DESIGN OF AC-DC CONTROLLED RECTIFIER FOR HYBRID ELECTRIC VEHICLE

K.K.Poongodi[1]

[1]Assistant Professor, Department of Electrical and Electronics Engg., Paavai Engg. College, Namakkal, India,

S.Preetha[2], D.Soundharya[2], P.Srimathy[2], S. Nagasoundarya[2]

[2]UG Student, Department of Electrical and Electronics Engg., Paavai Engg. College, Namakkal, India.

***

ABSTRACT:

Hybrid electric vehicles are important in automobile industry. However, the present-day hybrid electric vehicles are used battery as a secondary source of power. The global warming counter measure, reduction of carbon dioxide is released from vehicles and to increase the fuel efficiency in automobile industry. The auto-manufacturer are contributing their efforts for the development of hybrid electric vehicle.

The existing system was focused on the rectifier circuit. AC-DC conversion of electric power is used in many applications such as adjustable speed drivers, switch mode power supplies, uninterrupted power supplies and battery energy storage. AC-DC converters are referred as a rectifier and are implemented using diodes and thyristors to give an uncontrolled and controlled DC power with unidirectional and bidirectional power flow.

An AC-DC converter supplies an electric power from a commercial power system to an onboard high voltage battery. A highly efficient low-cost hybrid with three phase and three level rectifiers is introduced. A simulation model is implemented in MATLAB/ simulink to test and the results are verified the validity of the proposed system.

Key words- Hybrid electrical vehicle, Three level rectifier, SiC,

I. INTRODUCTION

As a global warming countermeasure, reduction of carbon dioxide released from vehicles and to improve the fuel efficiency in an automobile industry. The auto-manufacturer are contributing their efforts for the development of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), from which higher carbon dioxide reduction effects are expected. [2] An Environmental pollution and petroleum conflicts are becoming more serious, the pushes vehicle technologies in the aspects of energy conversation and environment protection. [3&5] A hybrid electric vehicles (HEVs) gives a more potential to save the fuel consumption and to reduce the pollution. A HEV is a vehicle driven by multiple power source and commonly refers to a combination of internal combustion engine (ICE) and electric motor (EM). A hybrid vehicle can drive on only the engine or purely batteries or a combination of both. Toyota prius, ford escape and mercury mariner are examples of this concept, as these cars can be come forward on battery power. They need a high range capacity battery pack for store energy battery in operation.[1] These vehicles have main choice to put a power path that it allows more flexibility in the drive by inter converting mechanical and electrical powers for distributing, at some costing troubles. To equalize the forces from each portion, the vehicle uses a differential linkage between the engine and motor are connected at the common point of the axle. The main choice on climate change, the insufficient of using fossil fuels and the increase of development in battery technology have focused and involved on global electric vehicle manufacturers to invest more cost to develop and proposed many modern HEV models. [4] The battery charging types such as the charging time, battery life and its efficiency is detected by the characteristics of the charger performance. The characteristics such as greater efficiency, low cost, less weight and reliability are considered as essential topology for the charger.

In this paper, mainly focused on the rectifier circuit. AC-DC conversion is widely used in several applications such as changing speed drivers, switch mode power supplies, uninterrupted power supplies and battery energy storage.[6-7] However ac-dc converters, popularly noted to as rectifier, are introduced to using diodes and thyristor to give uncontrolled and controlled dc power with unidirectional and bidirectional power flow.

An AC-DC converter which supplies electric power from a domestic or commercial power system to high voltage battery. In this paper, a highly efficient less cost hybrid three phase three level rectifier is introduced. At last, a simulation model is established in MATLAB/ Simulink to test and the result verified in the proposed system.

In this paper, a great efficient low-cost hybrid three-phase three-level rectifier is proposed. This rectifier applies SiC MOSFET and Si diode of SiC diode and Si IGBT. It presents very low switching losses because the reverse recovery losses of all the Si devices are rectified. At that time, the cost of total device of this rectifier is lower than the all-SiC-based rectifiers. In this paper, the high-power hybrid rectifier topologies are given in section II. The circuit operational analysis is given in section III. Section IV gives the simulation and experimental results. A comparison between several classic solutions and the proposed rectifier is carried out in Section V. Section VI concludes the paper.

II. REVIEW OF HYBRID HIGH POWER ACTIVE-FRONT-END TOPOLOGIES

There are many types of different topologies which are suitable for AFE (Active Front End) applications. whenever, it comes to a great power system which has a three-phase input and then many single-phase rectifier topologies such as conventional boost type rectifiers in [13-14] and bridgeless boost-type rectifiers in [15] become less attractive since three large capacitors are required under this situation. On the other hand, smooth operation in the switching schemes with required more additional components are not preferred in the high power and high region in the area. As a result, some possible rectifiers are considered in this section. From the high power hard-switching Si-based rectifier circuit, a large portion in the switching losses can be create and caused by the reverse recovery of the Si diode. As a result, in most of the hybrid circuit, SiC Schottky diode are replaced by the Si fast recovery diode and combine as pair with the Si IGBT or MOSFET. Among all these hybrid circuit in the vehicle, the classic two-level active rectifier is the most common one of per-phase circuit is shown in Fig. 1(a) where S1, S2 are Si IGBTs and D1, D2 are SiC Schottky diodes. To refer in Fig. 1 shows that by this the tuned and on the energy, losses can be reduced by 55%, and the reverse recovery losses in the SiC Schottky diode can be almost completely eliminated [14].

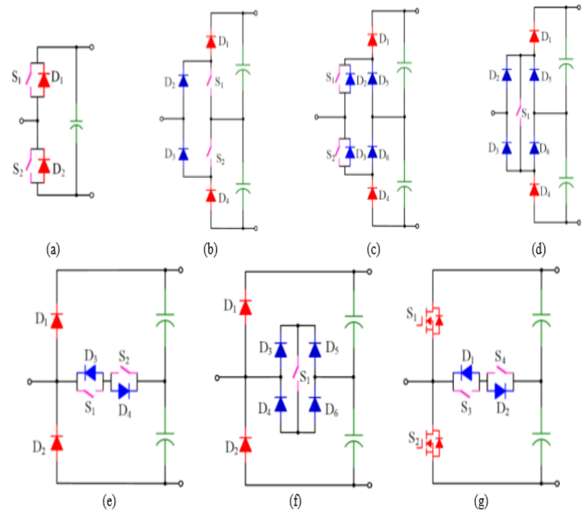


Fig. 1 Per-phase circuit of existing Hybrid PFC boost rectifiers: Diodes in Blue: Slow speed diode, Diodes in Red: Fast-Switching diode using SiC Schottky Diode, (a) Two-level rectifier, (b) Three-level NPC rectifier Type I, (c) Three-level NPC rectifier Type II, (d) Three- level NPC rectifier Type III, (e) Three-level T-type rectifier Type I (f) Three-level T-type rectifier Type II (g) SiC MOSFET & Si Switch Bi-directional Rectifier

However, the disadvantage of this circuit is that large AC-side filters and higher voltage rating devices are required by the two-level rectifier. These will increase the total cost as well as the total losses. In the other hand, the size of the filters and switching losses are decreased in three-level rectifiers. The per-phase circuits of different three-level rectifiers are given in Fig. 1(b)- (f). Three types of three-level neutral point clamped (NPC) rectifiers are demonstrated in Fig. 1(b)-(d). Among these three types, Type I shown in Fig. 1(b) is the most common one in the industry. It requires two fast switching diodes D1 and D4 where reverse recovery will always take place. In applications where high performance is required, D1 and D4 may be replaced by SiC Schottky diodes [10]. Type II is shown in Fig. 1(c) is proposed in [9-12] where active switches S1 and S2 have changed their positions. Another Type III NPC circuit with more diodes and fewer switches is given in Fig. 1(d). Although these two types of the circuit are slightly different with Type I, the position and the number of the fast switching SiC diodes are kept the same. Two types of three-level T-type rectifiers are given in Fig. 1(e) and (f) respectively [13]. Compared to the hybrid NPC rectifiers, these hybrid T-Type rectifiers use higher voltage-rating SiC diodes for D1 and D2. But much lower conduction losses are expected with T-type rectifier circuits. By summarizing the hybrid topology solutions given above, it can be found that in all SiC diode & Si switch hybrid circuits, the switching transient commutation is always between one Si active switch and one SiC diode. It means that the switching frequency of the Si device is always the same as the SiC diode (even higher in Fig. 1(d) and Fig. 1(f)). From the loss distribution given in [8,13], it is obvious that the Si devices still have high switching losses.

The further improvement of the power density based on these hybrid configurations are thus limited by their thermal constraint. Initial researches can be found on the device level, where one SiC MOSFET and one Si IGBT are packed together to form a new hybrid switch [7]. On circuit level, hybrid structures like the one shown in Fig. 1(g) have utilized the similar idea which the SiC diode & Si switch hybrid circuits have [11]. The problem is that the switching frequency of the Si switches is still the same as that of their SiC paired parts. The switching losses are too high for the Si devices while the potential of SiC MOSFETs has not been fully explored. In conclusion, the review of existing hybrid high power active rectifiers shows that the problem that limits the further improvement of the switching frequency and power density is the high switching losses on Si devices. Advanced circuit topology is yet to be investigated.

III. ANALYSIS OF PROPOSED SIC MOSFET & SI DIODE HYBRID THREE-PHASE THREE-LEVEL RECTIFIER

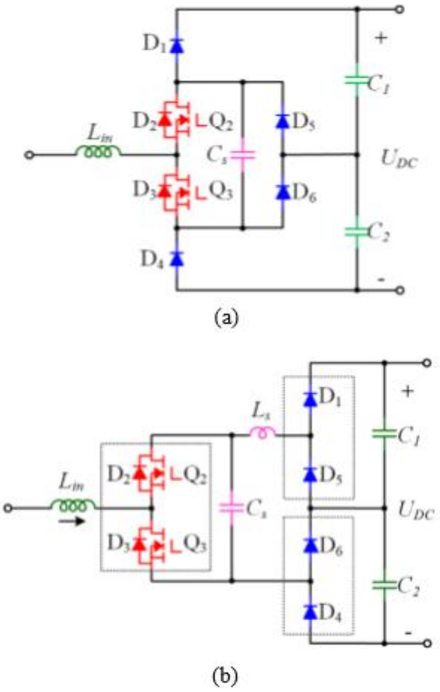
In this paper, a novel three-phase three-level hybrid rectifier is proposed whose per-phase circuit is given in Fig. 2(a). The circuit is derived from the classic NPC type three-level rectifier. The major difference between the proposed circuit and three- level NPC rectifier Type II shown in Fig. 1(c) is that for the proposed rectifier Q2 and Q3 are using SiC MOSFET instead of Si devices, while D1 and D4 are using low-speed Si diode instead of a high-speeding diode such as SiC Schottky diode. In this way, each phase circuit consists of four low-speed Si diodes and two SiC MOSFETs. Furthermore, an additional snubber capacitor Cs is added. This capacitor is critical for the proposed rectifier, especially when applying to the high power area where typically power modules will be adopted instead of discrete devices.

The equivalent circuit of the proposed rectifier which consists of SiC and Si power modules are given in Fig. 2(b). The two SiC MOSFETs form one half-bridge module, while the four Si diodes form two Si diode half-bridge modules. Whatever it uses the copper bar or laminated busbar to connect the SiC and Si modules, inevitable large stray inductance Ls exists between these two parts. The Cs is required to absorb the energy in Ls when Q2 or Q3 is forcibly turned off.

Table 1 Relationship between input voltage, voltage levels, and switching patterns

Input voltage/current	Voltage level	Q2	Q3
Negative	-1	0	1
Negative	-0	1	0
Positive	+0	0	1
Positive	+1	1	0

On the other hand, even if no Ls exists, the original DC link capacitor C1 and C2 still cannot realize the voltage clamping for Q2 and Q3 during their turning off since D5 and D6 will block the transient current. In later section, theoretical analysis and simulation will be given to identify the function of Cs. In the following part, the operational principle of the circuit is demonstrated to show how to realize low switching losses by eliminating the reverse recovery losses on those Si diodes. The equivalent circuits during the operation are given in Fig. 3(a)-(f). The gating strategy to generate each voltage level is given in table1.



(a)
(b)

Fig. 2 per-phase circuit of proposed hybrid three level rectifier, (a) Schematic of proposed rectifier, (b) Real implementation in high power application.

Since there are only two active switches per one phase circuit, the output voltage level is not only depended on the switching patterns but also highly related to the polarity of the input AC voltage, or in other words it is decided by the input AC current since the AC voltage and AC current are always in phase with each other if the unity power factor is realized. One switching period when the input voltage is positive is given as an example to show the operational principle. During this one switching period, Si diode D5 and D4 will be always in off-state. Their voltages are always equal to half of DC link voltage minus the voltage drop on their complimentary diodes D1 and D6 respectively.

[t0-t1]: The analysis starts from the interval when the circuit output is the voltage level "+0". At the moment, Q3 is on, Q2 is off, and the AC current goes through Q3 and D6 as the equivalent circuit Fig. 3(a) shows.

[t1-t2]: At the time t1, Q3 is turned off and the AC current is commutated to Q2's body diode D2. At this time, the Cs and vCs voltage is still lower than C1 voltage which is 1/2Udc.Therefore, D1 will not enter into the conduction mode. Now, the D1 voltage decreases gradually. The AC current charges Cs and continues to go through D6. The turn-off losses on Q3 can thus be lower due to the voltage clamping. The equivalent circuit is shown in Fig. 3(b). During this interval, the voltage on D1 will be equal to the voltage difference between vCs and vC1. After a period of short time delay, Q2 can be turned on and make the current go back to its MOS channel.

[t2-t3]: At the time t2, vCs becomes higher than vC1 and D1 begins to conduct. The equivalent circuit of this interval is shown in Fig. 3(c). However, the rising rate of iLs is limited. In this interval, Cs still acts as a snubber capacitor which resonates with Ls and the voltage on Cs continues to increase. The vCs and iLs can be calculated by (1) and (2) respectively. The IAC represents the instantaneous AC current during this switching period.

[t3-t4]: At the time t3, iLs becomes equal to the AC current. The voltage on diode D6 increases and the resonance between vCs and iLs will soon stop. The vCs becomes its maximum value, which is higher than vC1. This voltage will drop on D6. It can be found that the off-state voltage on D6 is much lower than 1/2Udc, which is almost equal to zero if the volume of Cs is large enough. At the same time, its reverse recovery current is limited by Ls. Thus, its reverse recovery losses can be neglected. On the other hand, the voltage of Cs is also maximum on all SiC devices. As a result, a reasonable volume should be chosen to minimize the system voltage stress. During this interval, the circuit output voltage level "+1". The AC current goes through Q2 and D1 as shown in Fig. 3(d).

[t4-t5]: At the time t4, Q2 is turned off. After a short- time delay, Q3 is turned on. The equivalent circuit is given by Fig. 3(e). The input inductor current is commutated from Q2(D2) to Q3. Cs begins to be discharged through Ls and D1. The voltage of D6 begins to decrease.

[t5-t6]: As soon as vCs becomes equal to vC1, its resonance with Ls starts again. The equivalent circuit is given by Fig. 3(f). At the time t6, iLs becomes zero and the resonance stops. The vCs becomes its minimum value, which is lower than vC1. This part of voltage will drop on D1. Theoretically, D1 should have experienced reverse recovery process. However, the changing rate of the current through D1 is limited by Ls. Moreover, the blocking voltage on D1 is only the voltage difference between vCs and vC1. Thus, its reverse recovery losses can also be neglected just like D6. After this interval, the equivalent circuit becomes the same as Fig. 3(a) shows where a new switching period begins.

The operational principle when the input voltage is negative is similar to when the input voltage is positive and will not go in details here. After the analysis, it will soon be found that the

Si diode D4 and D5 have the similar situation with D1 and D6, which is that the reverse recovery losses are minimized and the entire off-state voltage is undertaken by Q3 (D3) after the commutation. Under this mechanism, the reverse recovery losses and turn-on losses of the rectifier circuit can be minimized since all the losses are shifted from Si diodes to SiC MOSFETs or their body diodes. The switching frequency of all the Si diodes can be considered as equal to the line frequency. As a result, even general purpose diodes used in bridge rectifiers are also applicable for D1, D4, D5, and D6.

The commutation of the proposed circuit when AC current crossing zero is slightly different. When AC current is crossing zero, the current will be reversely blocked by the Si diodes. During this time, the AC current will charge or discharge the junction capacitor of all Si diodes. All these capacitors added together resonant with the AC inductor Lin. Since the amplitude of the current is very low during this interval, all Si diodes can still be considered as under the zero-current- switching (ZCS) condition and the switching losses are still minimized.

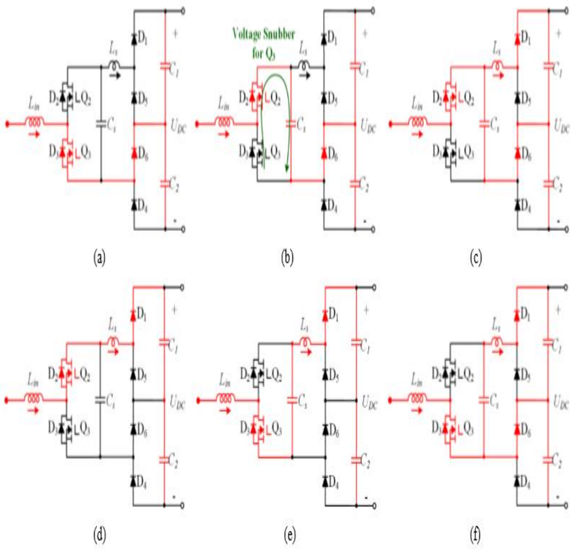


Fig. 3 Equivalent circuit of intervals when input voltage is positive (a) [t0-t1] (b) [t1-t2] (c) [t2-t3] (d) [t3-t4] (e) [t4-t5] (f) [t5-t6]

There is another benefit of applying this hybrid configuration. Compared with the NPC rectifier type I in Fig. 1(b) and the NPC rectifier type II in Fig. 1(c) where two discrete SiC diodes are implemented, the proposed circuit can be realized by implementing two Si diode half bridges and one SiC MOSFET half bridge. No customized power module with Si IGBT-SiC diode pair or Si MOSFET-SiC diode pair is required. Also, from the above analysis, it can also be inferred that the essence of the proposed rectifier is still an NPC Type three-level rectifier. Therefore, the modulation and control of the circuit are fully compatible with many well-developed strategies for other NPC Type three-level rectifiers.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The waveforms on devices in half of the circuit are given in Fig. 5. It can be found that the waveforms when the AC current is at its peak are exactly the same as the theoretical analysis. The voltage ripple on Cs is about 60V which meets the result. Thus, the maximum voltage on Cs as well as other SiC MOSFETs is all equal to 780V. At the same time, the off-state voltages on D1 and D5 during the positive cycle is also only 30V, which is much lower than 750V half DC voltage. It means that only the SiC MOSFET pair Q2 and Q3 have high-frequency hard-switching. On the other hand, the voltage waveforms on D1 and D5 when AC current is crossing zero become different. Resonance takes place between the AC inductor and the output capacitance of D1 and D5. ZCS switching is realized for D1 and D5. From simulation results, the proposed circuit should have low switching losses since the reverse recovery losses on all Si diodes are minimized.

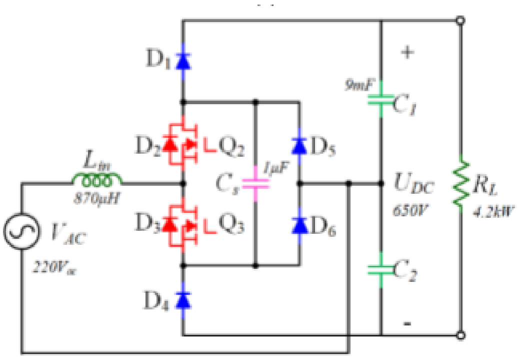


Fig.4 Single-phase circuit diagram

According to fig. when the input AC voltage is positive, the equivalent circuits of the rectifier are the same as Fig. 3 shows. Furthermore, since the stray inductance Ls and the AC current are small, the voltage ripple on Cs can be neglected. Therefore, according to the waveforms, the voltage on D1 and D6 are equal to zero, while the voltage on D4 and D5 are equal to half of the DC link voltage 325V. In those diodes reverse recovery losses are minimized.

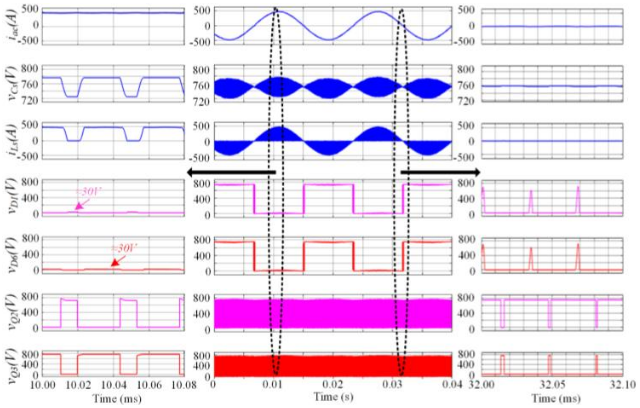


Fig. 5 Simulation results of proposed rectifier,

On the other hand, two SiC MOSFETs are complimentarily fast switching. The turning off of Q3 will change the voltage level of the circuit from “+0” to “+1”. Q2 will be turned on after a short deadtime to provide synchronous rectification. It can be found that D1 and D5 are switching under 60Hz. High efficiency can thus be achieved since only SiC devices are under high-frequency switching.

According to the measurement of total harmonics distortion (THD) of the AC current is 4.341%. Because that the input grid-side voltage contains significant contents of voltage harmonics, the AC side current also includes current harmonics. Better input voltage and advanced control scheme may decrease these current harmonics. The efficiency of the prototype operating under rated input voltage 220Vac and rated DC voltage 650V is evaluated. It can be found that, under 40kHz switching frequency, the overall efficiency can over 85%. The peak efficiency can reach up under 20kHz switching.

V. CONCLUSION

In this paper, a highly efficient three-phase three-level rectifier comprising SiC MOSFET & Si diode hybrid power stage is developed. It presents reasonable low cost in high power high voltage applications and at the same time achieves low switching losses because the reverse recovery losses on all Si diodes have been eliminated. Furthermore, this topology is easy to be configured as high-power type since all devices can use the half-bridge module.

According to the experimental results, the proposed rectifier can achieve over 85% high efficiency within a wide power range. In order to fully explore its advantages, a comparison is carried out under the specification where the DC bus is over 1000V. The results show that the proposed rectifier has the reasonable cost, and the switching losses and conduction losses are both lower compared to other hybrid or all SiC-based NPC type rectifiers. Thus, this circuit is favorable for high power density high DC voltage three-phase AC-DC applications such as EV charging station or AFE for the medium voltage drive system.

REFERENCES

[1] C. Li, J. Lei, G. Qingxin, Y. Zhang, S. Wang and D. Xu, "High power three-level rectifier comprising SiC MOSFET & Si diode hybrid power stage," in Proc. 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1-7.

[2] A. Q. Huang, "Power Semiconductor Devices for Smart Grid and Renewable Energy Systems," Proceedings of the IEEE, pp. 1-29, 2017.

[3] X. She, R. Datta, M. Harfman-Todorovic, G. Mandrusiak and J. Dai, "High Performance Silicon Carbide Power Block for Industry Applications," vol.53, pp. 3738-3747, 2017.

[4] Q. Guan, C. Li, Y. Zhang, W. Shuai and D. Xu, "An Extreme Highly Efficient Three-Level Active Neutral-Point-Clamped Converter Comprising SiC & Si Hybrid Power Stage," IEEE Transactions on Power Electronics, pp. 1, 2017.

[5] J. Millan, P. Godignon, X. Perpina, A. Perez-Tomas and J. Rebollo, "A Survey of Wide Bandgap Power Semiconductor Devices," IEEE Transactions on Power Electronics, vol.29, pp. 2155-2163, 2014.

[6] J. Minibock and J. W. Kolar, "Comparative theoretical and experimental evaluation of bridge leg topologies of a three-phase three-level unity power factor rectifier," in Proc. 2001 IEEE 32nd Annual Power Electronics Specialists Conference (IEEE Cat. No.01CH37230), pp. 1641-1646.

[7] J. W. Kolar and F. C. Zach, "A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules," IEEE Transactions on Industrial Electronics, vol.44, pp. 456-467, 1997.

[8] Y. Zhao, Y. Li and T. A. Lipo, "Force commutated three level boost type rectifiers," IEEE Transactions on Industry Applications, vol.31, pp. 155- 161, 1995.

[9] M. Schweizer, T. Friedli and J. W. Kolar, "Comparative Evaluation of Advanced Three-Phase Three-Level Inverter/Converter Topologies Against Two-Level Systems," IEEE Transactions on Industrial Electronics, vol.60, pp. 5515-5527, 2013.

[10] R. Teichmann and S. Bernet, "A Comparison of Three-Level Converters Versus Two-Level Converters for Low-Voltage Drives, Traction, and Utility Applications," IEEE Transactions on Industry Applications, vol.41, pp. 855-865, 2005.

[11] R. Yapa, A. J. Forsyth and R. Todd, "Analysis of SiC Technology in Two- Level and Three-Level Converters for Aerospace Applications," in Proc. 7th IET International Conference on Power Electronics, Machines and Drives (PEMD 2014), pp. 1-7.

[12] R. Lai, F. Wang, R. Burgos, Y. Pei, D. Boroyevich and B. Wang, et al., "A Systematic Topology Evaluation Methodology for High-Density Three- Phase PWM AC-AC Converters," vol.23, pp. 2665-2680, 2008.

[13] K. Yun-Sung, S. Won-Yong and L. Byoung-Kuk, "Comparative Performance Analysis of High Density and Efficiency PFC Topologies," Power Electronics, IEEE Transactions on, vol.29, pp. 2666-2679, 2014.

[14] J. Biela, J. W. Kolar and G. Deboy, "Optimal design of a compact 99.3% efficient single-phase PFC rectifier," in Proc. Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE, pp. 1397-1404.

[15] F. W. F. and Z. Z., "Overview of silicon carbide technology: Device, converter, system, and application," CPSS Transactions on Power Electronics and Applications, vol.1, pp. 13-32, 2016.