

# Three-Phase Rectifiers With Current Compensation Schemes - Part II: Active and Hybrid Configurations

Marco Rivera  
Faculty of Engineering  
University of Talca  
Curico, Chile  
marcoriv@utalca.cl

Daniel Faundez  
Faculty of Engineering  
University of Talca  
Curico, Chile  
dfaundez12@alumnos.utalca.cl

Johann Kolar  
Power Electronic Systems Laboratory  
ETH Zurich  
Zurich, Switzerland  
kolar@lem.ee.ethz.ch

Patrick Wheeler  
Dept. of Electrical & Electronic Engineering  
The University of Nottingham  
Nottingham, UK  
Pat.Wheeler@nottingham.ac.uk

Jose A. Riveros  
Faculty of Engineering  
University of Talca  
Curico, Chile  
jriveros@utalca.cl

Sergio Toledo  
Faculty of Engineering  
University of Talca  
Curico, Chile  
stoledo@utalca.cl

**Abstract**—The current injection schemes for unidirectional three-phase diode bridge rectifiers are widely utilised in industrial and aerospace applications. The additional circuitry in combination with modern control strategies mitigate the effects of the conversion in the mains, offers acceptable dynamic and reduces size/weight for the development of compact and robust power converters. This paper is the second part of this work and it overviews the most promoted self-commutated (active) and hybrids ac-dc configurations given in literature. The operation and characteristics of these proposals are reported in this review, extending the first part that focused the analysis on passive networks.

**Index Terms**—Ac-dc power converters, power conversion harmonics, power harmonic filters

## I. INTRODUCTION

Three-phase diode ac-dc power converters are the classical election for high-power unidirectional purposes [1, 2]. The easier solution to overcome the high amount of harmonic content in the ac-side of this topology apparently is the use of power filters connected in the mains side [3-5]. These are either passive, active or hybrid independent networks aimed to clean up the current spectrum with the impact in the normal behaviour of the system. However, these proposals can be applied only in some applications because they might affect the operation, need additional dc stages and provide complex design/control [6]. For uses in the aerospace field, alternative technologies should be developed to comply with their severe restrictions.

Current injection techniques are a suitable alternative for the mitigation of undesired features of the well-known diode bridge rectifiers [7]. In these ones, only a portion of the power converted is used for this purpose and its operation is intended to mitigate the particular issues of these specific ac-dc architectures. Thus, the enhancement of the ac currents is developed with high efficiency along with reduced size/weight. The injection circuits in charge of this task can be classified either as line-commutated (passive), self-commutated (active)

or hybrids [8]. The first one was analysed in part one of this work, whereas this paper carries on with this subject and overviews the last two designs describing their operation principles and performance.

The self-commutated and hybrid current injection strategies are more likely to be implemented in applications where high dynamic control of the output and ac currents with high quality are required [2]. They provide wide operation range, higher dynamic and smaller size compared to the passive designs presented in the first part [9]. The operation principle is to generate an appropriate current reference that is injected in the ac-side but supplied by the dc output. The current set-point is derived with the aim of cancelling the undesired spectral components and attain sinusoidal response in the input.

The active networks are capable of mitigating a wide range of harmonic components with use of power switches and current control strategies. However, they can be costly for medium and high power applications. Furthermore, diode bridges are usually selected for the sake of simplicity and the complexity required by some active control techniques may not be fulfilling this objective.

The proper association between the passive and active injection circuit is the aim of hybrid configurations. The design of the passive elements can be simplified covering only the mitigation of specific harmonic components. This scope also benefits the system with smaller passive components that imply reduced size/weight. The remaining harmonic frequencies are cancelled with the active stage, reducing the cost and complexity in the control of the current injector.

A general diagram of the topologies discussed in this work is shown in Fig. 1. The conventional diode bridge is the ac-dc converter stage and is associated to additional passive/active circuitry including current injection network to improve the conversion efficiency. The most popular schemes are presented in the following two sections of this paper. Finally, the conclusion of this survey is presented.

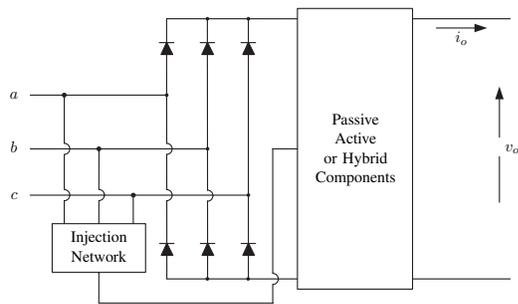


Fig. 1. Three-phase rectifier with current injection network

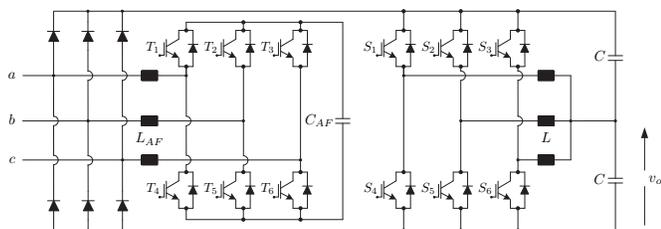


Fig. 2. Two-level three-phase active power filter and interleaved DC-DC buck-type converters

## II. SELF-COMMUTATED CURRENT INJECTION SCHEMES

### A. Six-Pulse Rectifier with a Three-Phase Active Power Filter and Interleaved DC-DC Buck Converter

The power converter shown in Fig. 2 was developed for fast electric vehicle charging applications [10]. This architecture comprises a six-pulse diode bridge and an active power filter (APF) in shunt connection, while the output dynamic is controlled with three interleaved buck-type converters. The APF can be designed at only 40% of the rated power of the charger and does not affect the rectifier's operation in case of faults, although the post-fault operation is done without the use of a power factor correction. Another limitation is that the APF does not contribute to the regulation of the dc output.

For this purpose, the two-level voltage source converter (VSC) is used for the APF stage is a conventional configuration. However, in applications where demanding high voltage, efficiency and quality restrictions along with low size/weight are demanded, the three-level topology is the suitable solution. The T-type and neural-point clamped (NPC) APF schemes are presented in figures 3 and 4, respectively. These designs increase the number of power switches and cost.

### B. Six-Pulse Rectifier with Active Third Harmonic Current Injection Rectifier

The active third harmonic current injection architecture is composed by an active circuitry supplied from the dc-link of the diode bridge rectifier and a dc-dc power converter that controls the load demand. Figure 5 depicts a configuration with a buck-type dc stage in the output. The current injection scheme is compounded by three bi-directional power switches

and a current shaping network. The latter, replaces the APF presented in the previous subsection, since the arrangement is capable of generating sinusoidal ac current in the mains. The control method is straightforward, the bi-directional switch is activated when the magnitude of its linked phase voltage has the medium value (the smallest absolute value) of the three-phase system [11]. Notice that the switching frequency of this technique is low and, consequently, compatible with high-power applications. However, for the control of bi-directional devices the four-step switching strategy is mandatory in order to avoid short circuit faults in the ac lines.

### C. Three-Phase Three-Switch Buck-Type PFC Rectifier

This three-phase active power factor correction (PFC) rectifier architecture employs an LC filter and modifies the conventional six-pulse design by adding a series power switch to each diode in a unidirectional current blocking arrangement [12] (see Fig. 6). This configuration allows voltage-independent controllability of the power flow in the dc-link. A limitation for low- and medium-power applications is the range of the commutation frequency (about 10 kHz) due to the high switching losses of the series power electronic devices.

### D. Active Three-Switch Buck-Type PFC rectifier

This is an alternative to the previous proposal [12], where the power commutation devices of the mains' side are arranged with a four-quadrant configuration as shown in Fig. 7. The four diodes along with the power switch of each leg are embedded in one package enhancing the utilisation of the silicon. The number of power switches is reduced, but at the cost of a higher number of power diodes that increase the conduction losses. The controllability is lessened compared with the previous rectifier, attaining only unidirectional power flow.

### E. Buck-Type Swiss Rectifier

This design combines a three-phase PFC rectifier, a buck-type dc-dc power converter and the active third harmonic current injection [13, 14] (see Fig. 8). This configuration enables the control of output voltage and ensure ohmic behaviour in the ac-side, achieving in this manner an outstanding efficiency in comparison to conventional topologies with buck-controlled dc outputs. The diodes operate in line-commutated mode in comparison to the previous two schemes, where the commutation of the power switches also controls these

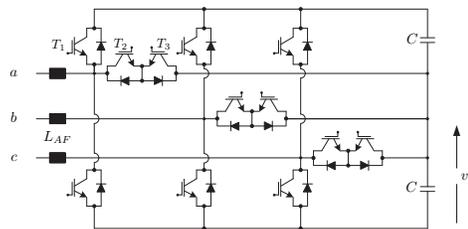


Fig. 3. Active power filter based on the T-type voltage source converter

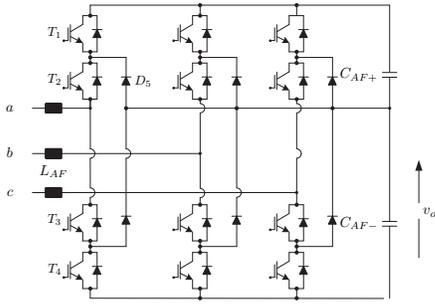


Fig. 4. Active power filter with I-type (NPC) voltage source converter

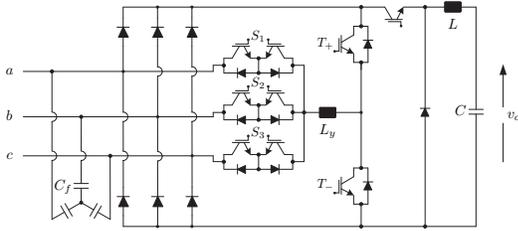


Fig. 5. Active third harmonic current injection rectifier with single DC-DC buck converter

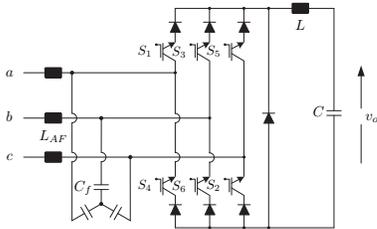


Fig. 6. Three-phase six-switch PFC rectifier with LC filter.

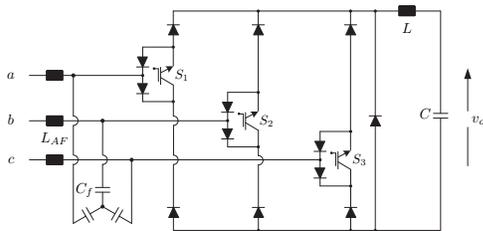


Fig. 7. Three-switch PFC rectifier with LC filter and free-wheeling diode.

semiconductors. The current injection strategy is the same as in subsection B, while  $T_+$  and  $T_-$  power switches are modulated by using triangular carriers in phase [15].

### F. Boost-Type Vienna Rectifier

This is a unidirectional ac-dc power converter with low switching stress, high power density and controlled output [16, 17]. The configuration of this rectifier is shown in Fig. 9. One bidirectional power switch, arranged with a controlled semiconductor connected to the dc output of a single-phase full-wave bridge, is included in each leg of the six-pulse bridge. The ac inputs of each single-phase rectifiers are one

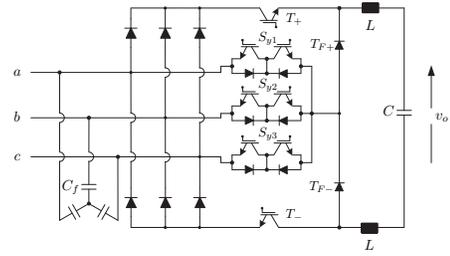


Fig. 8. Buck-type Swiss rectifier

phase of the mains and the mid-point of the dc-link. Alternative arrangements to attain the bidirectional self-commutated devices were reported in [12, 18] at the expense of using a total of six power switches.

This design achieves a three-level operation (input can be connected to mid-point of the dc-link or to  $\pm v_o/2$ ) with a simple control scheme for these characteristics. However, the conduction losses are high considering the number of devices within the circuit's path.

### G. Six-Pulse Rectifier with Three Bidirectional Switches

This proposal is comprised by a line-commutated three-phase bridge and three bidirectional power switches connected between the ac inputs and the mid-point of the dc-link [19-21], see Fig. 10. This simple structure only employs three low-power self-commutated devices that operate with a simple control scheme at a low switching frequency (similar to the third harmonic current injection technique). Notice that this architecture does not require connection to the neutral line of the three-phase power source and, consequently, the third order current harmonic along with their multiples are cancelled.

The clamping circuits used for protection are not needed in this model, taking into account the magnitude of the currents

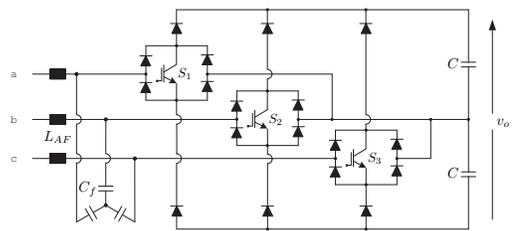


Fig. 9. Boost-Type Vienna rectifier

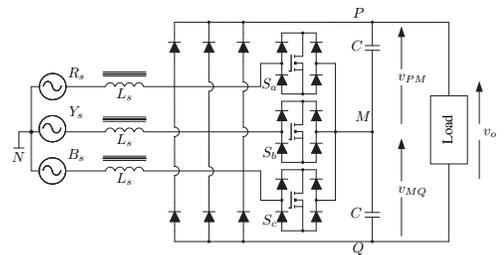


Fig. 10. Six-pulse rectifier with three bidirectional switches

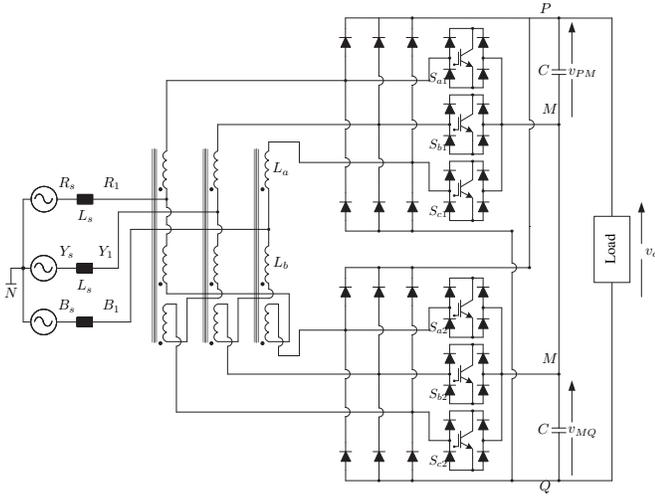


Fig. 11. 24-pulse rectifier with harmonic cancelling reactors

flowing through the bidirectional power switches.

All these features result in a rectifier with low-cost circuitry, quasi unitary power factor and wide operation range [20].

### III. HYBRID CURRENT INJECTION SCHEMES

#### A. 24-Pulse Rectifier with Harmonic Cancelling Reactors

This topology was introduced for mid-power applications [22]. The design employs two three-level diode rectifiers [21] connected in parallel and a coupling network of harmonic cancelling reactors sized at 13 to 18% of the converter's rated power as indicated in Fig. 11. The three cancelling harmonic reactors balance the current and damp the harmonic components. The six bidirectional power switches forces the commutation (control the conduction angle of the diodes) and generate input voltage wave-shaping to achieve a 24-pulse operation. The weight and size are reduced with respect to the passive proposals.

#### B. 12-Pulse Rectifier with Active Interphase Reactors

This is an 12-pulse rectifier with an active interphase reactor. Two proposals were reported in [23, 24] and the topologies are presented in figures 12 and 13, respectively. The galvanic transformer requires a small percent of the rated power, while the triangular current injection is a single-phase full bridge converter that employs only 2%. These requirements provide a reduced weight and size of the ac-dc power converter with quasi resistive behaviour in the mains side.

The scheme of Fig. 12 is fed by a  $\Delta$ -Y transformer (turn ratio of  $\sqrt{3}:1$  and 0.52% of the rated power, Fig. 14) to provide two three-phase voltages shifted by  $30^\circ$ . In comparison to the conventional 12-pulse architecture, the interphase reactor has an additional winding for the low-power injection network (2.27% of the rated power). This circuitry injects an appropriate current in order to attain quasi sinusoidal and high power factor in the input.

The last 12-pulse configuration, Fig. 13, is supplied by a  $\Delta$ -type autotransformer designed with only 18% of the rectifier's

rated power. The size is reduced, but two interphase reactor must be implemented in order to balance the current of the six-pulse rectifiers.

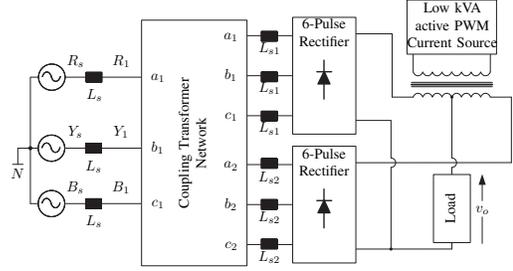


Fig. 12. 12-pulse rectifier with active interphase reactors (Alternative I)

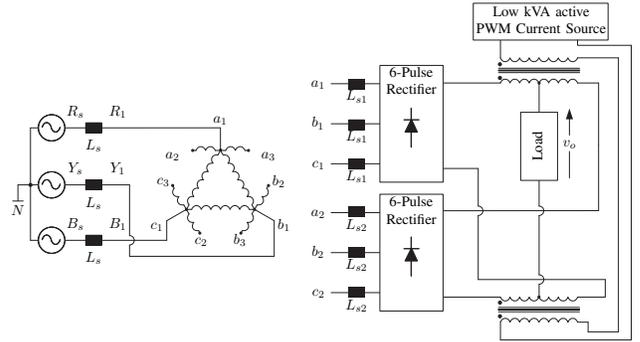


Fig. 13. 12-pulse rectifier with active interphase reactors (Alternative II)

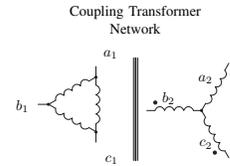


Fig. 14. Coupling transformer network of the 12-pulse rectifier with active interphase reactors

#### C. Hybrid 12-pulse Line Interphase Transformer (LIT) Rectifier Systems

This design is based on the passive 12-pulse LIT scheme [25]. The interphase reactor is located in the ac-side (three-phase configuration) and three different development with low impact in the mains were reported in [26, 27]. The architectures presented are the boost-type single- and two-switch hybrid rectifiers (SSHR and TSHR, respectively).

The SSHR is a 12-pulse rectifier with a single-switch dc-dc boost converter to control the dynamic of the output voltage, Fig. 15. The resulting ac phase currents have a sinusoidal shape with a small content of high frequency switching ripple due to the boost stage.

Figures 16 and 17 depict the TSHR schemes. The output voltage is controlled by means of two boost-type dc-dc power converters with interleaved configuration. The power switches  $T_1$  and  $T_2$  operate with the same duty cycles to lessen the

ac current ripple generated by the switching frequency. A considerable enhancement in the reduction of the ac ripple current is achieved with respect to the SSHR in detriment to higher losses in the galvanic iron due to the twice switching frequency pattern present in the LTI voltages.

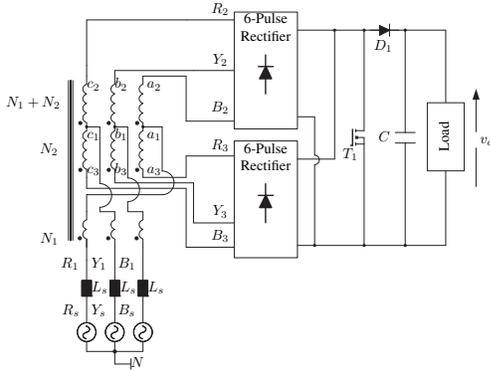


Fig. 15. Three-phase hybrid 12-pulse boost-type rectifier with single-switch topology (SSHR)

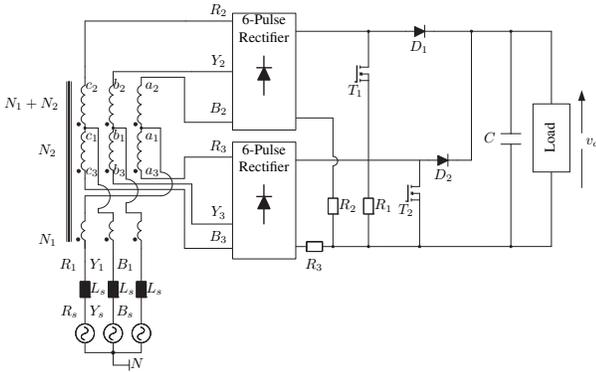


Fig. 16. Three-phase hybrid 12-pulse boost-type rectifier with two switch topology (TSHR)

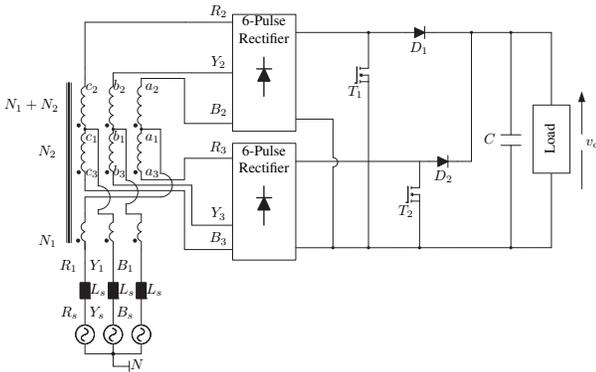


Fig. 17. New three-phase hybrid 12-pulse boost-type LIT rectifier with two switch topology

The performance of the TSHR is sensitive to the mismatch between the duty cycles of the power switches  $T_1$  and  $T_2$ . The difference between these values generates a zero-sequence

current that flows between the six-pulse bridges and cannot be balanced, since the LIT only performs this task with the phase currents. This would conduct higher stressed currents in the semiconductors and low frequency distortion in the ac currents. For these reasons, a closed-loop is needed to control the zero-sequence current and to avoid the described issues.

#### IV. CONCLUSIONS

The most promoted and popular ac-dc power converters with active and hybrid current injection topologies have been overviewed in this paper (second part of this work). These configurations report high dynamic in the output and sinusoidal behaviour in the ac-side. The main features of each design have been described and discussed. These proposals provide smaller size and weight than the passive-based low-pollution rectifiers being suitable for compact applications such as more-electric aircrafts.

#### ACKNOWLEDGMENT

The authors would like to acknowledge the MEC project number 80150056, FONDECYT Regular 1160690 and Post-doctoral 3170014 research projects and PROCENCIA R&D Grant under the reference 14-INV-097 for the economical support provided to develop this work.

#### REFERENCES

- [1] J. Solanki, N. Fröhleke, J. Böcker, A. Averberg, and P. Wallmeier, "High-current variable-voltage rectifiers: state of the art topologies," *IET Power Electronics*, vol. 8, no. 6, pp. 1068–1080, 2015.
- [2] J. Kolar and H. Ertl, "Status of the techniques of three-phase rectifier systems with low effects on the mains," in *Telecommunication Energy Conference, 1999. INTELEC '99. The 21st International*, 1999, pp. 16 pp.–.
- [3] R. N. Beres, X. Wang, M. Liserre, F. Blaabjerg, and C. L. Bak, "A review of passive power filters for three-phase grid-connected voltage-source converters," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 1, pp. 54–69, March 2016.
- [4] H. Akagi, "Active harmonic filters," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2128–2141, Dec 2005.
- [5] A. Hamadi, S. Rahmani, and K. Al-Haddad, "A hybrid passive filter configuration for VAR control and harmonic compensation," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2419–2434, July 2010.
- [6] R. N. Beres, X. Wang, F. Blaabjerg, M. Liserre, and C. L. Bak, "Optimal design of high-order passive-damped filters for grid-connected applications," *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2083–2098, March 2016.
- [7] N. Vazquez, H. Rodriguez, C. Hernandez, E. Rodriguez, and J. Arau, "Three-phase rectifier with active current injection and high efficiency," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 1, pp. 110–119, 2009.
- [8] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of three-phase improved power quality ac-dc converters," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 3, pp. 641–660, June 2004.
- [9] M. Rivera, D. Faundez, J. Kolar, P. Wheeler, J. Riveros, and S. Toledo, "Three-phase rectifiers with current compensation schemes - part I: Passive circuits," in *2018 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles International Transportation Electrification Conference (ESARS-ITEC)*, Nov 2018.
- [10] T. Soeiro, T. Friedli, and J. Kolar, "Three-phase high power factor mains interface concepts for electric vehicle battery charging systems," in *Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE*, 2012, pp. 2603–2610.

- [11] P. Pejovic, "A novel low-harmonic three-phase rectifier," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 49, no. 7, pp. 955–965, July 2002.
- [12] J. W. Kolar and T. Friedli, "The essence of three-phase pfc rectifier systems—part I," *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 176–198, Jan 2013.
- [13] T. B. Soeiro, F. Vancu, and J. W. Kolar, "Hybrid active third-harmonic current injection mains interface concept for dc distribution systems," *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 7–13, Jan 2013.
- [14] T. B. Soeiro, T. Friedli, and J. W. Kolar, "Design and implementation of a three-phase buck-type third harmonic current injection pfc rectifier sr," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1608–1621, April 2013.
- [15] T. Friedli, M. Hartmann, and J. W. Kolar, "The essence of three-phase PFC rectifier systems—part II," *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 543–560, Feb 2014.
- [16] J. W. Kolar, H. Ertl, and F. C. Zach, "Design and experimental investigation of a three-phase high power density high efficiency unity power factor PWM (VIENNA) rectifier employing a novel integrated power semiconductor module," in *Proceedings of Applied Power Electronics Conference. APEC '96*, vol. 2, March 1996, pp. 514–523 vol.2.
- [17] J. W. Kolar, H. Sree, U. Drofenik, N. Mohan, and F. C. Zach, "A novel three-phase three-switch three-level high power factor sepic-type ac-to-dc converter," in *Proceedings of APEC 97 - Applied Power Electronics Conference*, vol. 2, Feb 1997, pp. 657–665 vol.2.
- [18] Y. Zhao, Y. Li, and T. A. Lipo, "Force commutated three level boost type rectifier," *IEEE Transactions on Industry Applications*, vol. 31, no. 1, pp. 155–161, January 1995.
- [19] J. W. Kolar and F. C. Zach, "A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules," in *Proceedings of Intelec 94*, Oct 1994, pp. 367–374.
- [20] E. Mehl and I. Barbi, "An improved high-power factor and low-cost three-phase rectifier," *Industry Applications, IEEE Transactions on*, vol. 33, no. 2, pp. 485–492, 1997.
- [21] K. Oguchi and I. Maki, "A multilevel-voltage source rectifier with a three-phase diode bridge circuit as a main power circuit," *IEEE Transactions on Industry Applications*, vol. 30, no. 2, pp. 413–422, March 1994.
- [22] K. Oguchi, G. Maeda, N. Hoshi, and T. Kubata, "Coupling rectifier systems with harmonic cancelling reactors," *Industry Applications Magazine, IEEE*, vol. 7, no. 4, pp. 53–63, 2001.
- [23] S. Choi, P. Enjeti, H. Lee, and I. Pitel, "A new active interphase reactor for 12-pulse rectifiers provides clean power utility interface," in *Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE*, vol. 3, 1995, pp. 2468–2474 vol.3.
- [24] S. Choi, P. Enjeti, H.-H. Lee, and I. Pitel, "A new active interphase reactor for 12-pulse rectifiers provides clean power utility interface," *Industry Applications, IEEE Transactions on*, vol. 32, no. 6, pp. 1304–1311, 1996.
- [25] G. Gong, M. L. Heldwein, U. Drofenik, J. Minibock, K. Mino, and J. W. Kolar, "Comparative evaluation of three-phase high-power-factor ac-dc converter concepts for application in future more electric aircraft," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 727–737, June 2005.
- [26] K. Mino, G. Gong, and J. Kolar, "Novel hybrid 12-pulse line interphase transformer boost-type rectifier with controlled output voltage," in *Power Electronics and Motion Control Conference, 2004. IPEMC 2004. The 4th International*, vol. 2, 2004, pp. 924–931 Vol.2.
- [27] K. Mino, G. Gong, and J. W. Kolar, "Novel hybrid 12-pulse boost-type rectifier with controlled output voltage," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 41, no. 3, pp. 1008–1018, July 2005.