ISSN 1975-8359 [Print] / ISSN 2287-4364 [Online]
The Transactions of the Korean Institute of Electrical Engineers, vol. 72, no. 10, pp. 1180~1189, 2023
https://doi.org/10.5370/KIEE.2023.72.10.1180

Performance Evaluation of Auxiliary Leg based Three-phase Converters for Independent Output Power Control

독립적 출력 전력 제어가 가능한 보조 레그를 가지는 3상 컨버터들의 성능 평가 연구

Minh Hoang Nguyen · Sangshin Kwak
응웬 민 호앙* · 곽상신†

Abstract

This paper presents a comprehensive performance evaluation of a 3-phase 4-wire converter integrated with an auxiliary circuit designed for active thermal control techniques. This study starts by presenting an introduction to the importance of 3-phase 4-wire converters in power systems and their application in active thermal control technique based on per-phase control, which can extend the lifespan of particular phase leg or facilitate operation under uneven conditions. Additionally, the purpose and importance of auxiliary circuit is discussed in 3-phase 4-wire converter system. The examined converter systems includes 2-level and 3-level converters. To assess the converter's performance, a series of simulations were conducted using different output power in both balanced and unbalanced conditions. The results of these evaluations demonstrate the effectiveness of the 3-phase 4-wire converters with auxiliary circuit in active thermal control using different phase output powers. Comparative analyses are provided to highlight performance evaluation between various 3-phase 4-wire converter with auxiliary circuit using different switching devices.

Key Words

3-phase 4-wire, active thermal control, auxiliary circuit, NPC, TCC

1. Introduction

Because it is an essential element of distributed power supply, the 3-phase converter is anticipated to have the ability to manage an uneven load when operating independently and provide a consistent alternating current voltage [1]. Moreover, an additional concern arises from the varying wear-out conditions in each phase of the converter. The most straightforward approach for active thermal control involves reducing the converter's switching frequency to minimize the commutation events, which in turn extends the converter's lifespan [2]. Nevertheless, this resolution diminishes the converter's output performance. An alternative uncomplicated implementation involves varying the output power in each phase, but this necessitates a precise converter topology to ensure precise operation [3]. 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.

The growing utilization of power semiconductor devices is widely recognized as a source of significant challenges within the power systems. These components serve a crucial role in converters, however they are also notably vulnerable components [4]. Consequently, the reliability of power converters is substantially influenced by the performance of these power semiconductor components, necessitating the establishment of high-reliability standards for power converters. However, these active thermal control (ATC) approaches overlook the fact that the phase legs of converters can age differently. This discrepancy can result in variations in component quality and aging states. To enhance the performance of 3-phase converters, the allocation of electricity to phase legs is adjusted according to corresponding aging state. The primary objective is to minimize or delay any potential failures. The aging state can be monitored, as referenced in [5] and [6], and power is allocated accordingly. This means that phase legs with more advanced aging states receive less

† Corresponding Author : School of Electrical and Electronics Engineering, Chung-Ang University, Korea
E-mail: sskwak@cau.ac.kr
https://orcid.org/0000-0002-2890-906X
* School of Electrical and Electronic Engineering, Chung-Ang University, Korea.
https://orcid.org/0000-0003-1784-0842
Received: Sep. 12, 2023 **Revised:** Sep. 22, 2023 **Accepted**: Sep. 24, 2023

power or, in some cases, no power at all. This approach effectively postpones power-related failures in the phase legs, a situation analogous to unbalanced load conditions in real-world scenarios [7], [8].

Concerning 3-phase 3-wire converters, they are typically employed to supply power to balanced 3-phase loads. However, due to the absence of a mechanism for compensating for unbalanced currents, instances of uneven loads can lead to unequal voltage levels across the load's phases. During significant imbalances, the phase voltage across a load could approach the line voltage, which can be hazardous. In contrast, the 3-phase 4-wire system is capable of providing power to both evenly distributed 3-phase loads and those that are not balanced, including single-phase loads. Incorporating a neutral wire provides a route for handling uneven currents, enabling the 3-phase 4-wire converter to effectively handle the neutral current resulting from unbalanced loads or disturbances in the power grid. Furthermore, the 3-phase 4-wire system provides the ability to function with varying output power levels in each phase. This feature is well-suited for per-phase control to extend the lifespan of the most aged leg in the converter. Consequently, 3-phase 4-wire converters offer a significant advantage over their 3-phase 3-wire counterparts [9]. There are two primary configurations for enhancing the power quality of a 3-phase converter when it operates under unbalanced conditions. The 3-phase 4-leg converter proves to be more efficient in supplying power to a 3-phase unbalanced load compared to 3-phase converter. This efficiency arises since the connection between neutral point of load and additional leg, allowing for dual current controllers to manage the negative sequence current path. This topology is relatively straightforward [10], [11]. However, it's worth noting that this configuration may encounter electromagnetic compatibility issues with the neutral point due to susceptibility to high-frequency voltage transitions. Additionally, the control system for the fourth leg is complex and cannot operate independently, making controller development challenging [12]. Alternatively, the 3-phase converter with split dc-link capacitor can form 3-phase 4-wire configuration by connecting the midpoint of dc-link capacitor and neutral point of load. This setup enhances the ability of handling unbalanced loads in 3-phase converters [13], [14]. This feature allows for independent control of the three phases, effectively mitigating output voltage imbalances caused by unbalanced loads [15]. However, there is a limitation associated with this configuration: the unbalanced capacitor voltages restrict its applicability. As the degree of load imbalance increases, a higher capacitance is required. In summary, both the 3-phase 4-leg converter and the split dc-link capacitor 3-phase converter have their own advantages and disadvantages within power systems. To address the drawbacks of previous 3-phase 4-wire converters, an auxiliary circuit is introduced in the 3-phase 4-wire converter, combining aspects of both configurations, namely the additional leg. By managing neutral current, the auxiliary circuit can regulate capacitor voltages and minimize voltage fluctuations [16] - [18]. The auxiliary circuit reduces the need for high-capacity dc-link capacitors. Additionally, the connection between the neutral load and the midpoint of the dc-link capacitors helps to reduce ground-related voltage’s ripple, thus significantly decreasing leakage current.

This paper will give a comparison of these 3-phase 4-wire converter with auxiliary circuit topologies, specifically 2-level and 3-level converters, based on their output performance. Various kinds of switching components, encompassing both IGBTs and MOSFETs, have been employed in these converter configurations to assess their corresponding performance.

2. Conventional 3-phase 4-wire converter

As previously mentioned, the 3-phase 4-wire converter is even responsible for driving both single-load or 3-phase load. Practically, the 3-phase load might be unbalanced, leading to varying aging state on each phase leg of the converter, ultimately affecting its overall lifespan. To address the issue of differing remaining lifespan among these phase legs, hence, a need of ATC technique arises, which is relies on individual phase control. This strategy aims to prolong the lifespan of the more aged phase legs by ensuring they operate efficiently until the next maintenance cycle, minimizing their stress compared to the others. In Fig. 1(a), we can observe a scenario where phase leg a is the most aged, signifying that it has a shorter remaining lifespan compared to phase legs b and c. To alleviate the aging effects on phase leg a, the corresponding output power can be reduced, as illustrated in Fig. 1(a). This reduction of output power decreases the thermal stress experienced by the corresponding power switches, resulting in an extension of its operational lifespan. In Fig. 1(b), a situation different aging states between three legs is depicted, leading to variations in their respective power outputs.

The initial approach involves the utilization of divided DC-link capacitors in the 2-level 3-phase converter to create a 2-level 4-wire converter, illustrated in Fig. 2(a). Naturally, the neutral point can be directly linked to the midpoint of the divided

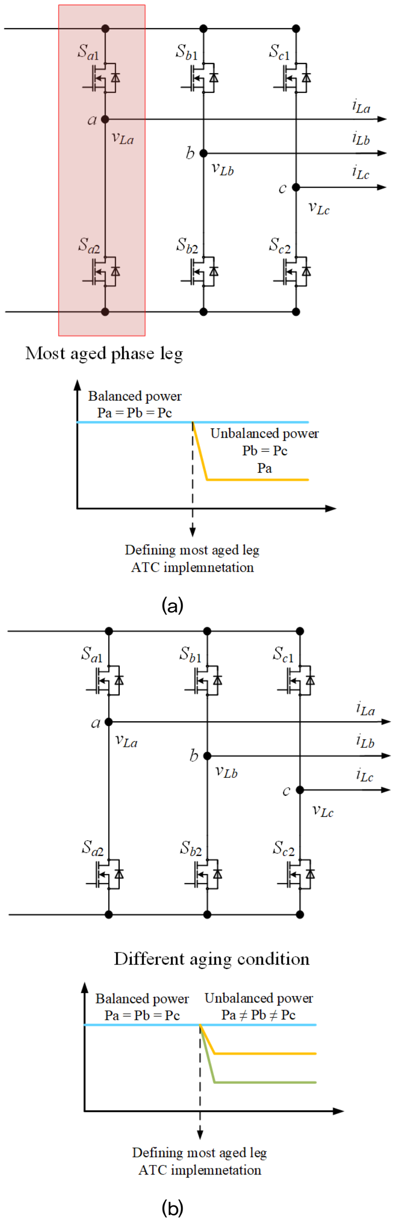


Fig. 1 Phase output power adjustment following aging state (a) The most aged leg is phase a (b) Three phase legs have different aging states.

dc-link capacitor. However, despite its straightforward design, this converter lacks practicality due to the significant capacitors needed to control neutral wire current and achieve balanced voltage distribution across the split capacitors in unbalanced situations. Fig. 2(b) depicts the setup of a 2-level 4-leg converter. This particular 2-level 4-leg converter consists of four identical half-bridge converters, thereby creating four converter legs. Each phase leg of the 2-level 4-leg converter comprises two power switches, represented by *a*, *b*, *c*, and *f*. S_{x1} and S_{x2} (x = a, b, c, f) represent the upper switch and lower switch, respectively. The neutral point of load and the middle point of the 4^{th} leg are connected. Unlike the 2-level 3-leg converter, the 2-level 4-leg converter provides autonomous control capabilities and attains a higher utilization ratio of the dc-link voltage. However, it's important to note that both the number of switching components and the associated costs for the 4-leg converter go up.

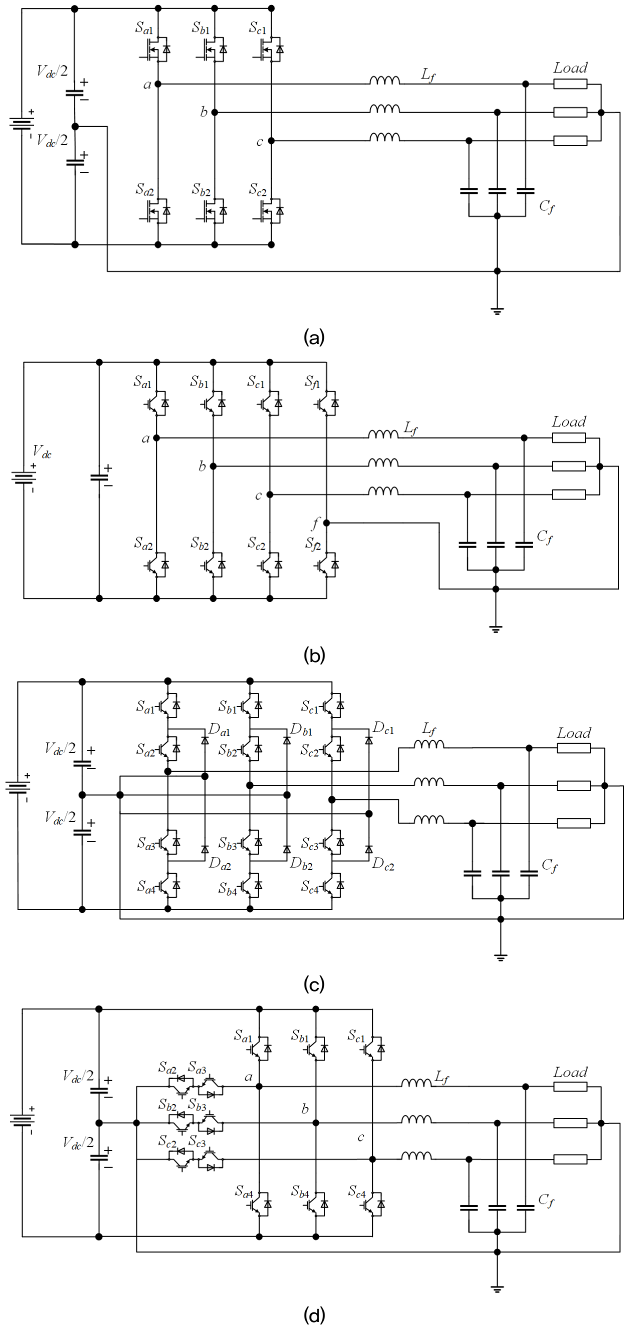


Fig. 2 Conventional 3-phase 4-wire converter (a) 2-level 4-leg converter (b) 2-level 4-wire converter with split dc-link, (c) 3-level 4-wire NPC converter, (d) 3-level 4-wire TCC converter.

3. 3-phase 4-wire converter with auxiliary circuit

For the effective operation of 3-phase 4-wire converters, the balancing of capacitor voltages must be maintained. Hence, a auxiliary circuit is added to 3-phase 4-wire converters to reduce the ripple in dc-link voltages. Moreover, the dc-link capacitor values are reduced using the auxiliary circuit. The configuration of the 2-level/3-level 3-phase 4-wire converter with an auxiliary circuit is illustrated in Fig. 3(a) - (c). This system comprises a dc-link, a 2-level/3-level 3-phase converter, and an auxiliary circuit. In contrast to the conventional 2-level/3-level 3-wire converter, this setup connects the neutral point of the load to the midpoint of the DC-link capacitors. As shown in Fig. 3, the 2-level/3-level converter receives power from a dc voltage source supplied by various distributed sources like fuel cells, photovoltaic devices, and wind turbines. The converter's outputs are connected to a 3-phase filter and the load. The auxiliary circuit consists of two switches (referred to as S_{r1} and S_{r2}), an auxiliary circuit inductor denoted as L_N and two capacitors, labeled as C_1 and C_2, as indicated in Fig. 3. This auxiliary circuit is used to maintain the stability of the capacitor voltages through controlling S_{r1} and S_{r2}. The 3-phase 4-wire converter with the auxiliary circuit has the following advantages: the capacitance of the split dc-link capacitors can be significantly reduced, the common-mode current/leakage current from the neutral point to the ground is eliminated, and the control of the auxiliary circuit is independent of the control of the 3-phase converter.

Because the 2-level/3-level 4-wire converter can be considered as three identical single-phase half-bridge circuit, the per-phase control strategy can be directly implemented. The per-phase voltage current control includes two parts as the dq- conventional voltage current control, as shown in Fig. 4. The voltage and

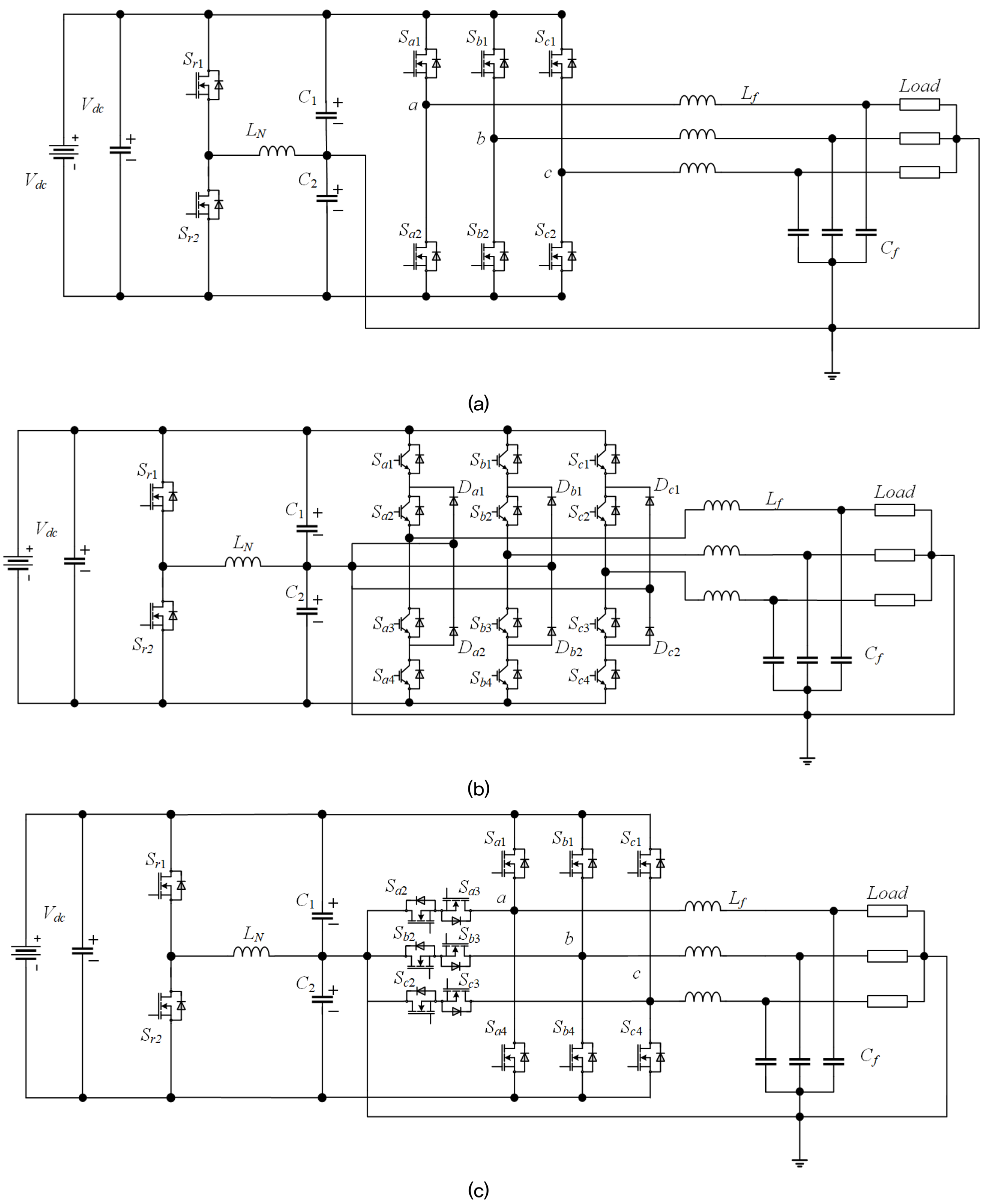


Fig. 3 Configuration circuit of the 3-phase 4-wire converter with auxiliary circuit (a) 2-level 4-wire converter, (b) 3-level 4-wire NPC converter (c) 3-level 4-wire TCC converter.

current control are implemented for each phase instead of both three phases. This allows generating different output power for each phase. Furthermore, in order to reduce the complexity of the controller, the modified proportional-integral (PI) controller, as shown in Fig. 4, is implemented to control directly the phase voltage and current. Equations (1) and (2) describe the modified PI voltage and current controller in s-domain, respectively. In that equations,

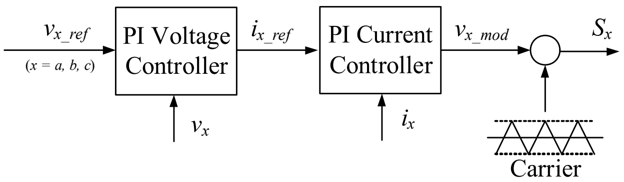


Fig. 4 Control of converter using voltage-current control based PI controllers.

$$i_{x.ref} = (v_{x.ref} - v_x)\times\left(K_{p.v} + \frac{K_{i.v}}{s}\times sign(v_{x.ref})\times v_{x.ref.unity}\right) \quad (1)$$

$$v_{x.mod} = (i_{x.ref} - i_x)\times\left(K_{p.i} + \frac{K_{i.i}}{s}\times sign(v_{x.ref})\times v_{x.ref.unity}\right) \quad (2)$$

In Fig. 5, it can observe the control diagram for the auxiliary circuit. Here, the voltage difference between the reference capacitor voltage and the lower capacitor voltage is regulated by a PI controller. Equation (3) describe the PI voltage controller in s-domain of capacitor voltage balancing task. The objective of this controller is to balance the capacitor voltages while producing the switching signals for the auxiliary circuit. On the other hand, the switching pattern for the auxiliary circuit can be also easily generated using a 50% duty cycle PWM for straightforward implementation.

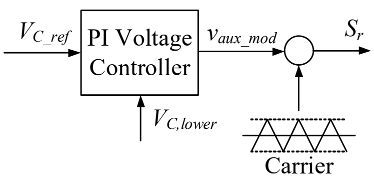


Fig. 5 Control of auxiliary circuit based PI controller.

$$v_{aux.mod} = (V_{Cref} - V_{Clower})\times\left(K_{p.vc} + \frac{K_{i.vc}}{s}\right) \quad (3)$$

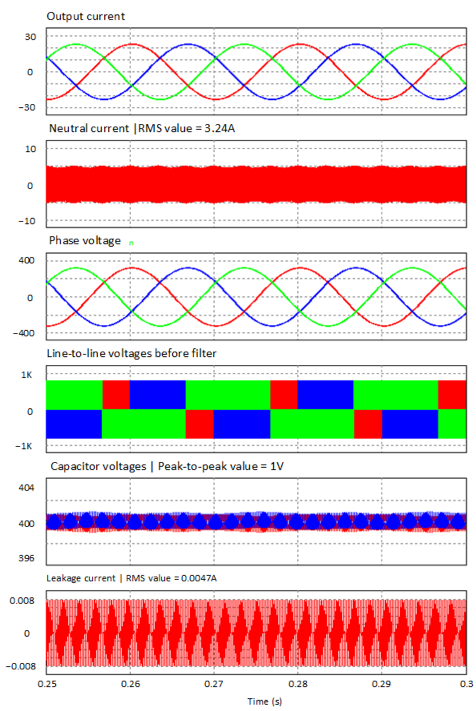
4. Performance comparison results

The performance comparison of 2-level 4-wire converter and 3-level 4-wire NPC/TCC converters using auxiliary circuit are investigated and verified through PSIM simulation results. The parameter of 2-level 4-wire and 3-level 4-wire converters using auxiliary circuit are listed in Table 1.

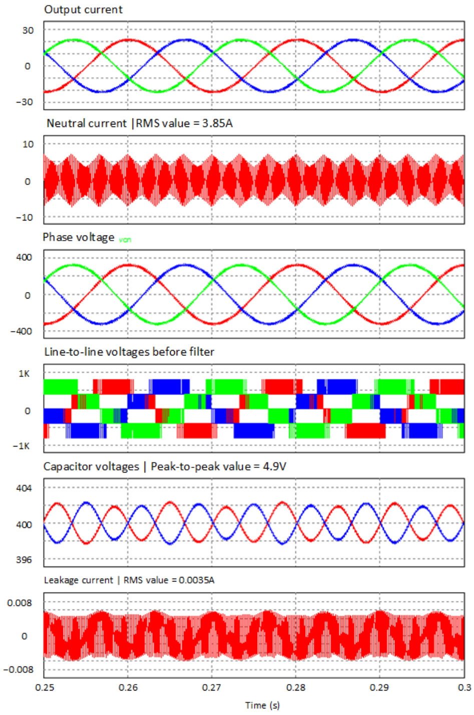
Table 1 2-level 4-leg and 3-level 4-wire converters with auxiliary circuit parameters.

	2-level 4-wire converter with auxiliary circuit	3-level 4-wire converter with auxiliary circuit
dc-link voltage	800V	800V
dc-link capacitance	200μF	200μF
Auxiliary circuit inductance	1m	1m
Output inductance	3.5mH	3.5mH
Output capacitance	4.7μF	4.7μF
Load resistance	15Ω	15Ω
Power	10kW	10kW
Phase voltage	220V	220V
Fundamental frequency	50Hz	50Hz
Switching frequency	10kHz	5kHz

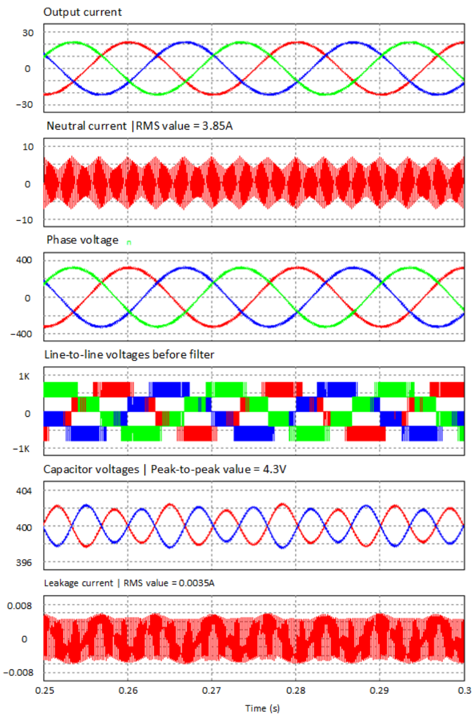
Fig. 6 depicts the simulation waveform of 2-level 4-wire converter, 3-level 4-wire NPC and TCC converters using auxiliary circuit under symmetrical operation (P_a = P_b = P_c = 3.3kW). The obtained result of output currents from all three converters exhibit a sinusoidal and balanced waveform. Prior to filtering, the line-to-line voltage of the 2-level 4-wire converter correctly comprises three distinct voltage levels, whereas the 3-level 4-wire NPC/TCC converter encompasses five levels in its



(a)



(b)



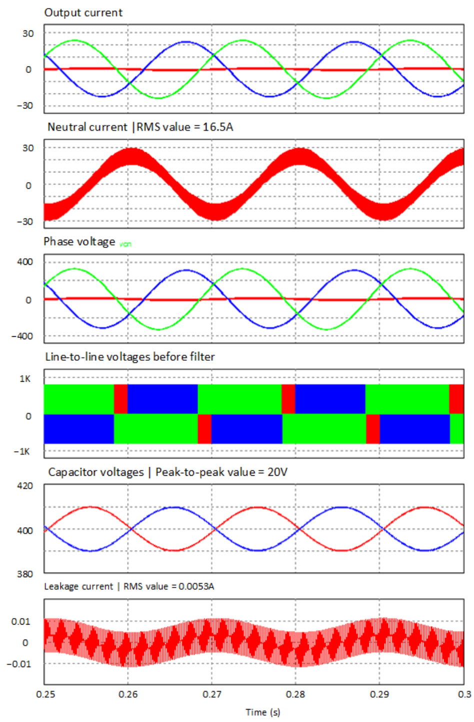
(c)

Fig. 6 Simulation waveform of (a) 2-level 4-wire converter, (b) 3-level 4-wire TCC converter, (c) 3-level 4-wire NPC converter under balanced operation (P_a = P_b = P_c = 3.3kW).

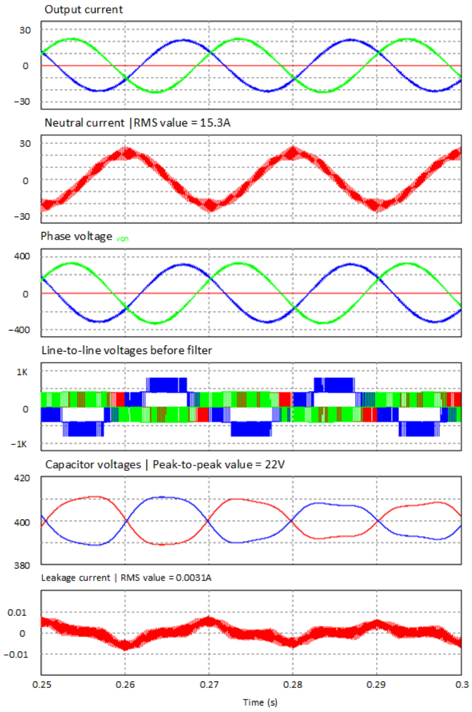
line-to-line voltage. The leakage current in 2-level 4-wire converter and 3-level 4-wire NPC/TCC converter are minor with rms value at approximately 4.7mA and 3.3mA, respectively, due to the neutral connection line. As can be seen. the dc-link capacitor voltages in both 2-level 4-wire and 3-level 4-wire converters are kept balance. The capacitor voltages in 2-level 4-wire converter has lower ripple than that of 3-level 4-wire converter.

In Fig. 7, it can observe the waveforms of three converter when they are operated asymmetrically with varying output power in each phase (P_a = 0kW, P_b = P_c = 3.3kW) are presented. Here, the magnitude of output currents and output voltages change correspondingly to the output power. Thanks to the neutral line, the output currents in phase b and c in both 2-level 4-wire and 3-level 4-wire converters are correct in terms of phase and magnitude. Meanwhile, the resulted neutral current contains sinusoidal component and increased magnitude of rms value. Regarding leakage current, they are similar to symmetrical operation. In both the 2-level 4-wire and 3-level 4-wire converters, the capacitor voltages are kept in a balanced condition close to the standard value, thanks to the auxiliary circuit. However, during asymmetrical operation, the peak-to-peak value of these voltages is higher compared to symmetrical operation. Consequently, it can be inferred that both the 2-level 4-wire converter and the 3-level 4-wire NPC/TCC converter function properly under asymmetrical conditions without any decline in their output performance.

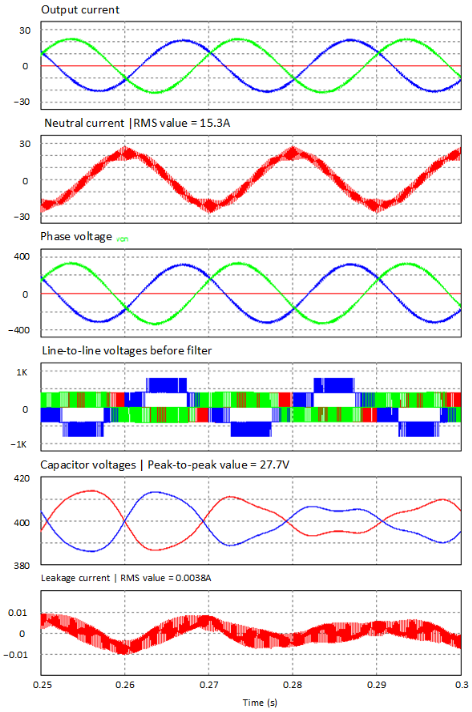
A down-scaled experimental prototype of 2-level 4-wire converter with auxiliary circuit is used to verify the control algorithm and operation of converter system. Fig. 8 shows the experimental waveforms of 2-level 4-wire converter with auxiliary circuit under both balanced and unbalanced conditions.



(a)



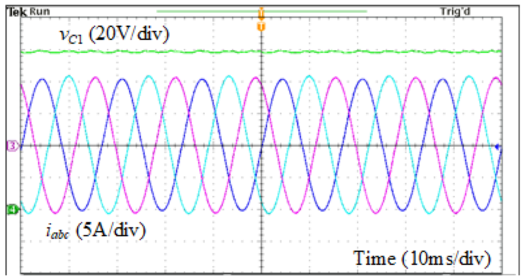
(b)



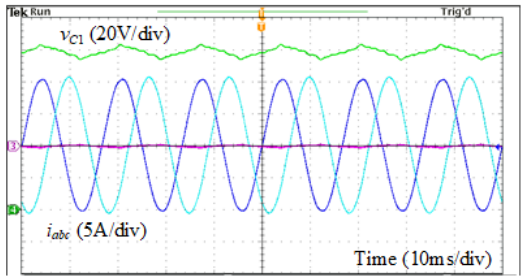
(c)

Fig. 7 SSimulation waveform of (a) 2-level 4-wire converter, (b) 3-level 4-wire TCC converter, (c) 3-level 4-wire NPC converter under unbalanced operation (P_a = 0kW, P_b = P_c = 3.3kW).

As can be seen in Fig. 8(a), under the balanced conditions, the output currents of 2-level 4-wire converter with auxiliary circuit are sinusoidal and balanced. The magnitude of upper capacitor voltage is correct to the nominal value with small ripple. Meanwhile, the waveform of 2-level 4-wire converter with auxiliary circuit under asymmetrical operation with different output power in each phase (P_a = 0kW, P_b = P_c = 0.5kW) are presented, as shown in Fig. 8(b). It can be seen that, the output current of phase a equals to zero, whereas the output current of phase b and c are correct in terms of phase and magnitude. Under unbalanced condition, the capacitor voltage has bigger voltage ripple than balanced condition. It is identical to simulation results, which verifies the correctness of control algorithm and operation of 2-level 4-wire converter with auxiliary circuit.



(a)



(b)

Fig. 8 Experimental waveforms of 2-level 4-wire converter with auxiliary circuit under (a) Balanced condition (P_a = P_b = P_c = 0.5kW). (b) Unbalanced condition (P_a = 0kW, P_b = P_c = 0.5kW).

Fig. 9 illustrate the leakage current comparison between 2-level 4-wire converter with auxiliary circuit and 3-level 4-wire converter with auxiliary circuit under the change of output power. As can be seen from Fig. 6, the leakage current in 4-wire converter is negligible due to the neutral line connection. As shown in Fig. 9, the leakage current of 2-level 4-wire converter with auxiliary circuit is higher than that of 3-level 4-wire converter with auxiliary circuit. However, the leakage current of 2-level 4-wire converter with auxiliary circuit does not change under the increase of output power. Meanwhile, the leakage current of 3-level 4-wire converter increases as the output power increases.

The study examines and assesses the performance of 2-level 4-wire converters and 3-level 4-wire NPC and TCC converters, all equipped with auxiliary circuits. These converters employ various switching devices, including IGBTs and MOSFETs

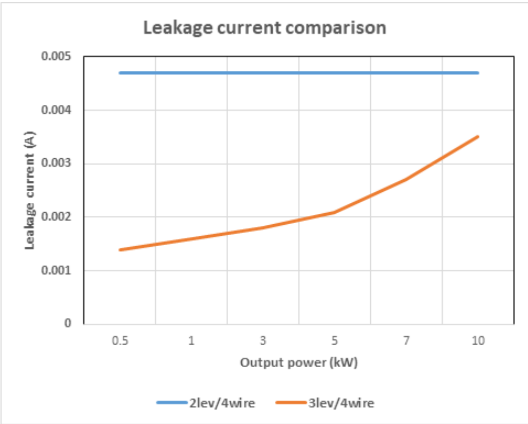


Fig. 9 Leakage current comparison between 2-level 4-wire and 3-level 4-wire converters.

sourced from different manufacturers. The SiC MOSFET C3M0021120K [19] is used for the upper and lower switches of 2-level 4-wire converter and 3-level converter. Since the middle switches in the 3-level TCC converter and the switches in the 3-level NPC converter only need to block half of the dc-link voltage, a SiC MOSFET (C3M0025065K) [20] with a 650V rating is employed instead of a SiC MOSFET with 1200V rating. Additionally, two IGBT modules FS3L25R12W2H3_B11 [21] and FS3L40R07W2H5F_B11 [22] are used for 3-level 4-wire TCC converter and 3-level 4-wire NPC converter, respectively. The converter's power loss is determined by utilizing the Thermal module within the PSIM software, and this is done using various types of switches, guided by the specifications provided in the device datasheets. The comparison of auxiliary circuit power loss is depicted in Fig. 10. It can be seen that the auxiliary circuit using IGBT has significantly high power loss compared to that of MOSFET in this study. The auxiliary circuit loss using MOSFET is about seven times lower than that of IGBT.

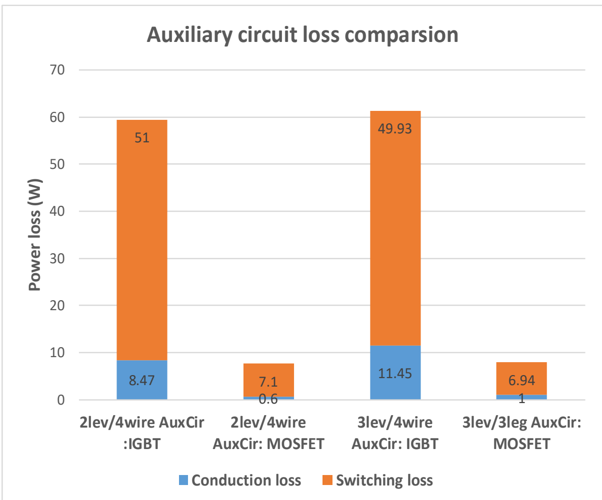


Fig. 10 Auxiliary circuit loss comparison between using IGBT and MOSFET.

The efficiency comparison between 2-level 4-wire converter and 3-level 4-wire converter with auxiliary circuit using different power switches is depicted in Fig. 10. As can be seen in Fig. 11(a) and (b), when using MOSFET in converter part, the 3-level 4-wire TCC converter has the highest efficiency with IGBT auxiliary circuit or MOSFET auxiliary circuit. Meanwhile, the 3-level 4-wire converters using IGBT in converter part have the lowest efficiency. It can be realized that, the system using MOSFET in both auxiliary circuit and converter circuit has the lowest power loss and the highest efficiency.

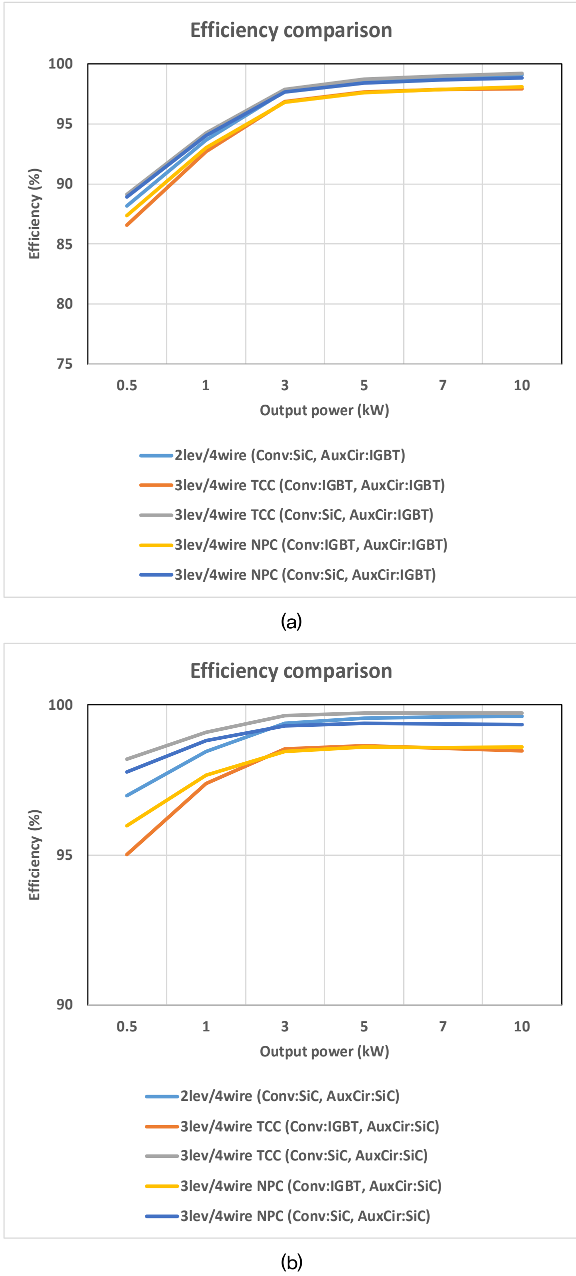


Fig. 11 Efficiency comparison between 2-level 4-wire converter using auxiliary circuit and 3-level 4-wire TCC/NPC converter using auxiliary circuit under changes of output power (a) Auxiliary circuit using IGBT, (b) Auxiliary circuit using MOSFET.

5. Conclusion

In summary, this paper makes a contribution to the field of power electronics by conducting a comprehensive comparison of various 3-phase 4-wire converters with auxiliary circuit. The performance comparison results reveal that, when MOSFETs are employed in power switches, the 3-level 4-wire TCC converter with an auxiliary circuit exhibits superior efficiency compared to both the 2-level 4-wire converter and the 3-level 4-wire NPC converter. The introduction of an auxiliary circuit into the 3-phase 4-wire converter effectively maintains the balance of capacitor voltages and concurrently reduces the required dc-link capacitance. Simulation results demonstrate that implementing ATC strategies, which involve adjusting phase output power in the 3-phase 4-wire converter with an auxiliary circuit, can be achieved without compromising output performance.

Acknowledgements

이 논문은 정부(과학기술정보통신부)의 재원으로 한국연구재단(No. 2020R1A2C1013413) 및 2021년도 정부(과학기술정보통신부)의 재원으로 한국연구재단-기후변화대응기술개발사업(2021M1A2A2060313)의 지원을 받아 수행된 연구로서, 관계부처에 감사드립니다

References

[1] L. L. Freris and D. G. Infield, Renewable energy in power systems, Second edition. Hoboken: Wiley, 2020.

[2] E. F. Fuchs and M. A. S. Masoum, Power conversion of renewable energy systems. New York [u.a.]: Springer, 2011.

[3] M. H. Rashid, Ed., Electric renewable energy systems. Amsterdam: Elsevier/AP, Academic Press is an imprint of Elsevier, 2016.

[4] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, “An Industry-Based Survey of Reliability in Power Electronic Converters,” in IEEE Transaction on Industrial Application, vol. 47, no. 3, pp. 1441−1451, May 2011.

[5] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner, “Condition Monitoring for Device Reliability in Power Electronic Converters: A Review,” in IEEE Transaction on Power Electronics, vol. 25, no. 11, pp. 2734−2752, Nov. 2010.

[6] P. Ghimire, A. R. de Vega, S. Beczkowski, B. Rannestad, S. Munk-Nielsen, and P. Thogersen, “Improving Power Converter Reliability: Online Monitoring of High-Power IGBT Modules,” in EEE Industrial Electronics Magazine, vol. 8, no. 3, pp. 40−50, Sep. 2014

[7] G. Carrasco, C. A. Silva, R. Pena, and R. Cardenas, “Control of a Four-Leg Converter for the Operation of a DFIG Feeding Stand-Alone Unbalanced Loads,” in IEEE Transaction on Industrial Electronics, vol. 62, no. 7, pp. 4630−4640, Jul. 2015.

[8] Y. Sun, J. Li, Z. Yin, and K. Zhu, “The Impact Analysis of Various Unbalance Factors on the PCC Voltage Imbalance,” in 2014 IEEE Electrical Power and Energy Conference, Calgary, AB, Canada, Nov. 2014, pp. 23−28.

[9] M.H. Nguyen and S. Kwak, "Comparative Study of 3-phase 4-wire Converter Topologies for Active Thermal Control Techniques," Transactions of the Korean Institute of Electrical Engineering, vol. 72, no. 9, pp. 1066-1075, 2023.

[10] Z. Liu, J. Liu, and J. Li, “Modeling, Analysis, and Mitigation of Load Neutral Point Voltage for Three-Phase Four-Leg Inverter,” in IEEE Transaction on Industrial Electronics, vol. 60, no. 5, pp. 2010−2021, May 2013.

[11] S.-J. Chee, S. Ko, H.-S. Kim, and S.-K. Sul, “Common-Mode Voltage Reduction of Three-Level Four-Leg PWM Converter,” in IEEE Transaction on Industrial Applications, vol. 51, no. 5, pp. 4006−4016, Sep. 2015.

[12] J. P. R. A. Mello, C. B. Jacobina, and M. B. de Rossiter Correa, “Three-Phase Four-Wire Inverters Based on Cascaded Three-Phase Converters With Four and Three Legs,” in IEEE Transaction on Industrial Applications, vol. 53, no. 6, pp. 5539−5552, Nov. 2017.

[13] M. Aredes, J. Hafner, and K. Heumann, “Three-phase four-wire shunt active filter control strategies,” in IEEE Transaction on Power Electronics, vol. 12, no. 2, pp. 311−318, Mar. 1997.

[14] P. Verdelho and G. D. Marques, “Four-wire current-regulated PWM voltage converter,” in IEEE Transaction on Industrial Electronics, vol. 45, no. 5, pp. 761−770, Oct. 1998.

[15] A. Mohd et al., “Control strategy and space vector modulation for three-leg four-wire voltage source inverters under unbalanced load conditions,” in IET Power Electronics, vol. 3, no. 3, p. 323, 2010.

[16] J. Zhang, R. Yokoyama, and J. She, “Neutral-point voltage control for a three-level DC-AC inverter using equivalent-input-disturbance approach,” in 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Aalborg, Jun, pp. 398−402, 2012.

[17] J. Liang, T. C. Green, C. Feng, and G. Weiss, “Increasing Voltage Utilization in Split-Link, Four-Wire Inverters,” in IEEE Transaction on Power Electronics, vol. 24, no. 6, pp. 1562−1569, 2009.

[18] M.H. Nguyen and S. Kwak, “Active Thermal Control Algorithm with Independent Power Control Based on Three-phase Four-wire Converter,” Transactions of the Korean Institute of Electrical Engineering, vol. 71, no. 7, pp. 967-978, 2022.

[19] C3M0021120K Datasheet, Cree, Inc.

[20] C3M0025065K Datasheet, Cree. Inc.

[21] FS3L25R12W2H3_B11 Datasheet, infineon.

[22] FS3L40R07W2H5F_B11 Datasheet, infineon.

저자소개

응웬 민 호앙(Minh Hoang Nguyen)

Minh Hoang Nguyen received the B.S. degree in electrical and electronics engineering from Hanoi University of Science and Technology, Vietnam, in 2016. He is currently pursuing the M.S and PhD combined degree in electrical and electronics engineering with Chung-Ang University, Seoul, South Korea. His research interests are control for multilevel converters.

곽상신(Sangshin Kwak)

Sang-Shin Kwak received the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 2005. From 1999 to 2000, he was a Research Engineer with LG Electronics, Changwon, South Korea. From 2005 to 2007, he was a Senior Engineer with Samsung SDI R&D Center, Yongin, South Korea. From 2007 to 2010, he was an Assistant Professor with Daegu University, Gyeongsan, South Korea. Since 2010, he has been with Chung-Ang University, Seoul, South Korea, where he is currently a Professor. His current research interests include the design, modeling, control, and analysis of power converters for electric vehicles and renewable energy systems as well as the prognosis and fault tolerant control of power electronics systems.