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Comparative Study of 3-phase 4-wire Converter Topologies for Active Thermal Control Techniques

능동 열 제어 기법을 위한 3상 4선식 컨버터 토폴로지들에 대한 비교 연구

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Abstract

This paper presents an in-depth investigation of different types of 3-phase 4-wire converters commonly used in power electronics applications. The paper begins by providing an overview of the significance of 3-phase 4-wire converters in modern power systems and their relevance in addressing per-phase active thermal control for prolonging the lifetime of specific phase leg or asymmetrical operation for unbalanced conditions. Subsequently, a detailed examination of various converter topologies, such as 2-level 4-leg converter and 3-level 4-wire converter, is presented. Each topology is explained, highlighting their operational mechanisms, control and applications. Additionally, the output performance comparison between different types of 3-phase 4-wire converters is evaluated in terms of output current total harmonic distortion (THD) value, leakage current root-mean square (RMS) value, and power losses. The performance comparison results are obtained by implementing in simulation environment of PSIM program.

Key Words

3-phase 4-wire, Carrier-Based Pulse-Width-Modulation, Per-phase control, NPC, TCC

1. Introduction

The worldwide advancement of industrialization leads to higher energy usage, which leads to the ongoing utilization of fossil fuels. The increased release of carbon dioxide into the atmosphere due to burning fossil fuels has expedited the process of global warming, giving rise to significant environmental apprehensions. There's a possibility that electricity production from renewable sources as solar panels, wind turbines, and biomass could replace the generation of electricity from fossil fuels. The growing need for environmentally friendly energy is causing a rise in interest towards distributed generation systems. These systems typically function either independently or by connecting to the main power grid. Specifically, when it comes to distant locations, operating independently proves to be more cost-effective compared to connecting to the grid. Nonetheless, in real-world scenarios, the devices linked to the power source may not be evenly distributed. Owing to being necessary component of distributed power supply, the 3-phase converter is expected to possess the capability to handle an imbalanced load during standalone operation and furnish a stable alternating current voltage [1]. Additionally, the different wear-out conditions in each phase of converter is another issues. The simplest active thermal control solution is reducing the switching frequency of converter to decrease the number of commutation, resulting in prolonging lifetime of converter [2]. However, this solution lowers the output performance of converter. Using different output power in each phase is another straightforward implementation but it requires specific converter topology to guarantee accurate operation [3], [4]. Therefore, various 3-phase 4-wire converters are developed for per-phase control by using different output power as well as operating in unbalanced conditions.

As for 3-phase 3-wire converter, this type of converter is usually used in feeding balanced three-phase loads. Since lack of a path for counteracting unbalanced current, instances of imbalanced loads will result in uneven voltages across the phases of the

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load. In situations of severe imbalance, the phase voltage across a load might approach the line voltage, posing a danger. Concurrently, the 3-phase 4-wire system has the capacity to supply power to both well-balanced 3-phase loads and those that are not balanced, including single-phase loads. The inclusion of a neutral wire facilitates a path for addressing uneven current, allowing the 3-phase 4-wire converter to manage the neutral current stemming from imbalanced loads or disruptions in the power grid. In addition, the 3-phase 4-wire offers the capability of operating under different output power in each phase. It is suitable for per-phase control to prolonging the lifespan of the most wear-out leg in converter. Therefore, 3-phase 4-wire converters offer an important advantage over 3-phase 3-wire converter.

Three primary configurations exist for enhancing the power quality of a 3-phase converter when handling an unbalanced load. One such approach involves a 3-phase composite converter, which integrates three individual single-phase converters. This arrangement remains functional even if one phase encounters a malfunction [5]. Despite the simplicity of its control method and the autonomy of each phase's control, the redundant circuit design leads to augmented costs and physical size. Compared to 3-arm configuration, the 3-phase 4-leg converter offers superior feeding of an unbalanced 3-phase load due to an increased bridge arm. This design connects the midpoint of the arm and the neutral point of the 3-phase load to a shared junction, allowing dual current controllers to regulate the negative sequence current path, resulting in a straightforward configuration [6], [7]. However, control over the fourth leg cannot be independent. Contrasted with the 4-leg structure, the split dc-link capacitor converter can also achieve a 3-phase 4-wire configuration, establishing a pathway for neutral current. This significantly enhances the converter's capacity to accommodate unbalanced loads, and the neutral point is clamped at half of the bus voltage through two split dc-link capacitors [8]. In instances where the neutral point voltage remains stable, the split dc-link capacitor 3-phase converter can be considered as three separate single-phase half-bridge converters. Consequently, independent control of the three phases becomes possible, effectively mitigating the issue of output voltage asymmetry caused by unbalanced loads. However, the split dc-link capacitor 3-phase converter faces challenges tied to the division of capacitor voltage. This problem emerges due to the inflow of neutral current into the capacitor or disparities between the two capacitors, which restricts its range of applications. Consequently, a higher capacitance becomes necessary as the degree of load imbalance increases.

In this paper, the comparison of these 3-phase 4-wire converter topologies, including 2-level 4-leg and 3-level 4-wire converters, based on output performance will be discussed in this paper. Various types of switching devices, including both IGBT and MOSFET, are used in these converter topologies to evaluate the output performance.

2. 2-level 3-phase 3-wire converter

The topology of the classical 2-level 3-phase 3-wire is depicted in Fig. 1(a). Within this setup, there exists a dc-source coupled with a 2-level 3-phase converter, which is linked to the load via a LC filter. The 2-level 3-phase converter is comprised of six power semiconductor switches. By proper controlling switching patterns of these devices, the converter can generate ac waveforms of varying frequency and magnitude output currents.

Fig. 1(b) illustrates the output current waveforms of 2-level 3-phase 3-wire converter in experiment using carrier-based pulse-width modulation (CBPWM) method. As is evident, the resultant currents are sinusoidal and evenly distributed.

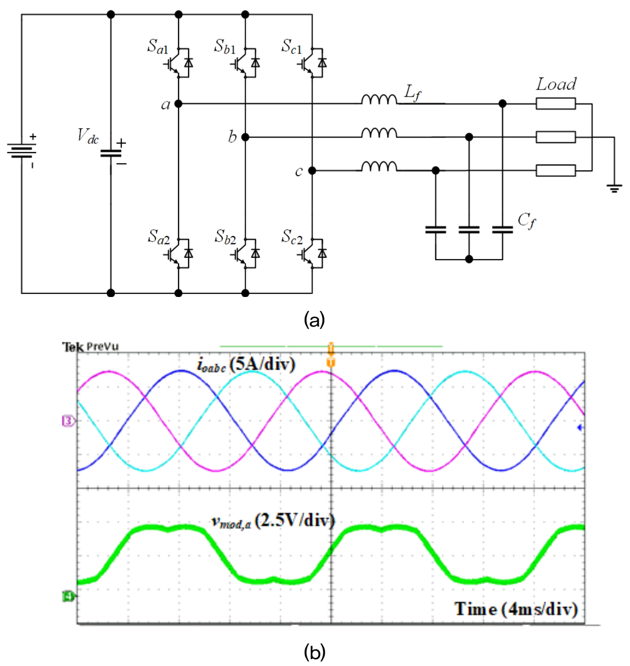


Fig. 1 (a) Typical configuration of 2-level 3-phase 3-wire converter, (b) Experimental waveforms of output current and a-phase modulation signal using CBPWM

As indicated earlier, the conventional 3-phase 3-wire converter does not provide a neutral wire, which makes it cannot accommodate single-phase loads or unbalanced power/load conditions. Additionally, different aging conditions between phase legs of 3-phase converter is a critical issue. When a phase leg is more aging than the remaining one due to uneven stress distribution or manufacturing process, the lifespan of entire converter will be decreased. Prolonging the lifespan of the most aged leg until the next maintenance by reducing the corresponding phase output power is a straightforward active thermal control solution [3], [4]. Here, the most aged leg will be operated with less output power than two remaining legs, as shown in Fig. 2, to improve its lifespan. However, the conventional 3-phase 3-wire converter will suffer potential issues with unbalanced currents and voltages. Hence, the 3-phase 4-wire converters for active thermal control through adjusting phase output power is crucial.

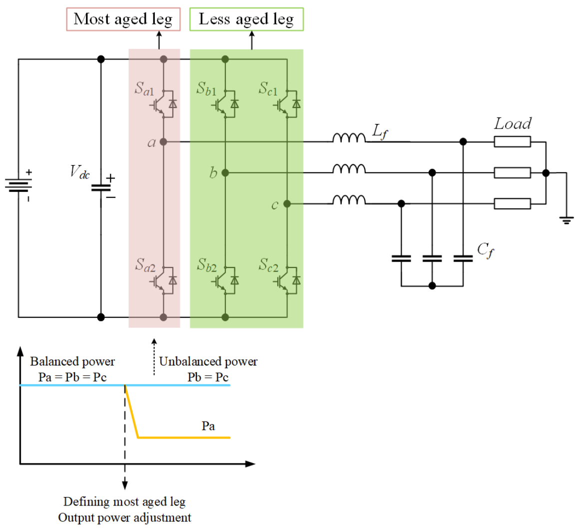


Fig. 2 Different aging conditions and active thermal control technique using different output power in each phase

3. 3-phase 4-wire converter

The first solution is using split dc-link capacitors for 2-level 3-phase converter to form 2-level 4-wire converter, as shown in Fig. 3. It is inherent that the neutral point can be directly connected to the mid-point of split dc-link capacitor. Although owing to the simple structure, this converter lacks feasibility due to the substantial capacitors required for regulating neutral wire current and attaining equal voltage distribution among split capacitors under unbalanced conditions.

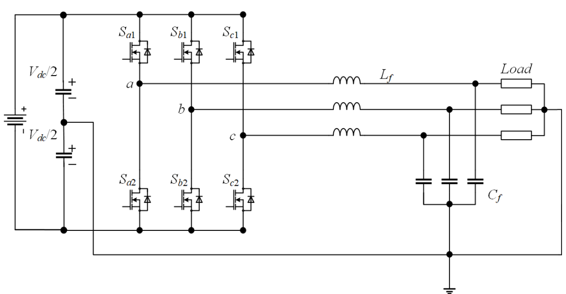


Fig. 3 2-level 3-phase 4-wire converter

Fig. 4 illustrate the configuration of 2-level 4-leg converter. This 2-level 4-leg converter comprises four identical half-bridge converters, forming four converter legs. Phase leg of the 2-level 4-leg converter includes two switch cells and indexed by letters *a*, *b*, *c*, and *f*. S_{x1} and S_{x2} (*x* = *a*, *b*, *c*, *f*) denote the upper and lower switches, respectively. The neutral point of load in the 2-level 4-leg converter is linked to the middle point of the 4^{th}. The ac-side terminal of each leg can be connected to one phase of a 3-phase ac grid or passive load or active load. The operation of switches S_{x1} and S_{x2} (*x* = *a*, *b*, *c*), determines the corresponding phase output voltage. When the upper switch S_{x1} turns ON, the lower switch S_{x2} is turned OFF because of complementary operation, the resulted converter output voltage v_{xf} equal to the dc source voltage V_{dc}. On the other hand, when the upper switch turns OFF, lower switch turns ON, leading to $v_{xf}=0$. In contrast to the 2-level 3-leg converter, the 2-level 4-leg converter offers independent control capability and achieves a greater utilization ratio of the dc-link voltage. Nonetheless, both the quantity of switching components and the expenses associated with the 4-leg converter increase.

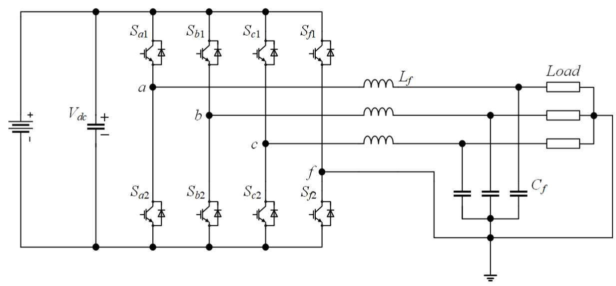


Fig. 4 2-level 3-phase 4-leg converter

In this study, CBPWM method shown in Fig. 5, developed in [9], is adopted to control the 2-level 3-phase 4-leg converter. In this context, the reference voltages, generated by including a suitable offset voltage, are compared to a triangular carrier. This process is identical to the symmetrically arranged 3D space vector PWM (SVPWM). The offset voltage is calculated as follows:

$$v_{fn} = mid\left(-\frac{V_{\max}}{2}, -\frac{V_{\min}}{2}, -\frac{V_{\max}+V_{\min}}{2}\right) \tag{1}$$

where $V_{\min} = \min(v_{af}, v_{bf}, v_{cf})$ and $V_{\max} = \max(v_{af}, v_{bf}, v_{cf})$. v_{af}, v_{bf}, v_{cf} are the reference voltages.

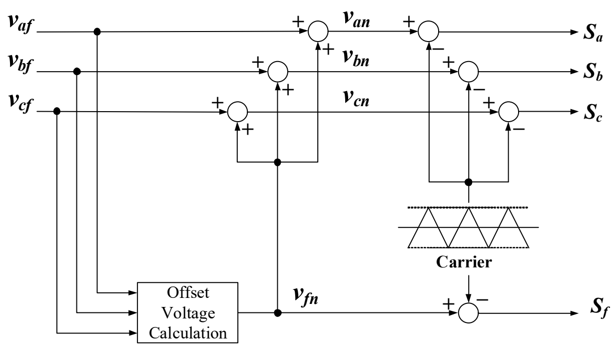


Fig. 5 CBPWM scheme for 2-level 3-phase 4-wire converter

The 3-level neutral-point clamped (NPC) converter is a type of multilevel converter that presents an option for diminishing the count of series connected power switches. As for 3-level NPC, every switching device is required to endure half of the dc-side voltage. This characteristic leads to a decrease in the quantity of switches to be interconnected. Furthermore, the 3-level NPC has the ability to furnish a 3-phase ac voltage exhibiting decreased harmonic distortion in comparison to a comparable 2-level converter. Fig. 6(a) depicts the configuration of a 3-level 4-wire NPC converter. The converter leg $a-$phase is composed of four switches S_{a1} to S_{a4} and two additional diodes, that is, D_{a1} and D_{a2}. The dc-link capacitor is separated to two identical ones. The dc-side midpoint is connected to the 3-level NPC via the clamping diode D_{a1} and D_{a2}. Another topology of the NPC converter is the transistor-clamped converter (TCC) or T-type converter, as shown in Fig. 6(b). The TCC converter employs identical switches to those found in a conventional 2-level converter since the half-bridge switches (S_{x1} and S_{x4}) withstand the whole dc-link voltage. The neutral point and each output terminal are connected by bidirectional switches (S_{x2} and S_{x3}). Different from the half-bridge switches the bidirectional switches withstand only half of the dc-link voltage. In 3-level 4-wire NPC/TCC converter, the neutral point is connected to the mid-point of split dc-link capacitor.

The operating conditions of the 3-level converter can be symbolized using switching states. Switching state [P] signifies that the switches S_{x1} and S_{x2} are at ON-state, resulting in the output pole voltage at $+V_{dc}/2$. Alternatively, switching state [O] designates that the switch S_{x2} and S_{x3} are turned ON, resulting in zero output pole voltage. The state where the switch S_{x3} and S_{x4} are ON, yielding an output pole voltage of $-V_{dc}/2$ is denoted by [N]. The operating status of the switches in the NPC converter and TCC converter are similar. In 3-level converters, the dc-link capacitor voltage balancing is crucial requirement for accurate operation. There are several PWM methods to control the 3-level 3-phase 4-wire converter, such as 3D SVPWM [10], CBPWM with neutral-point (NP) balancing [11], direct PWM [12], and so on.

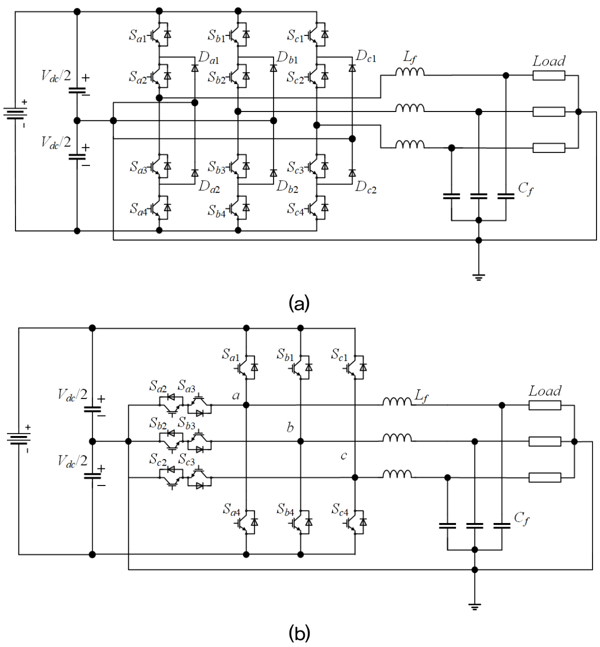


Fig. 6 (a) 3-level 4-wire NPC converter, (b) 3-level 4-wire TCC converter

In CBPWM with NP balancing [11], the neutral point current i_{NP}, which flows from the mid-point of dc-link capacitor voltage to the converter, is adjusted. The NP voltage control is depicted in Fig. 7. The sign of Δv_{np} and output current are identified by two hysteresis loops. If Δv_{np} is small enough, resulting in the sign of Δv_{np} is 0, $m=m_{\max}$. The converter operates with unipolar modulation. As an illustration, in situations where the value of Δv_{np} is extremely low, the balance of dc-link capacitor voltages is already satisfactory. Consequently, there is no necessity to modify the neutral point voltage, and the converter should naturally function with unipolar modulation. Likewise, when the output current is minimal (approaching zero), the supplementary switching associated with NP equilibrium will exert an inconsequential or negligible influence on the NP voltage. Thus, it becomes more energy-efficient for the converter to operate with unipolar modulation, resulting in reduced switching losses. If $v_{C1}>v_{C2}$ means sign of Δv_{np} is 1, and $i_x>0(x=a,b,c)$, the requirement for i_{NP} to be minimized is met, then $m=0$, resulting in bipolar modulation. Generally, when Δv_{np} and i_x have the same sign, $m=0$ to minimize i_{NP}. On the other hand, when Δv_{vp} and i_x have the opposite sign, $m=m_{\max}$ to maximize i_{NP}. The width of the hysteresis band is established at 5%. A broader hysteresis band signifies a higher tolerance for pronounced voltage imbalances, while a narrower hysteresis band necessitates more frequent switching, leading to elevated losses.

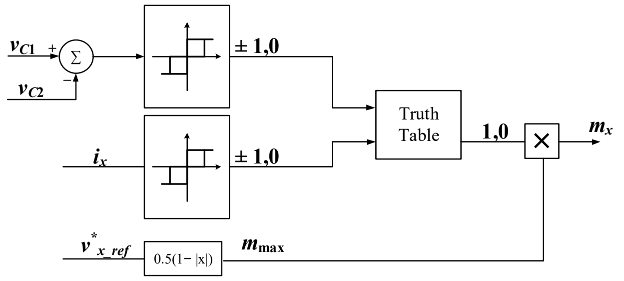


Fig. 7 NP voltage control diagram

The direct PWM approach in [12] involves a straightforward PWM strategy aimed at reconstructing the switching sequence to balance the NP voltage. Here, the duration of switching state [O] is divided into states [P] and [N]. A balancing factor B_x is defined to analyze the Δv_{np} as follows:

$$B_x = \frac{\Delta v_{np}}{|\Delta v_{np}|} i_x \,(x = a,b,c) \tag{2}$$

Following the sign of B_x, the selection of states [P] or [N] will affect the NP voltage. Fig. 8 illustrates the generating new switching sequence process in a-phase to interpret the direct PWM method. When the phase voltage of a-phase $v_{af} > 0$, the original switching sequence consists of only [O] and [P] states. To achieve balance NP voltage, state [N] is added to generate new switching sequence. The new switching sequence includes both three states. The same procedure is applied when $v_{af} < 0$, the new switching sequence is depicted in Fig. 8.

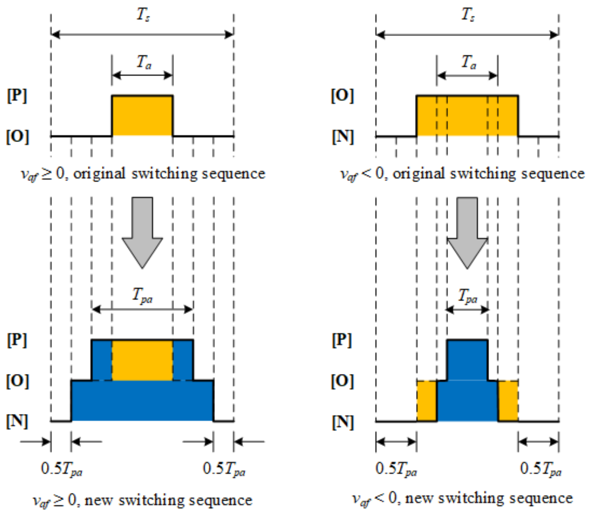


Fig. 8 Generating new switching sequence for NP voltage balancing

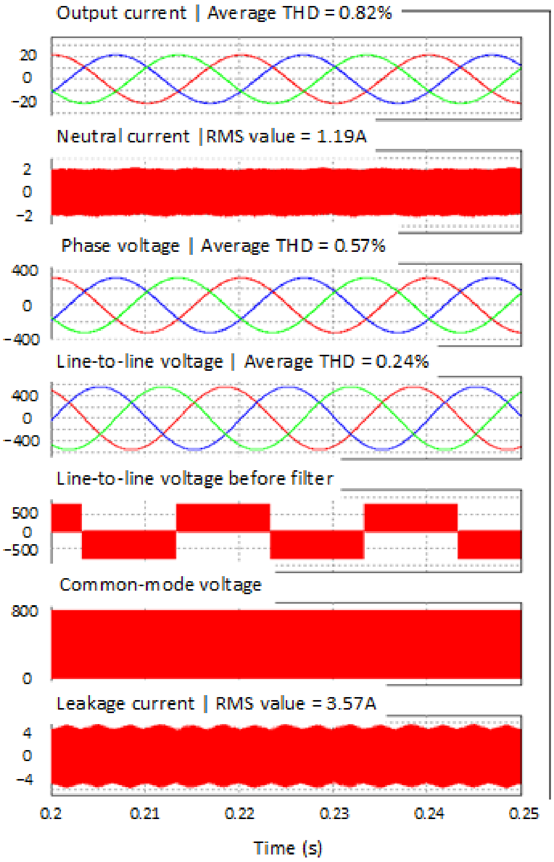
4. Verification results

The waveform of 2-level 4-leg converter and 3-level 4-wire NPC/TCC converter are investigated and verified through PSIM simulation results. The parameter of 2-level 4-leg and 3-level 4-wire converters are listed in Table 1.

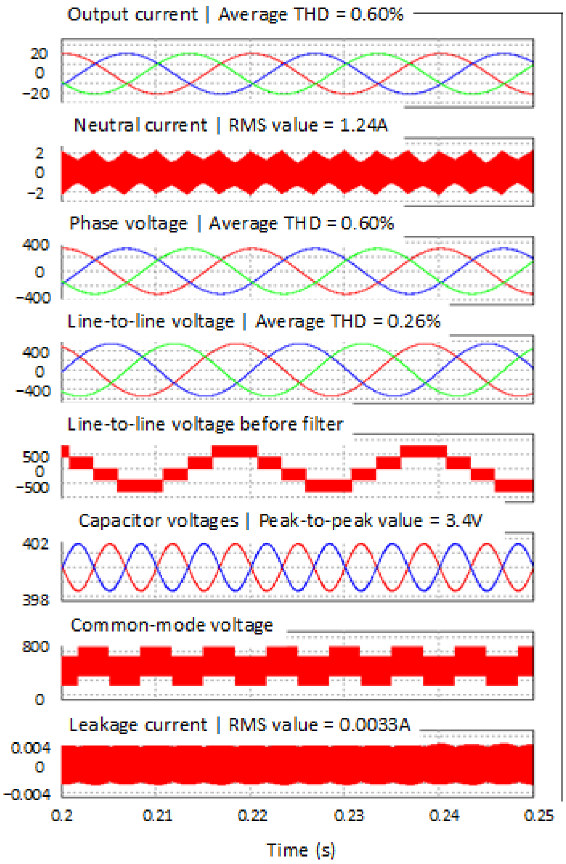
Table 1 Parameters of the 2-level 4-leg and 3-level 4-wire converters

	2-level 4-leg converter	3-level 4-wire converter
dc-link voltage	800V	800V
dc-link capacitance	1400μF	2800μF
Filter inductance	3.5mH	3.5mH
Filter capacitance	4.7μF	4.7μF
Load resistance	15Ω	15Ω
Output power	10kW	10kW
Output voltage	220V	220V
Fundamental frequency	50Hz	50Hz
Switching frequency	15kHz	7.5kHz

Fig. 9 depicts the simulation waveform of 2-level 4-leg converter, 3-level 4-wire NPC and TCC converters under symmetrical operation (P_a = P_b = P_c = 3.3kW). The resulted output currents obtained from three converters are sinusoidal and balanced. The output current of 2-level 4-leg converter has higher average THD than 3-level 4-wire NPC/TCC converters. The line-to-line voltage before filter of 2-level 4-leg converter correctly includes properly three voltage levels, while the 3-level 4-wire NPC/TCC converter includes five levels in line-to-line voltage. Regarding the common-mode voltage (CMV), the CMV of 2-level 4-leg converter ranges from 0 to V_{dc}, whereas the common-mode voltage of 3-level 4-wire NPC/TCC converter ranges from $V_{dc}/3$ to $5V_{dc}/6$. The leakage current in 2-level 4-leg converter is significantly high at RMS value of 3.57A. On the other hand, the corresponding leakage current of 3-level 4-wire NPC/TCC converter is negligible with RMS value at about only 3.3mA due to the link between the neutral load and mid-point of dc-link capacitors. Due to the NP voltage balancing strategy, the capacitor voltages in 3-level 4-wire NPC/TCC converter are balanced with small ripple.



(a)



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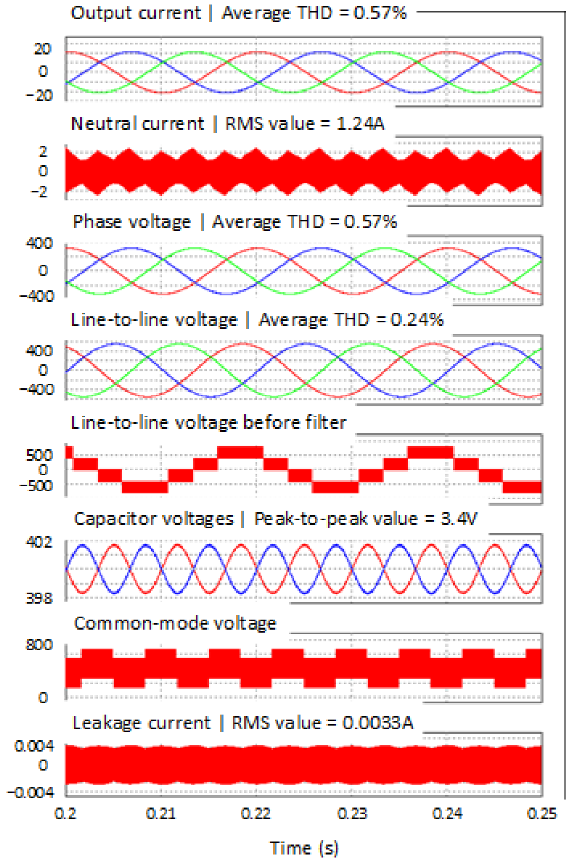
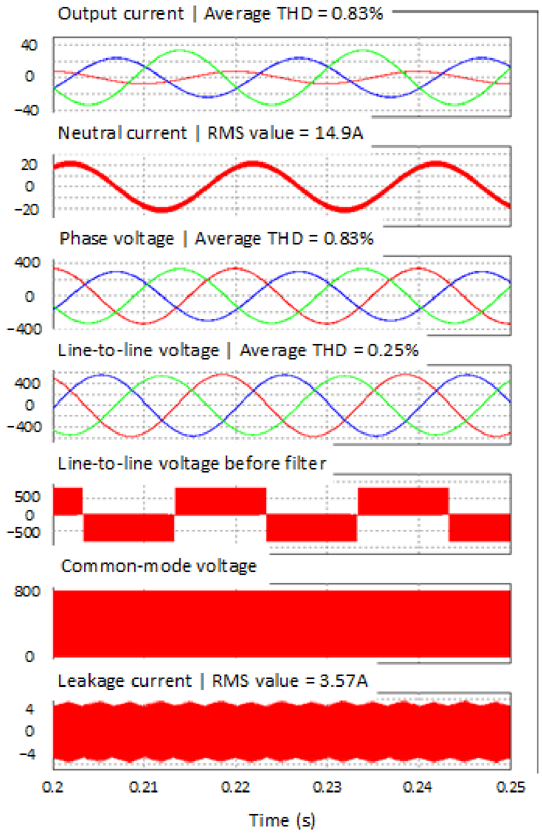


(c)

Fig. 9 simulation waveform of (a) 2-level 4-leg converter, (b) 3-level 4-wire NPC converter, (c) 3-level 4-wire TCC converter in balanced operation

In Fig. 10, the waveform of three converters under asymmetrical operation with different output power in each phase (P_a = 1kW, P_b = 4kW, P_c = 5kW) are presented. Here, the magnitude of output currents changes correspondingly to the output power. Meanwhile, the phase and line-to-line voltages are balanced. In 2-level 4-leg converter, thanks to the 4^{th} leg, the phase and line-to-line voltages are kept balanced with increased THD. As can be seen in 2-level 4-leg converter, the neutral current increases and has sinusoidal form due to the unbalanced output currents. Regarding the CMV and leakage current, they are similar to symmetrical operation. As for 3-level 4-wire NPC/TCC converter, the output current's magnitude changes properly following the output power. Meanwhile, the phase voltage and line-to-line voltage are kept balanced with increased THD value thanks to the neutral connection. The capacitor voltages are maintained in a balanced state around the standard value, with increased peak-to-peak value compared to symmetrical operation. In terms of CMV, the peak value of CMV in 3-level 4-wire NPC/TCC converter increases, but the RMS value of leakage current is the same to that of symmetrical operation. It can



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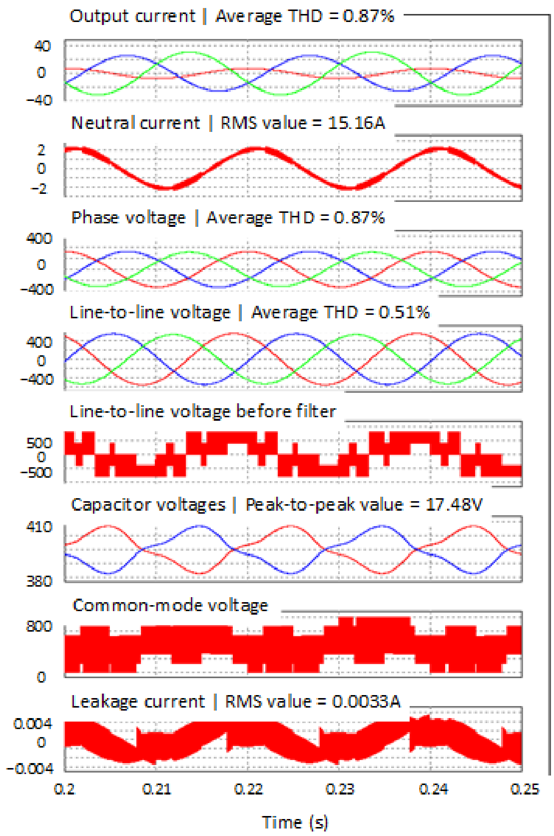

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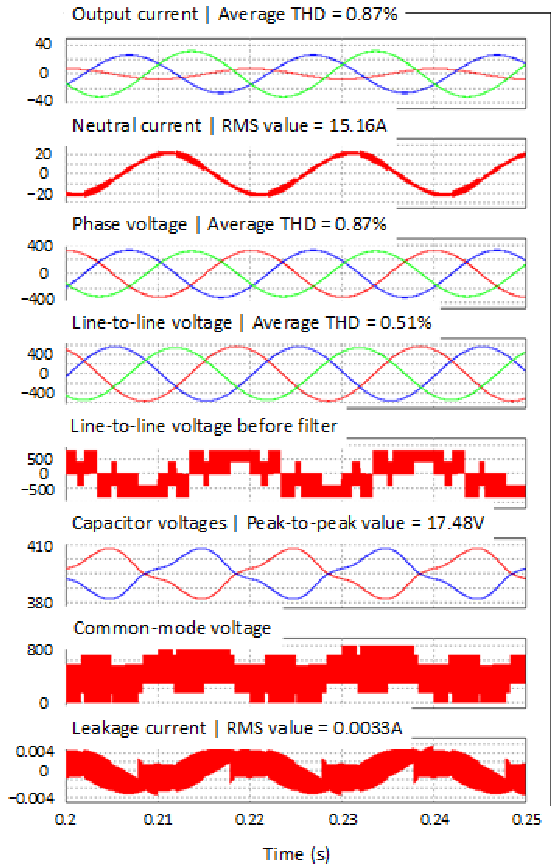


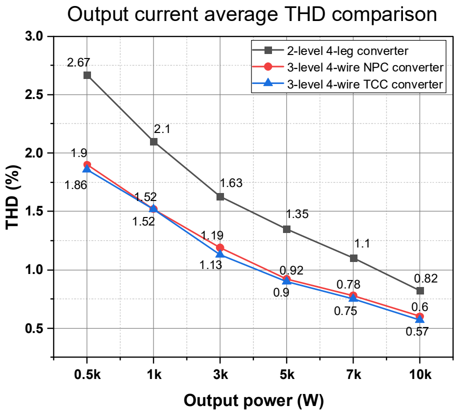
(c)

Fig. 10 Simulation waveform of (a) 2-level 4-leg converter, (b) 3-level 4-wire NPC converter, (c) 3-level 4-wire TCC converter in unbalanced operation

conclude that the 2-level 4-leg converter and 3-level 4-wire NPC/TCC converter operate correctly under asymmetrical operation without degradation in output performance.

5. Performance evaluation

The output performance comparison between 2-level 4-leg converter and 3-level 4-wire NPC/TCC converter are presented in Fig. 11. In Fig. 11(a), the output current average THD value comparison under the change of output power is depicted. It can be seen that the 3-level 4-wire NPC/TCC converter has lower THD value than that of 2-level 4-leg converter by approximately 30%. As for leakage current comparison in Fig. 11(b), the leakage current RMS value of 2-level 4-leg converter does not change under the variation of output power. Meanwhile, the leakage current of 3-level 4-wire NPC/TCC converter increases following the rise of output power, but it is negligible due to the neutral connection.



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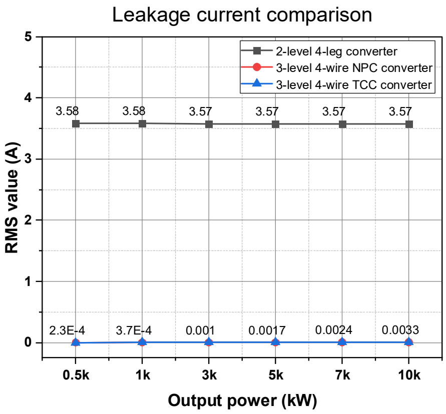
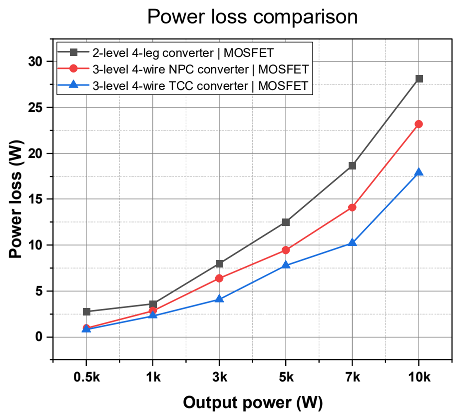


(b)

Fig. 11 Performance comparison between 2-level 4-leg converter, 3-level 4-wire NPC converter, and 3-level 4-wire TCC converter under changes of output power in terms of (a) Output current THD, (b) Leakage current

The performance of 2-level 4-leg converter and 3-level 4-wire NPC and TCC converters using different switching devices as IGBT and MOSFET from different manufacturers, are investigated and evaluated. The SiC MOSFET C3M0021120K [13] with Drain-source voltage of 1200V rating and the Drain-source resistance of 21mΩ, is used for the upper and lower switches of 2-level 4-leg converter and 3-level converter. Because the middle switches of 3-level TCC converter and switches of 3-level NPC converter are only blocking one half dc-link voltage, a SiC MOSFET C3M0025065K [14] with Drain-source voltage of 650V rating is used instead of 1200V rating SiC MOSFET. Additionally, two IGBT modules FS3L25R 12W2H3_B11 [15] and FS3L40R07W2H5F_B11 [16] are used for 3-level 4-wire TCC converter and 3-level 4-wire NPC converter, respectively. The power loss of the converter is calculated by using the Thermal module in PSIM software with different switch types based on the device datasheets. The efficiency is calculated by using only the output power and converter power loss. As can be seen in Fig. 12(a), when using MOSFET, the 3-level 4-wire TCC converter has the lowest power loss, while the 2-level 4-leg converter has the highest power loss. Meanwhile, when using IGBT modules for 3-level 4-wire NPC and TCC converters, at low output power, the power losses of two converters are similar. At high output power, the 3-level 4-wire NPC converter has higher power loss than 3-level 4-wire TCC converter. In Fig. 12(c), the efficiency of three converters using different kinds of power switch under



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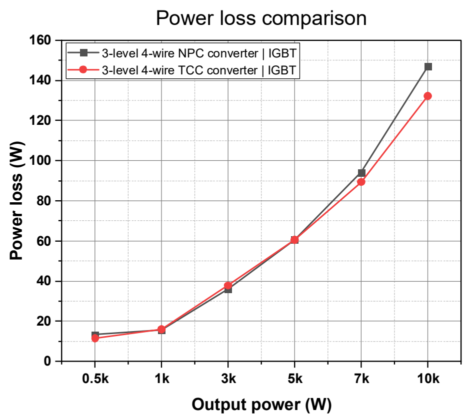

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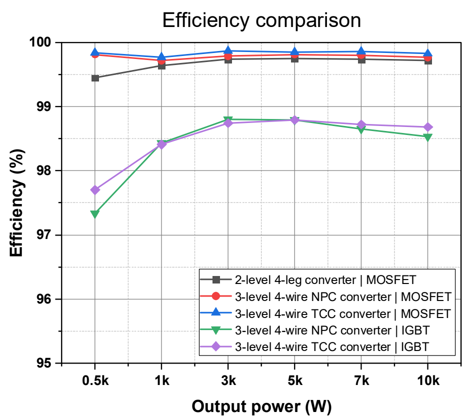

(c)

Fig. 12 Performance comparison between 2-level 4-leg converter, 3-level 4-wire NPC converter, and 3-level 4-wire TCC converter under changes of output power in terms of (a) Power loss comparison when converter uses MOSFET, (b) Power loss comparison when converter uses IGBT, (c) Efficiency comparison the change of output power is presented. The 3-level 4-wire TCC converter using MOSFET has the highest efficiency, while the 3-level 4-wire NPC/TCC converter using IGBT module has the lowest efficiency.

6. Conclusion

In conclusion, the paper contributes to the field of power electronics by offering a comprehensive analysis of various 3-phase 4-wire converters. As can be seen from the performance comparison results, the 3-level 4-wire TCC converter offers the highest efficiency when using MOSFET in power switches compared to 2-level 4-leg converter and 3-level 4-wire NPC converter. The 3-level 4-wire NPC/TCC converter also has low CMV and negligible leakage current composed to 2-level 4-leg converter. However, the control of 2-level 4-leg converter is straightforward to implement in practical systems. The comparative performance evaluation conducted in this study serves as a valuable resource for advancing the design and implementation of efficient and reliable power conversion systems.

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