3-D space modulation with voltage balancing capability for a cascaded seven-level converter in a solid-state transformer [J]. IEEE Transactions on Power Electronics, 2011, 26(12): 3778-3789
[4] Dujic D, Zhao Chuanhong, Mester A, et al. Power electronic traction transformer-low voltage prototype [J]. IEEE Transactions on Power Electronics, 2013, 28(12): 5522-5534.
[5] Besselmann T, Mester A, Dujic D. Power electronic traction transformer: efficiency improvements under light-load conditions[J]. IEEE Transactions on Power Electronics, 2014, 29(8): 3971-3981.
[6] Zhao Chuanhong, Dujic D, Mester A, et al. Power electronic traction transformer—medium voltage prototype[J]. IEEE Transactions on Industrial Electronics, 2014, 61(7): 3257-3268.
[7] Glinka M. Prototype of multiphase modular-multilevel converter with 2 MW power rating and 17-level-output voltage[C]//Proceedings of the 35th Annual Power Electronics Specialists Conference. Aachen, Germany: IEEE, 2004; 2572-2576.
[8] Glinka M, Marquardt R. A new AC/AC multilevel converter family[J]. IEEE Transactions on Industrial Electronics, 2005, 52(3): 662-669.
[9] Hugo N, Stefanutti P, Pellerin M, et al. Power electronics traction transformer[C]//Proceedings of 2007 European Conference on Power Electronics and Applications. Aalborg, Denmark: IEEE, 2007: 1-10
[10] Wang Xinyu, Liu Jinjun, Ouyang Shaodi, et al. Research on unbalanced-load correction capability of two SST topologies[J]. IEEE Transactions on Power Electronics, 2015, 30(6): 3044-3056.
[11] Ahmed H F, Cha H, Khan A A, et al. A highly reliable single-phase high-frequency isolated double step-down AC–AC converter with both noninverting and inverting operations[J]. IEEE Transactions on Industry Applications, 2016, 52(6): 4878-4887.
[12] Briz F, Lopez M, Rodriguez A, et al. Modular SSTs: modular multilevel converter versus cascaded h-bridge solutions[J]. IEEE Industrial Electronics Magazine, 2016, 10(4): 6-19.