Mohamed Tanta, Vítor Monteiro, J. G. Pinto, António Pina Martins, Adriano S. Carvalho, João L. Afonso

"Efficiency and Cost Estimation for a Static Frequency Converter and a Rail Power Conditioner Based on an Indirect Modular Multilevel Converter in Railways Applications"

ICEE International Conference on Energy and Environment: Bringing Together Engineering and Economics, Porto Portugal, June 2017.

ISBN: 978–972–95396–9–5

ISSN: 2183-3982872-8

Mohamed Tanta, Vítor Monteiro, J. G. Pinto, Antonio P. Martins, Adriano S. Carvalho and João L. Afonso "Efficiency and Cost Estimation for a Static Frequency Converter and a Rail Power Conditioner Based on an Indirect Modular Multilevel Converter in Railways Applications".
ICEE International Conference on Energy and Environment: Bringing Together Engineering and Economics, Porto Portugal, pp.313-319, June 2017. ISSN 2183-3982 ISBN 978 -972 -95396 -9 -5.

EFFICIENCY AND COST ESTIMATION FOR A STATIC FREQUENCY CONVERTER AND A RAIL POWER CONDITIONER BASED ON AN INDIRECT MODULAR MULTILEVEL CONVERTER IN RAILWAYS APPLICATIONS

Mohamed Tanta[1*], Vítor Monteiro[1], J. G. Pinto[1], António. P. Martins[2], Adriano. S. Carvalho[2] and João L. Afonso[1]

[1] Centro ALGORITMI – University of Minho, Guimarães – Portugal
[2] SYSTEC Research Center – University of Porto, Porto – Portugal

* Corresponding author: mtanta@dei.uminho.pt, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal.

KEYWORDS
Static Frequency Converter (SFC); Rail Power Conditioner (RPC); Modular Multilevel Converter (MMC).

ABSTRACT

This paper presents a comparative study between two different power electronics solutions for electrified railway substations to overcome some drawbacks which could appear on the public grid side. These drawbacks or troubles on the public grid side are mainly the harmonics and the negative sequence components (NSCs) of currents, which could become clear in the case of feeding single-phase locomotives or unbalanced loads. The static frequency converters (SFCs) and the rail power conditioners (RPCs) based on an indirect AC/DC/AC modular multilevel converter (MMC) are the main area of interest in this study, taking into consideration the costs estimation analysis between solutions, the efficiency and the power quality on the public grid side. Both systems of SFC and RPC based on an indirect MMC operate on medium voltage levels to feed the catenary line and to solve the problems of harmonics and NSCs. Along the paper are described the system architecture, the control algorithm, the inherent benefits, the estimated cost of implementation, and the operation efficiency based on computational simulation results for each system.

INTRODUCTION

Nowadays, electrified railways represent a special type of power system and they have negative effects on power quality and efficiency of the public grid side (Perin et al., 2015). These effects are normally associated with the AC supply traction grids and they have been discovered since the early use of AC grids. In particular interest are the harmonics distortion and the negative sequence components (NSCs) caused by the locomotives (Krastev et al., 2016). Normally, public grid currents are balanced and the problem of unbalancing only appears when the huge single-phase loads such as the locomotives are connected to the public grid side. This unbalance is unavoidable because the locomotives must be connected on a single-phase grid regarding to the pantograph-catenary schematic (Perin et al., 2015). As a result, the entire electric traction supply system of locomotives is normally a single-phase system and it mainly causes the unbalance between three-phase public grid side currents (Abrahamsson et al., 2012). Consequently, that creates adverse effects on electric devices and the power switches. Moreover, these impacts threat the safe and the economical operation on the public grid side. Besides, increasing the power losses of the feeder lines which lead to additional operation costs and sometimes, a misoperations of the protection relay devices (Krastev et al., 2016; Perin et al., 2015).
Normally, in some European countries like Germany, Austria and Switzerland, the single-phase AC traction grids operate on 15 kV, 16.7 Hz. On the other hand, the single-phase traction system can be merged with the public power system and, in this case, it operates on 25 kV, 50 Hz like the case of Portugal, Spain, France and Finland (Steimel, 2012). Considering that the last system of 25 kV, 50 Hz is more common among many countries, this study is performed for 25 kV, 50 Hz electrified railways traction grids.
Static frequency converters (SFCs) and rail power conditioners (RPCs) are the promising solutions in AC railways traction grids to solve the drawbacks of unbalance and current harmonics, thus increasing public grid power quality and efficiency (Krastev et al., 2016; Perin et al., 2015). Since the modular multilevel converter (MMC) is an attractive device in the medium voltage levels (Gruber and O'Brien, 2014), this converter has been integrated recently with the latest emerging solutions of SFCs and RPCs. MMC submodules (SMs) can be half-bridge or full-bridge ones according to the application, where normally MMC under full-bridge SMs can operate in 15 kV, 16.7 Hz railway substation and it is called

a direct AC/AC MMC. Moreover, Indirect AC/DC/AC MMC with half-bridge SMs is more convenient to operate in 25 kV, 50 Hz railways substations (Krastev et al., 2016).

MMC power electronics switches can operate with a lower switching frequency comparing with the conventional two-level converter and they can achieve multilevel output waveforms with less harmonics (Song et al., 2016). SFC system based on an indirect MMC can achieve harmonics filtering and load balancing, where the last is an inherent feature of SFC (Perin et al., 2015). Furthermore, RPC system based on an indirect MMC has the ability to compensate NSCs and harmonics by adopting a suitable control, then it represents a balanced traction load to the public grid (Luo et al., 2011). Indirect MMC control is different when it operates as a SFC or as a RPC, where this control is a big challenge and affects directly the output waveforms and the power quality on the public grid side (Liu et al., 2013; Song et al., 2016).

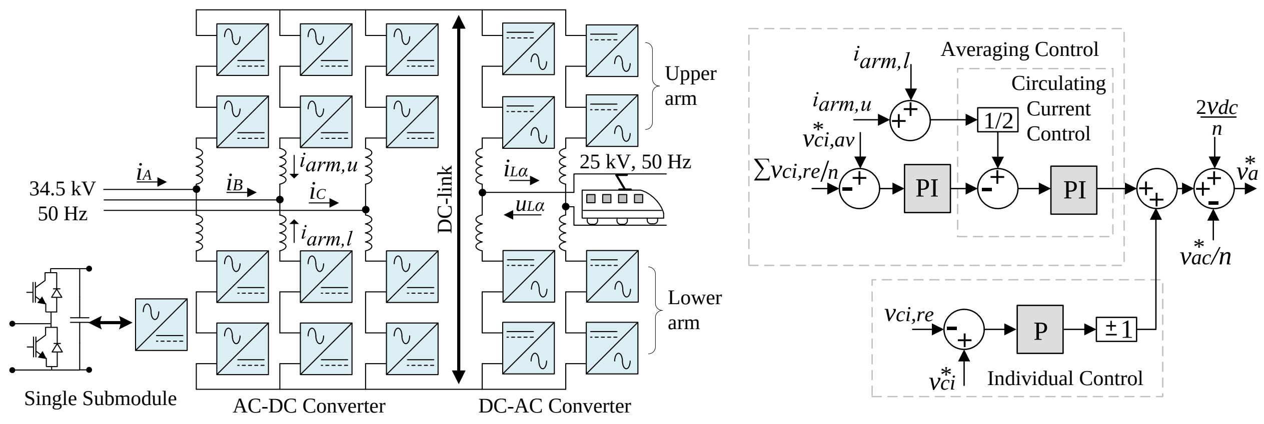
It has been noticed that over the last few years, railways substations have grown in use both of the indicated systems (SFC and RPC based on MMC) for the economic utilization of public grid. However, an estimated cost analysis and efficiency comparison for both indicated systems were never analyzed in the literature. In this context, the main contributions of this paper are: comparative study when the indirect MMC is used as a SFC to prevent the NSCs and harmonics from passing to the public grid, or when the MMC is used as a RPC to compensate NSCs and harmonics on the public grid side; estimating the costs of implementation between the SFC and the RPC based on an indirect MMC, taking into consideration analyzing the inherent benefits of both indicated systems from different perspectives. Next section presents in detail both systems and the control algorithms. Then, the paper shows some operational scenarios to establish an efficiency comparison for both solutions. The final section presents the main conclusions of this work.

SYSTEMS ARCHITECTURE AND CONTROL ALGORITHM

SFC Based on an Indirect MMC

SFC can achieve harmonics filtering because any harmonic currents produced by the locomotives side are prohibited to pass through the AC/DC converter and its DC-link. Besides, balancing the public grid side currents is also an inherent advantage of using SFC to feed the single-phase traction load (Perin et al., 2015). The topology in the Figure 1(a) is used when the output frequency has a value of 50 Hz, because at lower frequency levels such as 16.7 Hz, the indirect AC/DC/AC MMC requires large floating capacitors (Krastev et al., 2016) comparing with the direct AC/AC MMC. On the locomotive side, there is no need to use a power transformer because the MMC is a transformer-less converter and has the ability to operate at medium voltage levels below 66 kV. The indirect AC/DC/AC MMC consists of a three-phase AC/DC converter connected back-to-back to a single-phase DC/AC converter. MMC arms are connected through a coupled inductance 6.8 mH which operates as a converter's inner filter to suppress any fault currents that could appear on the locomotive side or between the MMC arms.

There are several control methods that can be applied, but the simplest, is the carrier phase-shifted sinusoidal pulse width modulation, because it has the ability to balance capacitors voltage and effectively reducing the harmonics (Liu et al., 2013). The carriers are shifted to each other by the angle of $360/n$, where n is the total number of SMs in both lower and upper arms. The control strategy is shown in the Figure 1(b) and is mainly consisting of the averaging control which ensures that the voltage of each capacitor in the leg is close to the average voltage $v^{*}_{ci,av}$ that is provided as a reference. It is implemented by summing the measured capacitors' voltages for each leg and divide the result by n. The output of the first proportional-integral (PI) controller is a reference value for the circulating current controller, where the reference current is compared to the actual one that is acquired by measuring the arms currents. The output signal is sent to the second PI controller as an input to achieve a closed loop control for the circulating current.



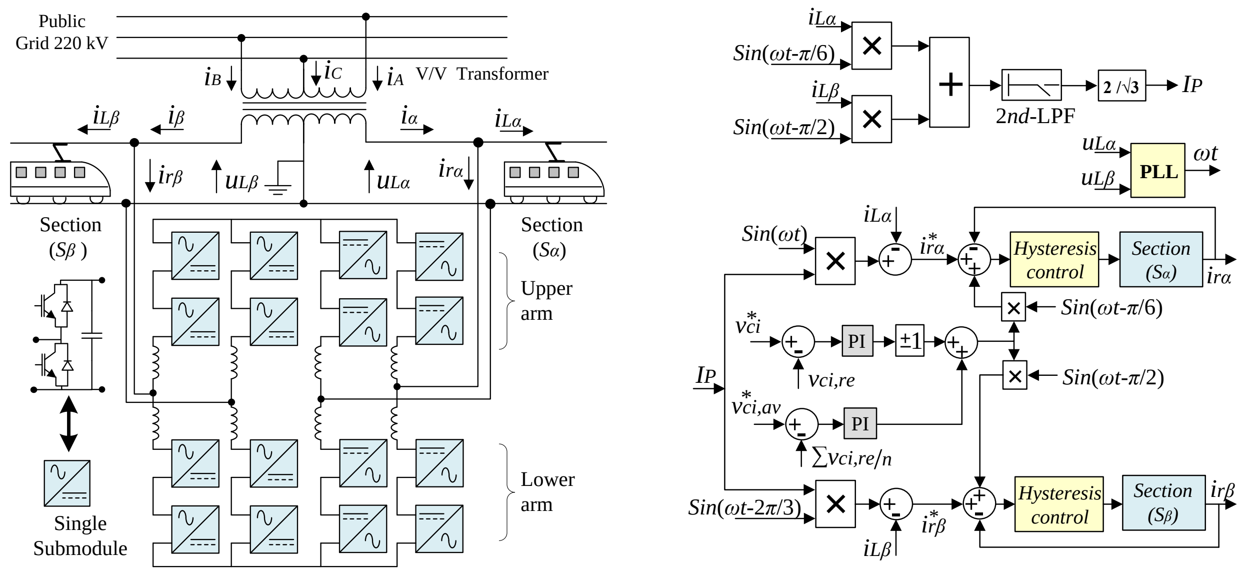
(a) (b)

Figure 1: SFC based on an indirect AC/DC/AC MMC: (a) SFC system topology; (b) SFC control algorithm.

The individual control is responsible to set every capacitor's voltage to its reference value v^*_{ci} and it uses a proportional controller to act dynamically in the balancing process in every switching period. The output of this proportional controller is multiplied by 1 if the current's direction is to charge the capacitors or by -1 if its direction is to discharge the capacitors (Rejas et al., 2015). The next step is to form an appropriate reference signal for each SM to send it to the modulator, where the total signal is compared with a reference signal divided by n. The output of the adder is shifted by the value of $2v_{dc}/n$, where v_{dc} is the DC-link voltage. Consequently, the final reference signal for each capacitor is now compared to its triangular carrier.

RPC Based on an Indirect MMC

Another prominent solution in the high speed electrified railways to overcome the drawbacks of current harmonics and NSCs on the public grid side is the use of RPC as shown in Figure 2(a) (Luo et al., 2011). The RPC consists of a step-down V/V high power transformer to feed the catenaries of two load sections (S_α) and (S_β) with 25 kV, 50 Hz and the primary windings of this transformer are normally connected to high voltage levels around 220 kV. The amount of NSCs depends on the topology of the traction power system, particularly, the type of the used traction power transformer (Zhang et al., 2016).
Indirect MMC with half-bridge SMs is the main part of this RPC and its control strategy is shown in Figure 2(b). The control is performed by using full system analysis and the mathematical equations which presented in (Luo et al., 2011; Wu et al., 2012; Zhang et al., 2016). The inputs of this control are the currents of both load sections $i_{L\alpha}$ and $i_{L\beta}$ and they have been corrected by multiplying them with the corresponded voltage signals, then the resulting signal has filtered by using a low pass filter (LPF) and multiplied with $2/\sqrt{3}$ to give the peak value I_P of phase α and phase β currents after compensation. Consequently, it is possible to acquire the instantaneous currents values of phase α and phase β after multiplying I_P with the corresponded sinewaves. The main purpose of this control is to calculate the total compensating currents (reference currents) $i^*_{r\alpha}$, $i^*_{r\beta}$ which the converter should give to present a balanced load with only positive sequence current components. The hysteresis controller is used for each converter to ensure a fast dynamic response and to track the reference currents values for both load sections (S_α) and (S_β), but this controller does not have the ability to achieve voltage balancing control between MMC SMs capacitors.



(a) (b)

Figure 2: RPC based on an indirect AC/DC/AC MMC: (a) RPC system topology; (b) RPC control algorithm.

As the case of SFC control in Figure 1(b), voltage balancing control for MMC SMs is also required here to guarantee an equal voltage for all SMs. The upper PI controller is used to correct the difference between the actual and the reference value for each SM capacitor voltage. The output signal for this controller is multiplied by 1 if the current's direction is to charge the capacitor and by -1 if its direction is to discharge the capacitor. The lower PI controller is used to operate dynamically in the average voltage balancing process. The actual average voltage value in this case is calculated and compared to the reference average voltage value $v^*_{ci,av}$. Obtaining the actual value is possible by summing the measured capacitors voltages for each leg and dividing the result by the number of SMs per leg n. Both PI controllers are used to maintain a constant value of the converter's DC-link. Then, the output of both controllers should be synchronized with the corresponding voltage signals.

INHERENT BENEFITS AND COST ESTIMATION

Different abilities or inherent benefits for both systems have presented in the Figure 3(a). Both of SFC and RPC are able to achieve phase balancing on the public grid side, and each system has some advantages over the other one. SFC has a better fault current limitation on the locomotive side because of existing a coupled inductance connected dire ctly to the catenary line and it can perform a frequency conversion because it has a DC-link. Nevertheless, because of using a V/V power transformer, the RPC system has a better overload capability than the SFC (Perin et al., 2015). Consequently, overloading the SFC is not recommended because it may damage the switching devices (IGBTs) or the SMs capacitors.
The catenary's voltage of SFC has a direct relation with the indirect MMC performance. Therefore, the SFC is less robust and has a worse power factor correction than the RPC. Moreover, SFC can accept load sharing with other devices, which is not possible in the case of RPC (Gazafrudi et al., 2015).
SFC can prevent the harmonics from passing to the public grid side and it represents a balanced load without NSCs on the public grid side, while the RPC has the ability to compensate these harmonics and NSCs, and it also represents a balanced load on the public grid side. The passive filters on the public grid side are required in both systems to compensate some additional harmonics (Perin et al., 2015). Furthermore, the RPC system with a V/V power transformer contains a neutral section which separates the catenary line for two load sections, while using the SFC eliminates completely the need of a neutral section in the catenary line.
The estimated total costs for both systems are close to each other and they have been analyzed in the Figure 3(b). Cost estimation analysis took in to account the same output voltage level of MMC and eight factors to make the comparison: The number of IGBTs, number of SMs capacitors, the coupled inductors between MMC arms, using passive filters on the public grid side to compensate harmonics, the required sensors which are important to obtain the control signals, the power rating of the IGBTs, implementation of the control algorithm for each system and the need of a power transformer.

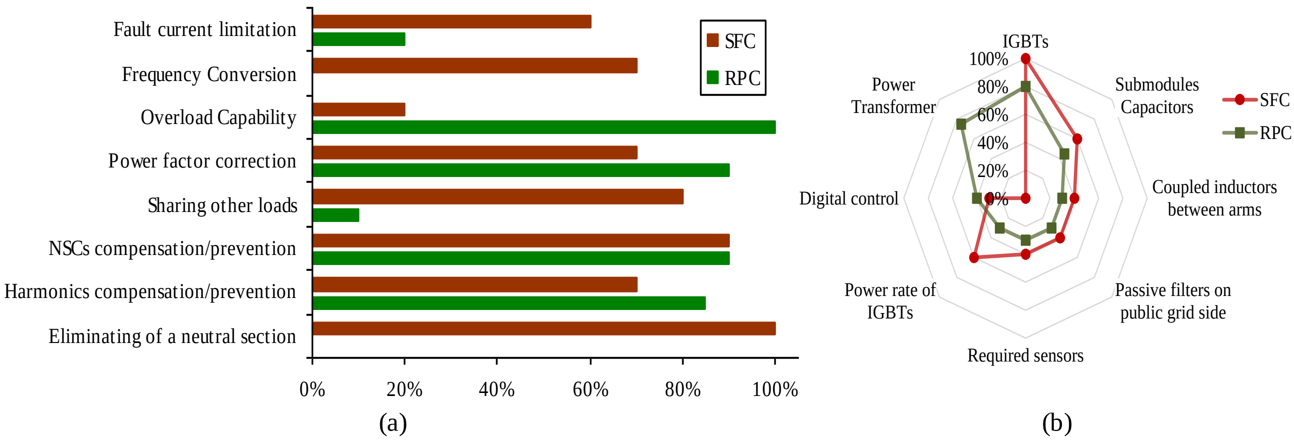


Figure 3: Comparison between SFC and RPC based on an indirect MMC: (a) different inherent benefits and the abilities for each system; (b) estimated cost of implementation.

From Figure 1(a) and Figure 2(a), SFC system requires more IGBTs, SMs capacitors and coupled inductors between MMC arms than the RPC system. Consequently, that requires the use of many current and voltage sensors in the SFC system. In addition, the power rating of the IGBTs is a very important factor to estimate the costs of each system, because the locomotive power in the case of SFC is mainly handled by the MMC's IGBTs, while in the case of RPC, this power took a path through the V/V power transformer and the MMC's function in this case is just to compensate harmonics and NSCs (Luo et al., 2011). As a result, the power rating of the IGBTs in SFC system should be more than what it is in the RPC system and that increases the total costs of SFC system.
V/V power transformer is one of the main parts of RPC system to step-down the input voltage and to obtain two load sections. The step-down transformer is not required in the SFC system, especially when the SFC is connected to the medium voltage levels and when the power electronics devices can withstand with the medium voltage values. However, V/V transformer increases the total costs of RPC system and it makes the system much more reliable solution than the SFC in electrified railways applications (Gazafrudi et al., 2015).
Figure 1(b) and Figure 2(b) show that the RPC control is more complex than the SFC one and the passive filters are often required on the public grid side for both indicated systems to compensate some additional harmonics which could appear from the IGBTs switching frequency. As a result, both systems of SFC and RPC have almost a close estimated cost of implementation, taking into account that the cost depends highly on the required MMC voltage level, because a higher voltage level determines more IGBTs and more SMs capacitors. Due to of some restrictions and the limited pages

of this paper, Figure 3(b) does not present in detail the relative costs of each analyzed parameter and it only gives a percentage ratio of the cost for each equipment, after considering the total price of IGBTs in SFC system as a reference to estimate the costs of other power devices.

SIMULATION RESULTS

This section presents some simulation results that related to the power quality on the public grid side and the efficiency for both indicated solutions of SFC and RPC. The simulation models for both SFC and RPC based on an indirect MMC have been obtained by using *PSIM* software for power electronics simulation, taking into consideration the same locomotive load power 4.8 MW to establish an efficiency comparison between both solutions of SFC and RPC. The locomotive is normally modeled as a resistive load (R_1) connected in parallel with an uncontrolled bridge rectifier on the secondary side of the locomotive transformer. The output of this single-phase rectifier is connected with an inductive load (R_2, L_2). The values of these parameters in the model are: ($R_1 = 0.8\ \Omega$, $R_2 = 1\ \Omega$, $L_2 = 2$ mH) and the turns ratio of the locomotive transformer is $k = 17$, where the voltage on the primary windings (catenary voltage) is 25 kV, 50 Hz. The MMC voltage levels in both solutions have exactly the same value of 5 levels, then the number of SMs in each converter's arm is four SMs.

Figure 4 shows the simulation results for both systems, where i_A, i_B, i_C are the public grid side currents, u_α and $i_{L\alpha}$ are the locomotive voltage and current respectively, η is the total efficiency for the indicated system and $PF_{L\alpha}$, PF_s are the power factors for load section side and public grid side respectively. Public grid currents are balanced and have sinusoidal waveforms when using the SFC or the RPC. Nevertheless, SFC normally requires to use high values of the coupled inductors or passive filters to decrease the harmonics currents and that can decrease the power factor on the public grid side as shown in the Table 1. Besides, public grid currents have a higher value of the total harmonic distortion (THD) when using the SFC comparing to the RPC waveforms. Public grid voltages are different for both cases, where the SFC operates on the medium voltage levels of 34.5 kV and the RPC operates on high voltage levels around 220 kV as shown in Figure 1(a) and Figure 2(a). Therefore, public grid currents i_A, i_B, i_C for both cases have different values.

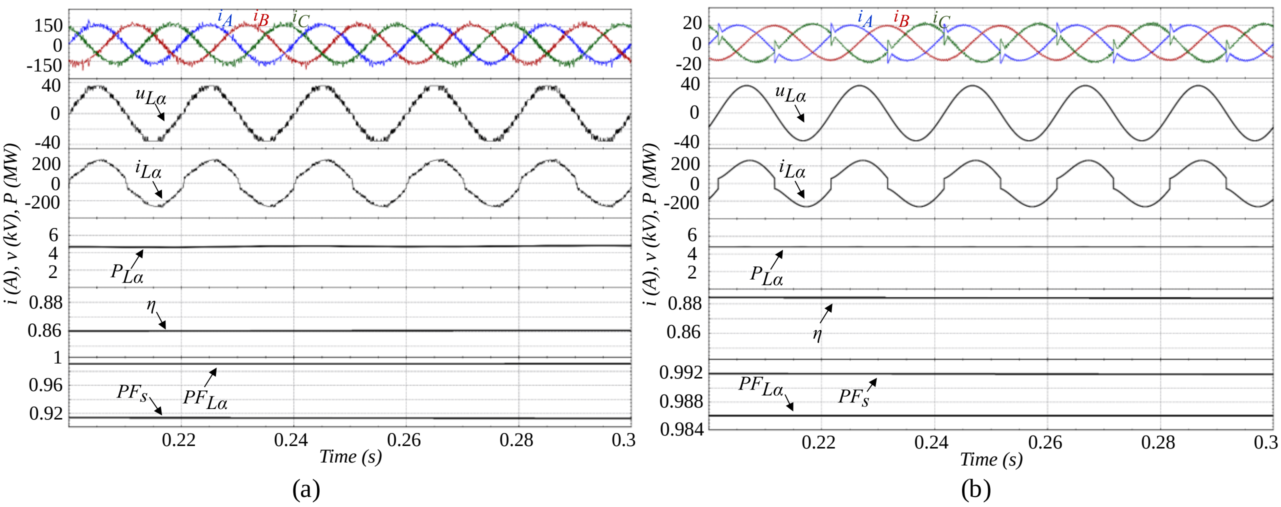


Figure 4: Simulation results for both systems: (a) SFC based on an indirect MMC; (b) RPC based on an indirect MMC.

Figure 4 shows the main power quality and efficiency waveforms which summarized in the Table 1 after applying the same load power in both systems. When using the RPC system, public grid currents have less harmonics contents (the THD is lower) and the public grid has a higher power factor value comparing with the case of SFC. The total losses of RPC system can mainly classified into: V/V power transformer losses (copper losses and iron losses) and the losses in the power electronics devices (IGBTs, inductors and the capacitors), while the total SFC losses depend only on the ones in the power electronics devices. Although of using a V/V power transformer in RPC, the results show that RPC has a better total efficiency because it uses less number of IGBTs, SMs capacitors and coupled inductors. Consequently, it operates with less power losses than the SFC. Load side power factor in both cases has an equal value because all load's parameters such as power, current and voltage are the same.

Table 1: THDs, power factors and efficiency when using both of SFC and RPC systems.

The system	(THD) i_A	(THD) i_B	(THD) i_C	$PF_{L\alpha}$	PF_s	η
SFC	11.3%	11.0%	11.2%	0.985	0.915	86.0%
RPC	9.4%	4.8%	9.5%	0.986	0.992	88.4%

The catenary voltage $u_{L\alpha}$ has a multilevel waveform in SFC system because it is created by a DC/AC MMC, while, in RPC case, it has completely a sinusoidal waveform because it is resulting from the secondary windings of V/V transformer. Locomotive currents in both solutions have similar waveforms because the simulation model has been considered the same locomotive parameters.

CONCLUSION

In this paper is done a comparative study between the static frequency converter (SFC) and the rail power conditioner (RPC) based on an indirect AC/DC/AC modular multilevel converter (MMC) in electrified railways applications. The inherent benefits and the estimated cost analysis for each system have been described in this paper. The simulation results showed that both of the studied systems have the ability to present balanced and sinusoidal currents on the public grid side without negative sequence components (NSCs). Athought the SFC system has more inherent benefits than the RPC, such as the ability of frequency conversion, accepting load sharing with other SFC systems, eliminating of neutral sections and presenting a better fault current limitation on the catenary line, the RPC is more robust and efficient for electrified railways applications, because it can be overloaded, presents a better public grid power factor correction and has an improved performance to compensate harmonics currents and NSCs on the public grid side.
The SFC normally requires the use of higher values of passive filters on the public grid side, besides the coupled inductors between the converter's arms to suppress the current harmonics and fault currents of the public grid. This high value of inductance could affect negatively the public grid side power factor and in some cases, the total SFC efficiency. The estimated cost of implementation for the SFC depends highly on the required MMC voltage level and the power rating of the switching devices (IGBTs), while in RPC case, it highly relies on the cost of V/V power transformer besides the required MMC voltage level. Both systems have a close estimated cost of implementation; however, the SFC tends to be more expensive than the RPC when the required voltage level and the power rating of the IGBTs are high.

ACKNOWLEDGMENT

This work has been supported by COMPETE: POCI-01-0145-FEDER-007043 and FCT – Fundação para a Ciência e Tecnologia within the Project Scope: UID/CEC/00319/2013.
Mohamed Tanta is supported by FCT doctoral scholarship with a reference PD/BD/127815/2016.

REFERENCES

Abrahamsson, L.; Schütte, T.; and Östlund, S. 2012. "Use of converters for feeding of AC railways for all frequencies". Energy Sustain. Dev. 16, 368–378.

Gazafrudi, S.M.M.; Langerudy, A.T.; Fuchs, E.F.; and Al-Haddad, K. 2015. "Power Quality Issues in Railway Electrification: A Comprehensive Perspective". IEEE Trans. Ind. Electron. 62, 3081–3090.

Gruber, R; and O'Brien,D. 2014. "Use of Modular Multilevel Converter (MMC) technology in rail electrification". In AusRAIL PLUS 2014, Doing it Smarter. People, Power, Performance, 24-26 November 2014, Melbourne, Vic, Australia

Krastev, I.; Tricoli, P.; Hillmansen, S.; and Chen, M. 2016. "Future of Electric Railways: Advanced Electrification Systems with Static Converters for ac Railways". IEEE Electrification Mag. 4, 6–14.

Liu, G.; Jiang, Q.; and Wei, Y. 2013. "Study on Capacitor Voltage Balancing Control of Modular Multilevel Converter at Low Frequency". Int. J. Comput. Electr. Eng. 196–200.

Luo, A.; Wu, C.; Shen, J.; Shuai, Z.; and Ma, F. 2011. "Railway Static Power Conditioners for High-speed Train Traction Power Supply Systems Using Three-phase V/V Transformers". IEEE Trans. Power Electron. 26, 2844–2856.

Perin, I.; Nussey, P.F.; Cella, U.M.; Tran, T.V.; and Walker, G.R. 2015. "Application of power electronics in improving power quality and supply efficiency of AC traction networks". In 2015 IEEE 11th International Conference on Power Electronics and Drive Systems, pp.1086–1094.

Rejas, M.; Mathe, L.; Burlacu, P.D.; Pereira, H.; Sangwongwanich, A.; Bongiorno, M.; and Teodorescu, R. 2015. "Performance comparison of phase shifted PWM and sorting method for modular multilevel converters". In 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), pp.1–10.

Song, S.; Liu, J.; Ouyang, S.; and Chen, X. 2016. "A modular multilevel converter based Railway Power Conditioner for power balance and harmonic compensation in Scott railway traction system". In 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), pp.2412–2416.

Steimel, A. 2012. "Power-electronic grid supply of AC railway systems". In 2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp.16–25.

Wu, C.; Luo, A.; Shen, J.; Ma, F.J.; and Peng, S. 2012. "A Negative Sequence Compensation Method Based on a Two-Phase Three-Wire Converter for a High-Speed Railway Traction Power Supply System". IEEE Trans. Power Electron. *27*, 706–717.

Zhang, D.; Zhang, Z.; Wang, W.; and Yang, Y. 2016. "Negative Sequence Current Optimizing Control Based on Railway Static Power Conditioner in V/V Traction Power Supply System". IEEE Trans. Power Electron. 31, 200–212.