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The Advantage of SiC MOSFET for Three-phase Four Legs Converter in Off-grid Applications

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Abstract

Commercial and industrial (C&I) side energy storage system (ESS) is booming recently with its economy, flexibility, and grid friendliness. In the off-grid application scenario, the unbalanced load capability and output power quality are important indicators of its power conversion system (PCS). The three-phase four legs(3P4L) converter has the strongest ability to supply unbalanced loads but compared to the three-phase three legs (3P3L) topology, the cost increases and the output AC voltage harmonic distortion is higher. SiC MOSFETs can significantly increase the switching frequency compared with IGBTs due to their superior material characteristics. In this paper, the theoretical analysis combined with the simulation results show that SiC MOSFETs are more suitable for 3P4L converter, which is a cost performance solution.

1 Introduction

With the process of global decarbonization, renewable energy power generation accounted for a higher and higher penetration rate, in this context, the introduction of ESS effectively inhibits the volatility of new energy power generation, and PCS as the core device of ESS is widely applied. In C&I applications, there may be single-phase loads and three-phase non-linear loads. When the three-phase load is unbalanced, since the inverter output impedance is not zero, according to the symmetrical component method, the output voltage will contain both negative and zero-sequence components, at which point the output voltage will no longer be balanced, and the traditional three-phase, three-wire(3P3W) topology does not have the capability of compensating for the zero-sequence component due to the lack of N wire. Three-phase, four-wire(3P4W) converter topologies are necessary to meet the single-phase power supply requirements and suppress the three-phase unbalanced voltages.

1.1 Transformer method for three-phase four wire power supply

By adding a transformer to the traditional 3P3W converter, a 3P4W power supply can be easily realized, as shown in Figure 1. The primary side of the transformer is delta connection, and the secondary load side provides a midline current path to the load via Yn-connection. The zero-sequence component could be short-circuited in the primary side by the delta connection, the system only needs to consider the control of positive and negative sequence components, which is conducive to simplifying the control scheme. But when the load imbalance degree is large, this topology cannot well maintain the voltage balance, the zero-sequence component in the load voltage depends on the leakage impedance of the transformer [1], and in addition, the transformer also increases the system volume and cost greatly.

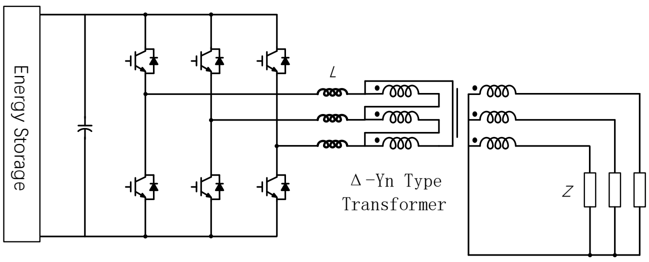

Fig. 1. 3P4W topology with Δ-Yn type transformer

1.2 Three legs split capacitor topology

Three-phase, three legs(3P3L) converter can also realize a 3P4W power supply by splitting the DC capacitor, the neutral point of the load is directly connected to the midpoint of the DC-link capacitor of the three-phase converter, this solution does not require the additional power devices and transformers, etc. The cost is relatively low. However, when the load is unbalanced, the unbalanced current flows into the DC capacitor, considering the lifetime of the capacitor, the capacity demand becomes larger, and at the same

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time, it is necessary to add the midpoint unbalance control strategy as well as the zero-sequence control. The output phase voltage of this topology can only jump between two levels (-Vdc, +Vdc), the harmonic suppression effect is lower than the 3P3W system, and thus the output current waveform aberration is also higher. Due to the addition of zero-sequence path, SVPWM modulation cannot control the zero-axis component, and 3d-SV or carrier modulation is required [2]. For this topology, the utilization rate of DC voltage is not high and the ability to suppress the three-phase unbalance voltage is relatively limited.

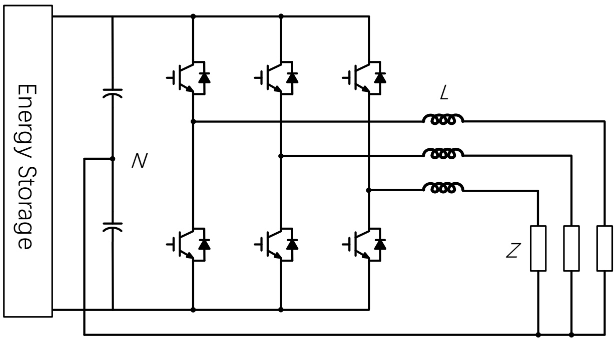

Fig. 2. 3P4W split capacitor topology

1.3 Balancing leg type split capacitor topology

3P4W topology with a balancing leg is also widely used, the neutral point of the load is also connected to the midpoint of the DC-link capacitor, and the balancing leg is connected to the midpoint of the DC bus via a high-frequency inductor. By controlling the power device switching to regulate the midpoint voltage, the balancing bridge current and the N-line current cancel each other to ensure the midpoint voltage is relatively stable, the three-phase bridge control method is the same as that of the split-capacitor topology, and balancing bridge control uses the inductance current as the inner loop, and the difference between the positive and negative bus voltages as the input of the outer-loop control [3]. For this topology, the capability of suppressing three-phase imbalance has been improved, to a certain extent, it depends on the hardware capability of the balancing leg.

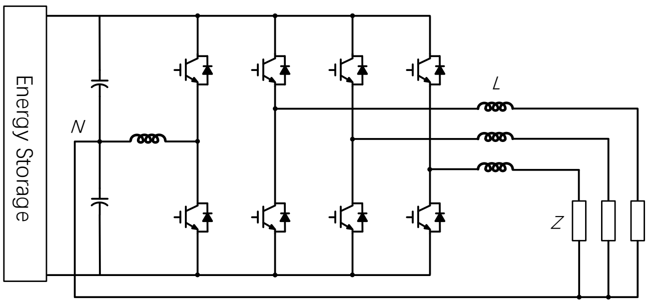

Fig. 3. 3P4W topology with balancing leg

1.4 Three-phase four legs topology

For the 3P4L topology as showed in Fig.4, the neutral point of the load is directly connected to the ac point of the fourth leg, this branch provides a path for the unbalanced current as well as adding a control degree of freedom, which can decouple the three-phase voltages into three independent single-phase controls. The third harmonic injection carrier modulation method or 3d-SV modulation is used in the control to achieve higher DC voltage utilization compared to the above topologies, as will be discussed in the next section. 3P4L topology increasing a certain amount of hardware cost with the strongest ability to suppress the three-phase imbalance, and the capacitance capacity demand of the DC side is smaller compared to that of a split-capacitor topology, which is also conducive to reducing the size of the device. This paper presents a study and benchmarking based on this topology.

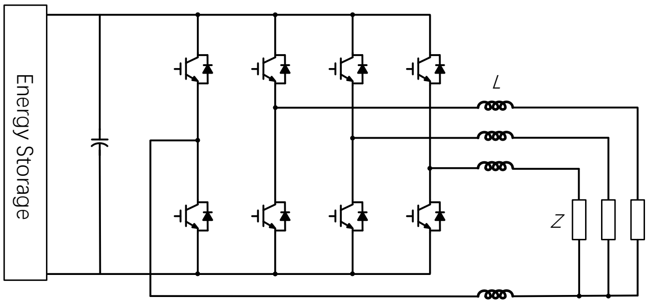

Fig. 4. Three phase four legs topology

1.4.1 Modulation method of 3P4L converter

Modeling and analysis of the 3P4L converter topology shows that compared to the strongly coupled 3P3L converter, each phase of the 3P4L topology is independent and can be decomposed into three full-bridge converters [4], especially when the three-phase loads are unbalanced, the output phase voltages do not affect each other, and they can be independently controlled by the V/F method and build up the output voltage.

The third harmonic injection carrier modulation strategy or the 3d-SV modulation method is usually adopted to obtain better DC voltage utilization and smaller harmonic distortion. For the 3P4L topology, the 3d-SV modulation space is a hexagonal prism structure in the αβγ coordinate, γ represents the zero-sequence component.

$$V_\gamma = \frac{1}{3}(V_a + V_b + V_c)$$

The judgment of the triangular prism region where the vector is located and the process of vector synthesis is relatively complex, and the practical application of engineering is not friendly enough compared with that of the third harmonic injection carrier modulation

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method. And research has shown that the two are normalized in the final modulation effect [5].

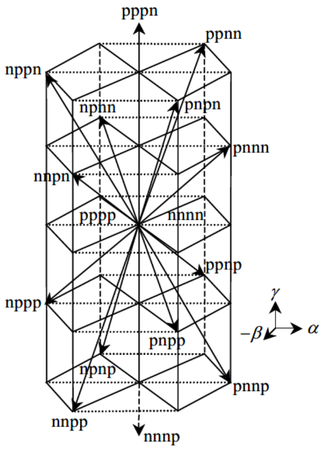

Fig. 5. Switching vector of 3P4L topology

For the third harmonic injection carrier modulation method with 3P4L topology, the modulation waveform is shown in Fig. 6 and its mathematical expression is:

$$M_a = \frac{2}{\sqrt{3}} msin(\omega t) + \frac{\sqrt{3}}{9} m(3\omega t)$$
$$M_b = \frac{2}{\sqrt{3}} msin(\omega t - 120^{\circ}) + \frac{\sqrt{3}}{9} m(3\omega t)$$
$$M_c = \frac{2}{\sqrt{3}} msin(\omega t + 120^{\circ}) + \frac{\sqrt{3}}{9} m(3\omega t)$$
$$M_n = \frac{\sqrt{3}}{9} m(3\omega t)$$

m is the modulation ratio.

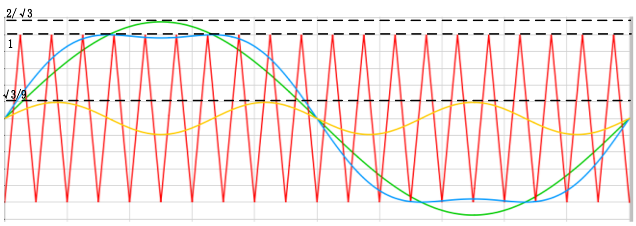

Fig. 6. 3P4L topology modulation waveform

The blue curve in the above figure corresponds to the 3P4L converter A-phase modulation waveform, The phase difference between phase B and C is 120 degrees. Perform Fourier expansion on it, the amplitude of the fundamental component is $\frac{2}{\sqrt{3}} sin(\omega t)$, meaning that compared with the SPWM, improved the utilization of the DC voltage. The fourth leg is directly applied to the triple-frequency sinusoidal waveform for modulation, so that the triple-frequency component can be canceled out in the output of the phase voltage. This modulation method is easy to realize and widely used in engineering.

2 SiC MOSFET characteristics

Over the past two decades, Si IGBT has dominated power semiconductor applications in medium to high-power power electronics. Compared to Si MOSFET, their bipolar conductivity allows for a further increase in the on-state current, while the device has a good voltage blocking capability. However, with the changing application requirements, such as high-frequency, high-voltage, and high-power density scenarios, IGBTs are also facing device bottlenecks. The development of third-generation wide-bandwidth power semiconductor technology, represented by SiC MOSFET, provides ideas to solve the above problems. SiC material itself has several significant advantages over Si material, such as a higher breakdown field, superior thermal conductivity, and higher electron drift velocity, etc. SiC MOSFETs are believed to replace IGBTs for better performance in a variety of applications, such as energy storage system, where using SiC MOSFETs to improve efficiency can bring distinct economic benefits. The higher switching frequency of SiC MOSFET also improves the power quality of the inverter's grid-connected output.

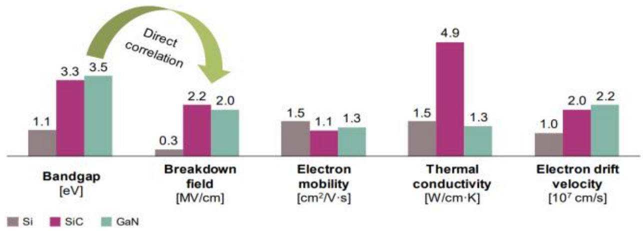

Fig. 7. Comparison of different semiconductor materials

2.1 Conduction behaviour

Si IGBT has a pnpn four-layer structure generating a further junction voltage of the additional pn junction at the collector side [6]. Therefore, the output characteristics of Si IGBTs include a knee voltage drop from the pn junction while the output characteristic curve of the SiC MOSFET is like a positively proportional straight line, so that in the low-current region, the SiC MOSFET has a significantly smaller conduction loss, as showed in fig.8.

In addition, SiC MOSFET can reverse conduction, the current can flow from the source to the drain through the same channel, and the on-resistance is very small. So, in practice, it is recommended to use such a synchronous rectification mode (3rd quadrant operation). Minimizing the dead time as much as possible can help reduce the conduction time of the body diode and further reduce conduction loss [7].

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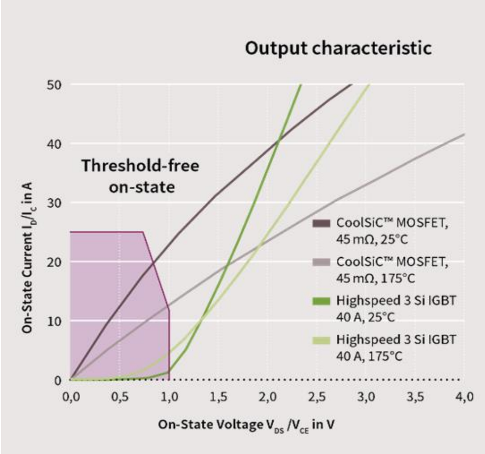

Fig. 8. Conduction characteristic comparison between SiC MOSFET and IGBT

2.2 Switching behaviour

Compared to Si IGBT, SiC MOSFETs offer better switching performance regarding both turn-on and turn-off. SiC material has a higher electron drift velocity than Si material, at the same time, SiC MOSFET due to its unipolar conductive properties, there is no tail current phenomenon compared to the IGBT, so that turn-off loss is greatly reduced. With the very small reverse recovery energy of SiC diode, the turn-on loss of SiC MOSFETs is also much smaller than the Si IGBT. The figure below shows a benchmark comparison of switching losses between SiC MOSFET and IGBT at the same current level. SiC MOSFET shows significant lower switching losses and smaller temperature dependence at the same current.

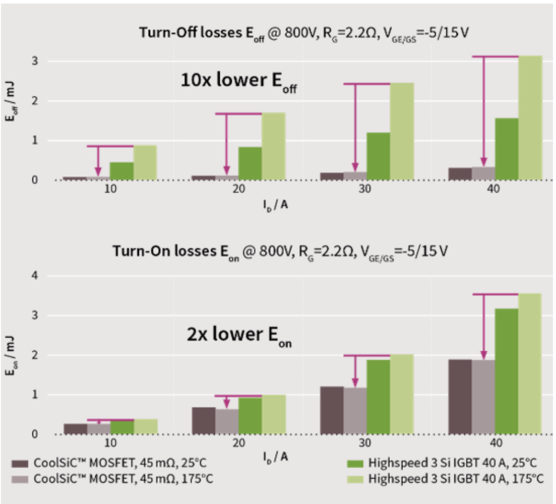

Fig. 9. Switching losses of SiC MOSFET compared with Si IGBT at different temperature

3 Value proposition of SiC MOSFET in 3P4L converter

Due to the introduction of the fourth phase-leg, compared with the traditional 3P3L topology, the number of output phase-voltage levels is reduced from five (±2U_{dc}/3, ±1U_{dc}/3, 0) to three (±U_{dc}, 0). So naturally, the output load voltage and current distortion of the 3P4L topology are larger compared with the 3P3L topology, so at this time the application of SiC MOSFETs to increase the switching frequency can effectively improve the power quality.

3.1 Different THD performance between 3P3L and 3P4L converters

Under the same operating conditions and circuit parameters, the phase voltage, and current waveforms of the 3P4L and 3P3L converters output are shown in Fig 10. The voltage step is reduced in 3P4L topology, resulting in higher harmonic content. Under the same filter parameters condition, the output current THD of the 3P4L converter is 49.5% worse than the 3P3L converter. Therefore, to satisfy the system harmonic requirements, the 3P4L converter is necessary to apply interleaved topology or three-level topology or increase the output filter inductance, which will increase the system cost a lot. Whereas the two-level topology with a lower filter inductance, the SiC MOSFETs solutions can satisfy the system harmonic requirements because of the significant higher switching frequency.

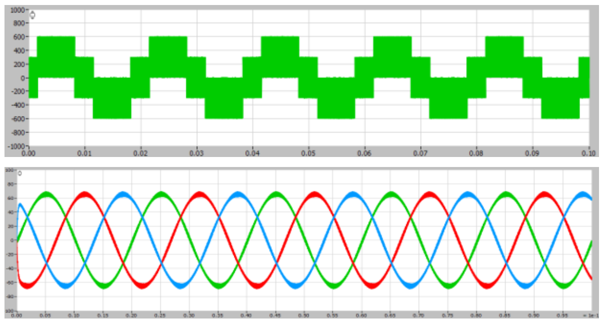

Fig. 10a. Phase voltage and current of 3P3L output, current THD=3.23%

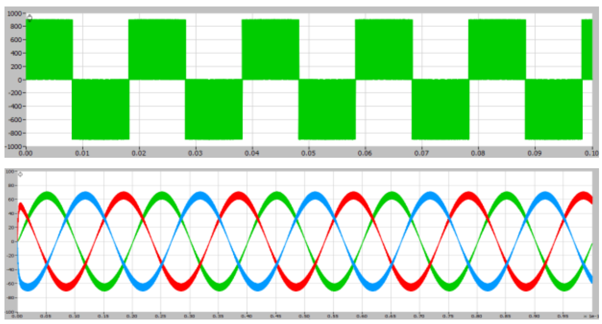

Fig. 10b. Phase voltage and current of 3P4L output, current THD=4.83%

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3.2 Simulation

In this section, the PLECS simulation tool is used to quantitatively compare the performance difference between IGBT applied to T-NPC 3P4L converter and SiC MOSFET applied to 2L-3P4L by taking the C&I 3P4L PCS discharging condition in both grid-connected and off-grid as an example. The results show that under the same phase current THD index, the SiC solution has certain advantages in terms of losses, efficiency, filter inductance parameter reduction, system simplification, etc., which makes it a more suitable and cost-effective solution for this application.

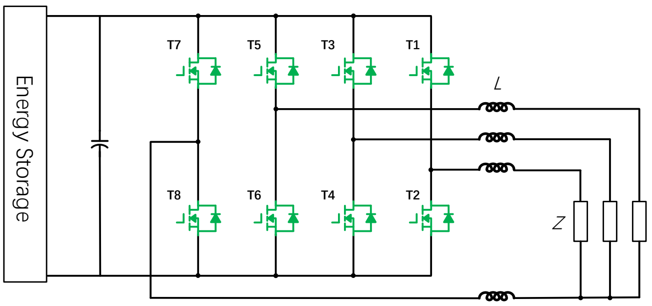

Fig. 11. SiC MOSFET in 2L 3P4L topology

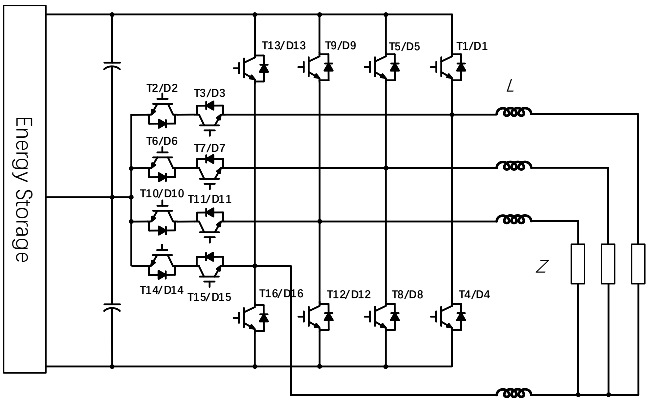

Fig. 12. Si IGBT in T-NPC 3P4L topology

3.2.1 Comparison under three-phase load balancing working condition

The discharge condition of 125kW rated power PCS is simulated, for the 2L-SiC solution, IMZA030R12M1H 6 parallel is used, while for T-NPC IGBT solution, IKY75N120CH7 6pcs parallelling is deployed in the vertical switch and the horizontal switch is also designed in 6pcs parallelling with the same current 650V IGBT IKZA75N65EH7, and the other simulation conditions are listed in the Table 1.

In the 110% long-term overload condition, IGBT is limited by the switching losses, and the switching frequency is generally less than 20kHz, in order to achieve the same THD, the T-NPC 3P4L converter needs a larger filtering inductance. The simulation takes THD=3.15% as an example, the filtering inductance of the 2L-SiC scheme is 142uH, while the filtering inductance of T-NPC solution requires to be increased to 223uH.

Table.1 the typical operating conditions for the 125kW C&I PCS

Parameter	Value
V_{DC}	900Vdc
U_{out}	400Vac
f_{sw}	20kHz(IGBT) 32kHz(SiC)
PF	1
$Rg_{on/off}$	1Ω/5Ω (SiC) 10Ω/10Ω (IGBT)
$T_{heatsink}$	80℃
Overload	110% long-term

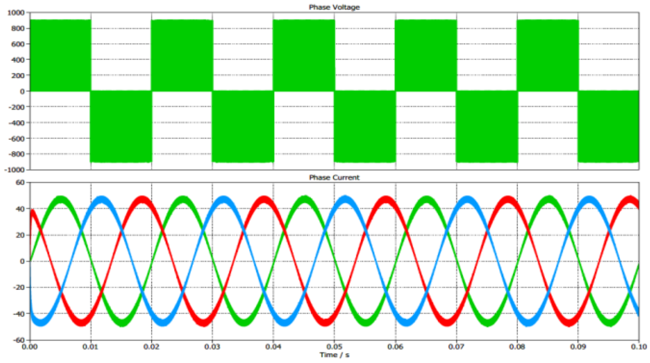

Fig. 13. Phase voltage and current of 2L-SiC, current THD=3.15%

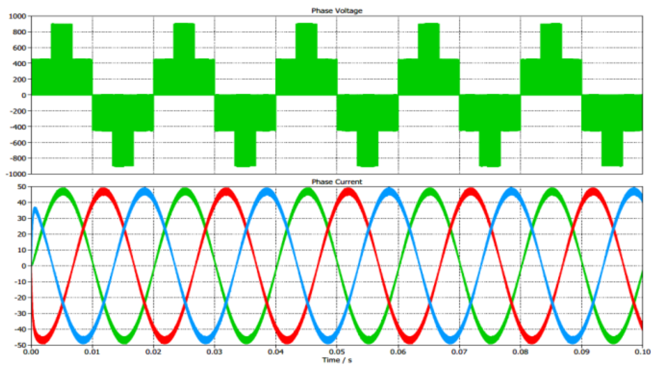

Fig. 14. Phase voltage and current of T-NPC, current THD=3.14%

In the case of three-phase load balancing, for the 2L-SiC solution, the single SiC MOSFET losses is about 36.3W, the maximum junction temperature is 132.3°C, and the PCS efficiency reaches 99.03% (only considering the power semiconductors losses). Regarding to the T-NPC IGBT solution, the vertical switch, such as T1, is the power device with the highest losses, and the loss of a single IGBT is about 35.5W, due to a larger chip size, the maximum junction temperature is 116.5°C, but the overall efficiency is lower than the former, 98.58%. Due to the balanced three-phase load,

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the N-line current is very small and the power device losses in the fourth phase-leg are quiet low.

In summary, under the three-phase load-balanced condition, for the 3P4L converter, employing the 2L-SiC solution can simplify the circuit topology, reduce the number of power devices by 50%, reduce the inductance value by 36%, and improve the efficiency by about 0.5% under the same output phase-current THD.

3.2.2 Comparison under 100% unbalanced working condition

100% unbalanced condition means that there is one phase-leg together with the fourth leg constituting a single-phase output, the remaining two phases do not work, the simulation takes 110% overload condition, single-phase full-power output as an example, i.e., single-phase output power is:

$$P_{single-phase} = \frac{1}{3} \times 125kW \times 110\%$$

For the 2L-SiC solution, power losses of T1/T2 and T7/T8 are comparable, 34.5W and 34.3W respectively. But the maximum junction temperature of the two is 6°C difference, 129.8°C and 123.8°C respectively, as showed in Fig.15, which is due to the fourth leg being equivalent to the output triple frequency component, embodied in the power device for a smaller junction temperature fluctuation.

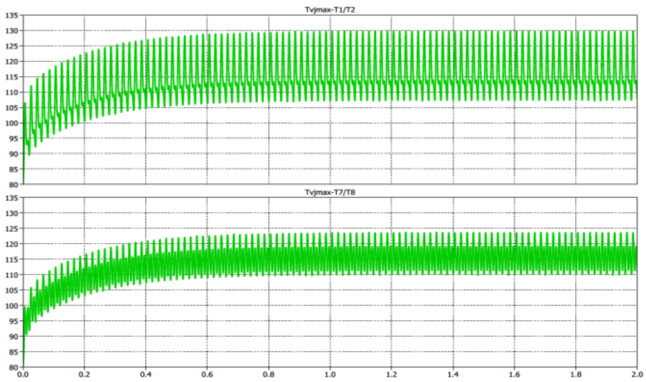

Fig. 15. Different junction temperature fluctuations between T1/T2 and T7/T8.

For the T-NPC IGBT solution, taking phase A as an example, the losses of the vertical switch T1/T4 is the same as that of the three-phase load balancing condition, which is 35.3W, with a maximum junction temperature of 116.2°C. However, under 100% imbalance, the horizontal switch of the fourth leg has a longer conduction time, with a loss of 19.0W for T14/T15 and 19.5W for D14/D15. The conduction loss accounts for a relatively large proportion. Currently, the horizontal switch of the fourth leg is the highest junction temperature point, which is 128.5°C. Overall, under 100% unbalanced operating conditions, the maximum junction temperature difference of the two solutions is very small.

4 Conclusion

Three-phase four-wire converters are widely used in C&I ESS applications, among which the three-phase four-legs converter has the most excellent unbalanced load carrying capability and flexible single-phase power supply capacity. The third harmonic injection carrier modulation method is often used to improve the DC voltage utilization rate as well as convenient decoupling of the three-phase control. For three-phase four legs PCS, the two-level SIC MOSFET solution has several advantages over the three-level IGBT solution, one is that it greatly simplifies the system topology and reduces the number of power devices, and the other is that considering the balanced and unbalanced conditions, the maximum junction temperatures of the two are basically the same, but in the case of the same THD of the output current, the former has a higher efficiency, and a smaller filtering inductance can be applied, so it has a higher power density, and realizes a certain degree of cost-effectiveness in the system.

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