



## A Direct Power Feeding System for AC railway Networks Using Modular Multilevel Converter

Hamed Jafari Kaleybar<sup>1</sup>, Hossein Madadi Kojabadi<sup>2\*</sup>, Seyed Saeed Fazel<sup>3</sup>, Federica Foiadelli<sup>4</sup>, Morris Brenna<sup>5</sup>

<sup>1,2</sup>Department of Electrical Engineering, Sahand University of Technology, Tabriz, Iran

<sup>3</sup>School of Railway Engineering, Iran University of Science and Technology, Tehran, Iran

<sup>4,5</sup>Department of Energy, Politecnico di Milano, Milan, Italy

### ARTICLE INFO

#### Article history:

Received: 14.03.2018

Accepted: 24.05.2018

Published: 15.06.2018

#### Keywords:

Electric railway system

Traction substation

Modular Multilevel Converter

Power Quality

### ABSTRACT

Traditional railway power supply systems impose substantial power quality problems (PQ) on the utility network, such as unbalance, harmonics and a large amount of reactive power. This paper proposes a topology based on three-phase to single-phase modular multilevel converters (MMC) to obviate these problems. The MMC based traction substations (TSS) are connected directly to the utility grid through the three-phase side of MMC. The proposed system symmetrically transfers active power from three-phase grid to the single-phase overhead catenary system (OCS) which compensate negative sequence current (NSC), reactive power and harmonics simultaneously. Eliminating bulky traction transformers (TT), integrating OCS, removing the neutral sections and increasing the train speed are the advantages of the proposed system. The precise simulations are provided to verify the performance of the proposed method.

## 1. Introduction

In recent years, the 25 kV single-phase AC system has been widely exploited in high-speed and long-distance railway lines. The single-phase supply and load characteristics of locomotives in this system lead to substantial power quality (PQ) problems like negative sequence current, harmonics, voltage fluctuation and low power factor (PF) [1-3]. To deal with these problems, different methods and strategies have been presented in the literature. Various balanced transformers such as Scott, Roof-delta, Impedance-matching, and Woodbridge have been adopted in TSS to eliminate NSC [4-6]. However, with variable and unequal traction loads, the system still remains unbalanced. Adopting the FACTS instruments, passive filters and active power filters are the other utilized methods of compensation which have deficient

compensation [7-9]. Introducing the railway power conditioner (RPC), a significant evolution in compensation has been performed [10-12]. The conventional RPC based railway system is illustrated in Figure 1. The RPC consists of two back-to-back (B2B) converters with a common dc-link capacitor which is installed at the secondary side of the TSS. It can transfer active and reactive powers from one feeder section to adjacent section and compensate harmonics. This system usually adopts two split catenaries supplied by different phase conductors of the 3-phase industrial system in every TSS. The sections are isolated by neutral section (NS) with the length of several hundred meters. Crossing the NS, the speed of the train will be decreased and the passengers may feel uncomfortable. Furthermore, switching the power supply of train in each NS needs the expensive switches and controllers. Therefore,

\*Corresponding author

Email address: hmadadi64@yahoo.ca

the procedure of one track line according to active power compensator (APC) was presented as the co-phase traction power supply systems (TPSS) [13, 14]. The APC can balance the active power consumed by two secondary-side windings of the TT and improve the reactive power together with mitigating harmonics. Figure 1 demonstrates the co-phase supply system. The NS number has been decreased by half. The remained NS are replaced by section insulators and the need for insulation has been decreased. However, the voltage of TT cannot be controlled and the terminals of catenaries cannot be connected directly. In addition, the train should reduce its speed when pantographs cross the insulated sections. To link the whole catenary system together and eliminate the neutral and insulation sections, an advanced co-phase system introduced in [15, 16]. As shown in Figure 2, this system is based on the 3-phase to single-phase converter. From high-voltage (HV) side, the 3-phase rectifier based converter transfers power from the utility into the capacitor and charge it in the form of dc power. Then, the full-bridge converter acts as an inverter and transfers dc power to the catenary. This structure has the capability of transferring the active power from HV utility to single-phase catenary, link the catenaries, and compensate the harmonics and reactive power simultaneously.

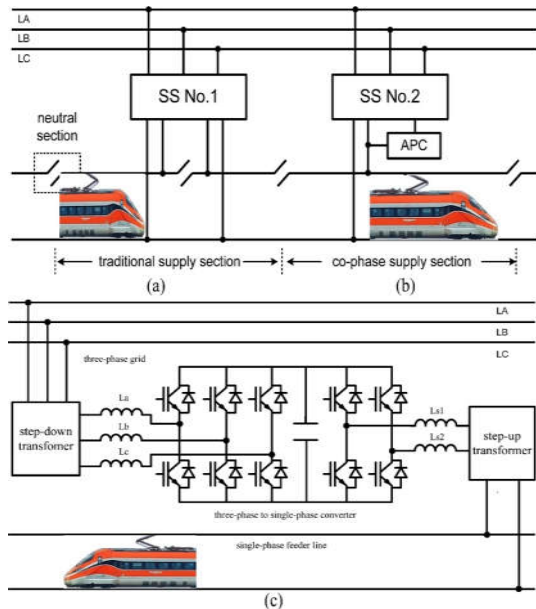


Figure 1. Three various TPSSs. (a) Conventional. (b) Co-phase. (c) Advanced co-phase.

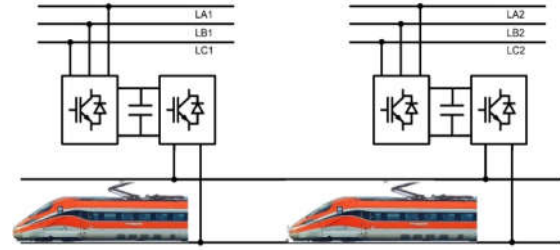


Figure 2. Indirect ac-dc-ac converter TPSS.

Despite this, the DCMC-based ac-dc-ac converter in this system requires a complex dual control system both in rectifier and inverter section. Moreover, this topology adopts two high-capacity step-down transformers (SDT) to subtract the voltage rating of switches. This bulky transformer results in less compensation capacity, high switching frequency, high power loss as well as large size ac filter. Accordingly, a transformerless method can be a good choice. Recently, by the development of high power semiconductors, modular multilevel converters have attracted experts' attention in the subject of power systems and railway interties. In this paper, a new power supply topology based on direct AC/AC MMC is presented. The schematic of the proposed system is shown in Figure 3. The suggested system does not require NS and IS and hence the OCS is uniformed and linked.

The rest of this paper is organized as follows. Section 2 describes the proposed system topology and operation principles of MMC. In section 3, the control concepts of proposed MMC are studied in details. In section 4, simulation results and analysis are provided and compared. Finally, section 5 concludes this article.

## 2. System Configuration

### 2.1. MMC converter based topologies

Considering the widespread development of MMCs, they have been identified as an excellent solution in many aspects of electric railway systems. Different MMC based converters have been used in TSS to supply the train powers. The easy to access to a high voltage level, avoiding the defects of static and dynamic voltage balancing, large switching loss, and high harmonic content of the device are the foremost advantages of MMCs. In Japan Tokaido Shinkansen, a new Electronic Frequency Converter (EFC) to replace Rotary Frequency Changer (RFC) has been built and used [17, 18].

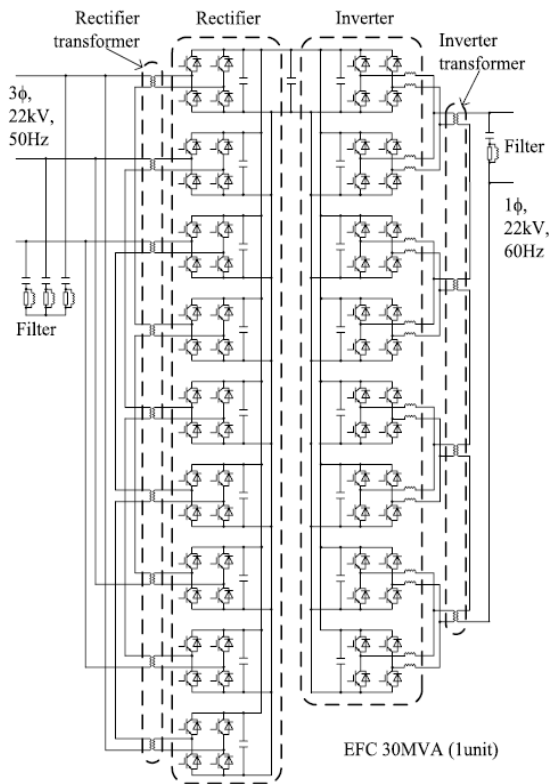


Figure 3. Modular multilevel ac-dc-ac topology as Electronic Frequency Converter (Japan Shinkansen) [17]

The proposed EFC extracts 60Hz single-phase ac in the output side. In fact, EFC transforms 3-phase 50Hz ac into 60Hz single-phase ac. Figure 3 illustrates the 30 MVA EFC topology consisting of a h-bridge cascaded multiple ac-dc-ac converters. The presented EFC has capability of controlling over-current suppression, reducing faults-current, and getting hardness to short faults.

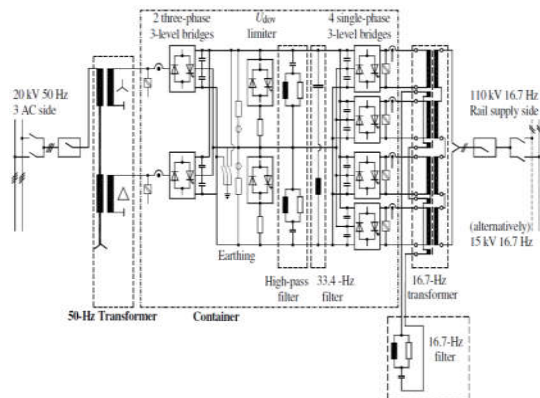


Figure 4. Diode clamped cascaded ac-dc-ac supply converter topology (ABB) [19]

These developments lead to the capacity reduction of the EFCs and the interconnect operation with them, using interlink signals. This makes EFC a flexible and useful power supply [18].

Nowadays, the two European giant electric railway companies are mainly ABB and Siemens. Each of these companies has provided a specific structure to supply the train's power. The main circuit structure of ABB company adopts diode clamped cascaded ac-dc-ac converter topology. This topology is provided by Deutsche Bahn. In 1995, Deutsche Bahn (German Railway Company) proposed a 15-MW standard railway intertie converter developed to replace old single-phase power stations and rotary converters. The 3-phase line-side converters used in this structure are similar to three-level construction. Figure 4 displays the structure of this supply converter. In this topology, the bridges of both sides are operated with 50 Hz switching frequency in order to get minimal line interference. The output voltages of the 16.7 Hz inverters are switched synchronously. Also, a relatively small 16.7-Hz filter is implemented via secondary windings of the two transformers [19].

The topology presented by Siemens adopts modular multilevel ac-dc-ac conversion topology. It is demonstrated in Figure 5.

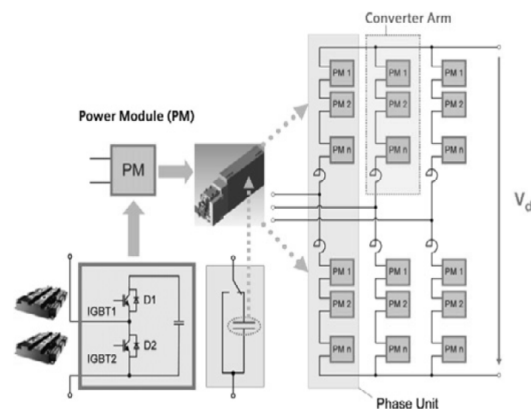


Figure 5. Modular multilevel ac-dc-ac topology (Siemens) [20]

The branches of MMC contain unipolar converter cells (UC). Each phase includes the two branches with number of N UCs [20, 21]. The presented indirect converter system in this Figure has a 3-phase and a 2-phase MMC which is connected to a dc terminals as can be seen in Figure 6.

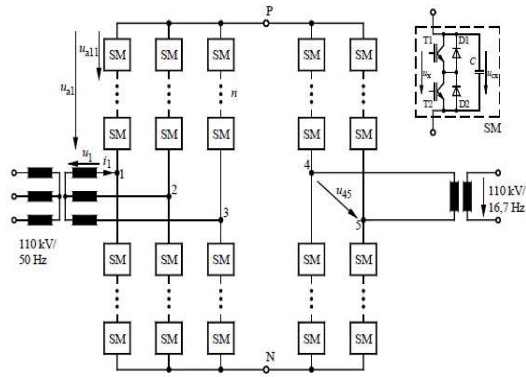


Figure 6. Modular multilevel ac-dc-ac topology [21]

The inductors in each branch facilitate controlling of the currents in each branch. In this structure, there is no need for additional ac filters because of the increased number of voltage levels and the higher switching frequency.

The 3-phase to single-phase MMC applied in the proposed TPSS has a direct conversion. The structure of the MMC topology based on ac-ac direct converter is demonstrated in Figure 7. The branches in direct MMC consist of bipolar cells (BCs) and branch inductors. Since the converter is usually connected to the high-voltage grid the isolation transformers should be used in field application. The converter is comprised of three independent single-phase branch pairs. Each converter arm consists of N identical sub modules and is equipped with bipolar cell and an

inductor. Each converter module has an individual DC-link capacitor. The branch inductors in this configuration are essential to limit the current harmonics. The increasing number of sub-modules in MMC can decrease the rated voltage level of power switching devices and leads to eliminate the SDT and its mentioned disadvantages.

### 2.2. Technical and performance comparison

Choosing a suitable power supply system for high-power and high-capacity railway systems are important, especially in case of assessing their suitability and future projection. To illustrate the main advantages of the proposed method, a comparative table based on the utilization and economic factors is presented in Table 1. As demonstrated in the table, independency for transformers and filters are one of the major advantages of these types of systems. Also, due to the conversion topology, the efficiency of the proposed system is high. However, the power electronics based converters investment costs are high. This has restricted their use on new power supply railway systems.

### 3. Control Concept

The implemented control strategy for the proposed MMC is based on controlling of the

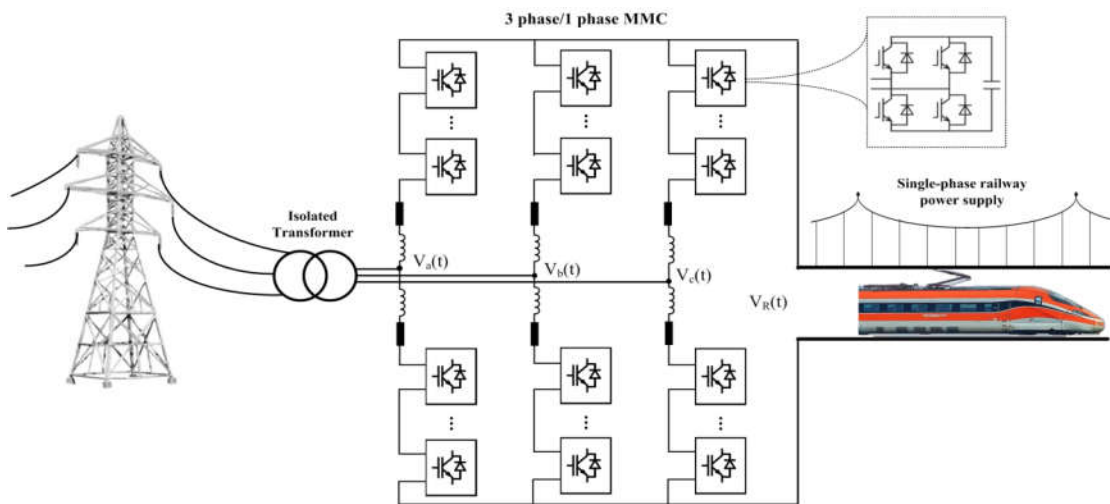


Figure 7. Proposed TPSS based on direct 3-phase to single-phase MMC

Table 1. Performance comparison of different power supply system's topology

Topology Type	PQ problems mitigation	Input/output filter	Transformer	Utilization speed of trains	Total manufactured cost	Efficiency
Traditional power supply	✓	No need	Need	✓	✓	✓
Co-phase power supply	✓✓	No need	Need	✓✓	✓	✓✓
Advanced co-phase power supply	✓✓	No need	Need	✓✓✓	✓✓	✓✓
Diode-clamped cascaded ac-dc-ac topology	✓	Need	Need	✓✓✓	✓✓✓	✓✓
MMC ac-dc-ac circuit topology	✓	No need	No need	✓✓✓	✓✓✓	✓✓✓
Cascaded multiple ac-dc-ac topology	✓	Need	Need	✓✓✓	✓✓	✓✓
Direct MMC method	✓✓	No need	No need	✓✓✓	✓✓✓	✓✓✓

active and reactive power, line current, branch current and energy in the branches. Furthermore, the voltages of individual cell in each branch should be stabilized. There is a widespread discussion about the stabilization of the individual cell voltages in the literature [22] and therefore it is not mentioned in this paper. A branch of the proposed MMC is connected to an ac terminal of grid voltage and another ac terminal is connected to an ac voltage  $V_R(t)$  with ac current  $i_R(t)$ . The branch power which is related to the input power and output power of the branch can be defined as in Equation (1).

$$P_{br}(t) = (V_R(t) - V_x(t)) \times i_{br}(t) \Big|_{x=a,b,c} \quad (1)$$

The ac terminal power is as follows:

$$P_x(t) = V_x(t) \times i_x(t) \Big|_{x=a,b,c} \quad (2)$$

The branch current contains half of the ac output current and one third of the terminal current  $i_R(t)$  as:

$$i_b(t) = \frac{i_U(t)}{2} + \frac{i_R(t)}{3} \quad (3)$$

Substituting (3) in (1) the branch power can be calculated as:

$$P_b(t) = \frac{V_R(t)i_U(t) - V_U(t)i_U(t)}{2} + \frac{V_R(t)i_R(t) - V_U(t)i_R(t)}{3} \quad (4)$$

It should be noted that the average amount of the power must be zero to avoid each cell capacitor to be overcharged or discharged during the operation. Calculating the dc parts of the power and substituting  $V_R(t) = \sqrt{3}V_U(t)$  and

$i_R(t) = \frac{1}{2\sqrt{3}}i_U(t)$ , the dc or average part of the branch power is zero.

#### 4. Simulation Results

To validate the effectiveness of the proposed configuration, simulations are modeled in two cases by using MATLAB SimPowerSystems Toolbox. The nominal power in the rail feeder is considered as  $S_N = 10$  MVA with the nominal voltage of  $V_R = 25$  kV. An inductance of 0.1 p.u. is applied on the catenary side to limit short circuit currents in failure situation. The design of the MMC proposed system depends on the interior protection equipment. The maximum MMC converter output voltage is determined based on the customer requirements. In railway systems, a maximum transient overvoltage is considered as 20%. Therefore, the maximum transient overvoltage in designing is assumed as 30kV. Thus, the maximum converter voltage is 42.5kV. The number of cells in MMC topology are calculated based on the cell voltage. According to this voltage the switch module for the cells are determined.

Considering the 4.5kV IGBT modules with 2.9 kV and voltage fluctuation of +/-10%, the number of  $N=16$  cells per branch are determined to have the capability of blocking the overvoltage of 42.5kV. With  $N=16$ , the superposition of the three branch output voltages is going to be a 48-level waveforms.

The proposed TPSS is simulated for two various cases with both 16.67 Hz and 50 Hz outputs separately.

**A. Case 1: railway terminal power supply with 16.67 Hz**

The inconvenience of ac motors working with large loads at the industry frequency led to the progress of the 16.67 Hz system in some European countries like Switzerland, Germany and Austria. In this situation, the traditional ac converter-based systems connect the utility to the catenary via the rotary or static converters. However, the main disadvantages of these methods is the higher losses and high capacity. Therefore the MMC converters can be an appropriate alternative.

In this case the output voltage frequency of MMC converter is assumed to be 16.67 Hz. Figure 8 illustrates the voltage waveforms related to grid, output and branches of the proposed MMC.

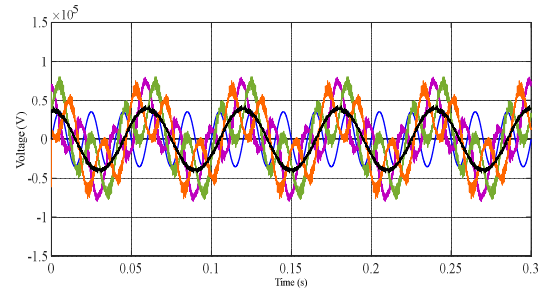


Figure 8. Case 1- Voltage waveforms of 3-phase to single-phase MMC: Input grid voltage 50 Hz (blue), 48-level output voltage of converter 16.67 Hz (black) and the branch voltages

In Figure 9 these waveforms are separated and are clearly presented. As illustrated, the input 3-phase 50 Hz voltages are converted to single-phase 16.67 Hz voltage which is made of 48 levels. The distinguished and enlarged parts of output voltage show the superposition of the

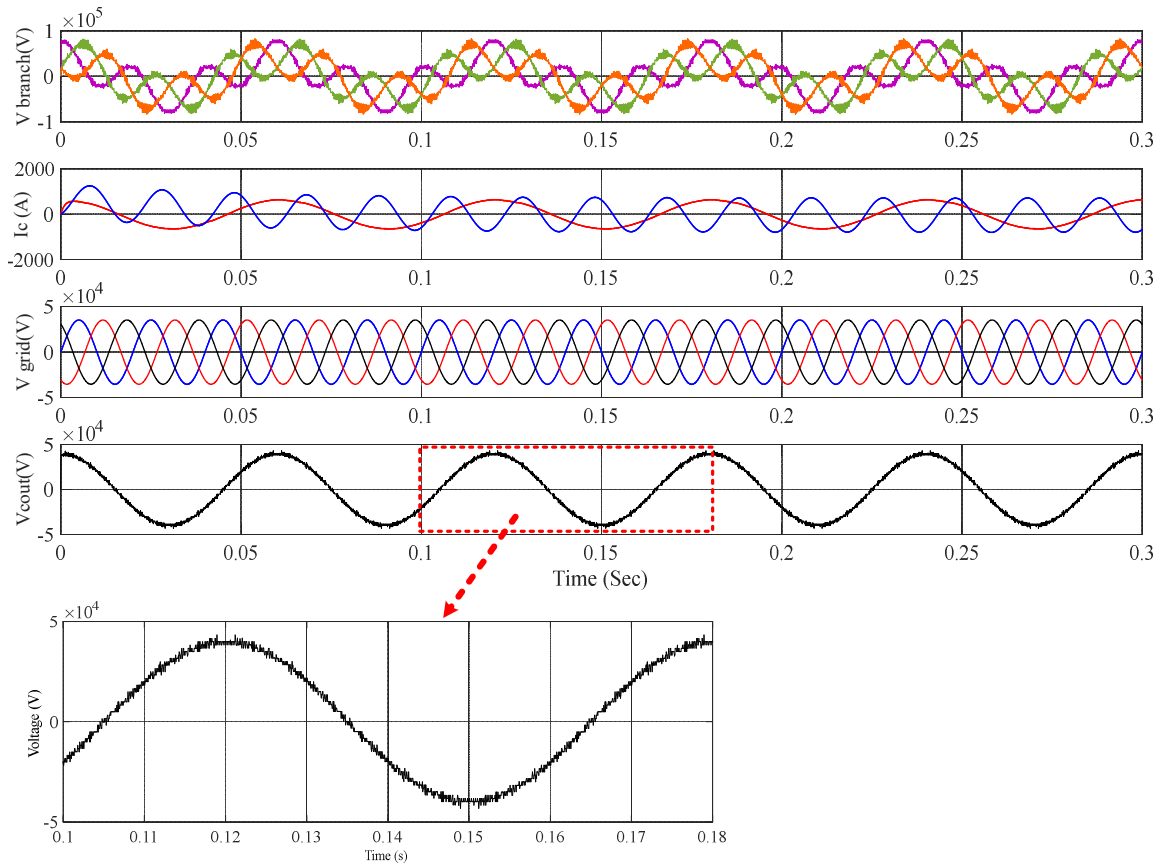


Figure 9. Case 1- Voltage and current waveforms of 3-phase to single-phase MMC: From top: branch voltages, input (50 Hz) and output (16.67 Hz) currents, 3-phase grid voltages (50 Hz), output voltage of converter (16.67 Hz) and the zoomed part of 48-level output voltage

three branches output voltages to a 48-step waveform 16.67 Hz.

A. Case 2: railway terminal power supply with 50 Hz

In this case the output voltage frequency of MMC converter is assumed at 50 Hz.

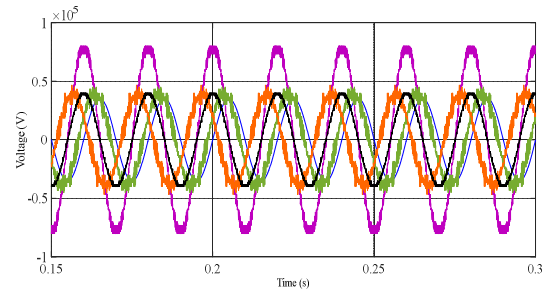


Figure 10. Case 2- Voltage and current waveforms of 3-phase to single-phase MMC: Input grid voltage 50 Hz (blue), 48-level output voltage of converter 50 Hz (black) and the branch voltage

Figure 10 illustrates the voltage waveforms related to grid, output and branches of proposed MMC. In Figure 11 these waveforms are separated and clearly presented. The input 3-phase 50 Hz voltages are converted to single-phase 50 Hz voltage which is made of 48 levels. The one cycle enlarged parts of output voltage shows the superposition of the three branches output voltages to a 48-step waveform 50 Hz.

5. Conclusions

The widespread development of power electronics has revolutionized electric railway networks and made the converter based and transformerless rail interties systems to the forefront. In this paper the direct MMC based conversion system for railway power supply system is presented. At first, the existing principal railway power supply systems are described and evaluated. Then a 48-level direct MMC based traction power supply system is

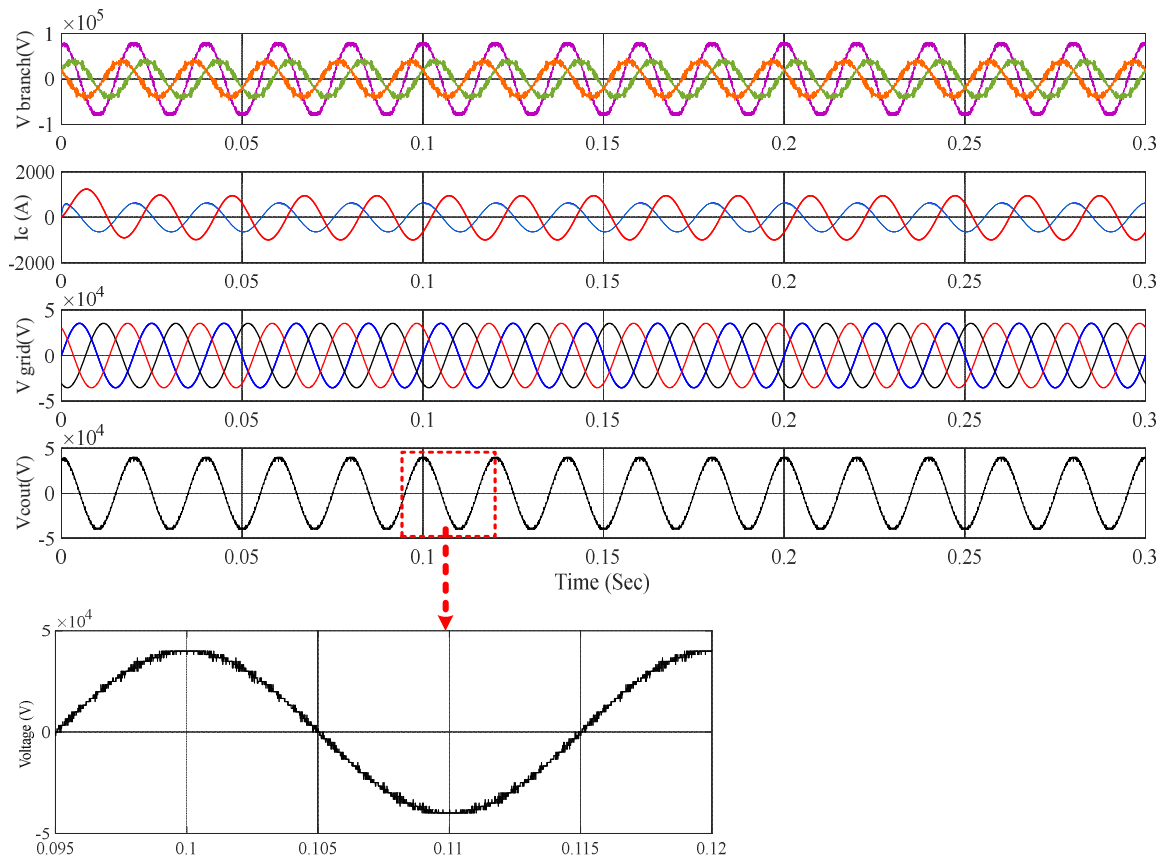


Figure 11. Case 2- Voltage and current waveforms of 3-phase to single-phase MMC: From top: branch voltages, input (50 Hz) and output (50 Hz) currents, 3-phase grid voltages (50 Hz), output voltage of converter (50 Hz) and the zoomed part of 48-level output voltage

proposed. The reduced number of substations, omitting the traction transformers, OCS integrates, removing the neutral sections and increasing the train speed are the foremost privileges of the proposed system. These advantages together with the capability of controlling the power attending to technical and economic constraints has turned the MMC based systems a good choice to become the future railway power supply system.

### References

- [1] S.M. Mousavi Gzafrudi, A. Tabakhpour Langerudy, E.F. Fuchs and K. Al-Haddad, Power quality issues in railway electrification: A comprehensive perspective, in IEEE Transactions on Industrial Electronics, Vol.62, No.5, (2015), pp.3081-3090.
- [2] H.J. Kaleybar, H.M. Kojabadi, S.S. Fazel, F. Foiadelli, An intelligent control method for capacity reduction of power flow controller in electrical railway grids, Electric Power Systems Research, Vol. 165, (2018), pp.157-166.
- [3] H.J. Kaleybar, H.M. Kojabadi, M. Brenna, F. Foiadelli and S.S. Fazel, An active railway power quality compensator for 2×25kV high-speed railway lines, 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Milan, 2017, pp.1-6.
- [4] H.E. Mazin and W. Xu, Harmonic cancelation characteristics of specially connected transformers, Int. J. Electric Power Systems Research, Vol.79, No.12, (2009), pp.1689-1697.
- [5] H.J. Kaleybar, H.M. Kojabadi, M. Fallah, S.S. Fazel, C. Liuchen, Impacts of traction transformers on power rating of Railway Power Quality Compensator, in 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), (2016), pp.2229-2236.
- [6] C. Bin-Kwie, G. Bing-Song, Three phase models of specially connected transformers, IEEE Transactions on Power Delivery, Vol. 11, No. 1, (1996), pp.323-330.
- [7] M. Salehifar, M. Ranjbar, A. Amirahmadi, A. Shoulaie, A combined system of passive filter and TCR for power quality improvement in a 25-kV electrified railway system, in 2009 International Conference for Technical Postgraduates (TECHPOS), (2009), pp.1-5.
- [8] L. Wu, W. Mingli, Single-phase cascaded H-bridge multi-level active power filter based on direct current control in AC electric railway application, IET Power Elec., Vol. 10, No.6, (2017), pp. 637-645.
- [9] A. Benslimane, J. Bouchnaif, M. Azizi, K. Grari, Study of a STATCOM used for unbalanced current compensation caused by a high speed railway (HSR) sub-station, in 2013 International Renewable and Sustainable Energy Conference (IRSEC), (2013), pp. 441-446.
- [10] H. Morimoto, M. Ando, Y. Mochinaga, T. Kato, J. Yoshizawa, T. Gomi, T. Miyashita, S. Funahashi, M. Nishitoba, S. Oozeki, Development of railway static power conditioner used at substation for Shinkansen, in Proceedings of the Power Conversion Conference-Osaka 2002 (Cat. No.02TH8579), Vol.3, (2002), pp.1108-1111.
- [11] A. Luo, C. Wu, J. Shen, Z. Shuai, F. Ma, Railway static power conditioners for high-speed train traction power supply systems using three-phase V/V transformers, IEEE Transactions on Power Electronics, Vol.26, No. 10, (2011), pp.2844-2856.
- [12] K. Shishime, Practical applications of the railway static power conditioner (RPC) for conventional railways, Meiden Review, Vol.3, No.156, (2012), pp.38-41.
- [13] K.W. Lao, M.C. Wong, N. Dai, C S. Lam, L. Wang, C.K. Wong, Analysis of the effects of operation voltage range in flexible DC control on railway HPQC compensation capability in high-speed co-phase railway power, IEEE Transactions on Power Electronics, Vol.33, No.2, (2018), pp.1760-1774.
- [14] B. Xie, Y. Li, Z. Zhang, S. Hu, Z. Zhang, L. Luo, Y. Cao, F. Zho, R. Luo, L. Long, A compensation system for cophase high-Speed electric railways by reactive power generation of SHC&SAC, IEEE Transactions on Industrial Electronics, Vol.65, No.4, (2018), pp.2956-2966.
- [15] M. Chen, Q. Li, C. Roberts, S. Hillmansen, P. Tricoli, N. Zhao, I. Krastev, Modelling and performance analysis of advanced combined co-phase traction power supply system in electrified railway, in IET Generation, Transmission & Distribution, Vol. 10, No.4, (2016), pp.906-916.



- [16] X. He, A. Guo, X. Peng, Y. Zhou, Z. Shi, Z. Shu, A traction three-phase to single-phase cascade converter substation in an advanced traction power supply system, *Energies*, Vol.8, No.9, (2015), pp.9915-9929.
- [17] T. Shimizu, K. Kunomura, M. Kai, M. Onishi, H. Masuzawa, H. Miyajima, M. Otsuki, Y. Tsurumg, Application of electronic frequency converter to the Shinkansen railyard power supply, *IEEJ Journal of Industry Applications*, Vol.4, No.4, (2015), pp.315-322.
- [18] K. Kunomura, M. Onishi, M. Kai, N. Lio, M. Otsuki, Y. Tsuruma, N. Nakajima, Electronic frequency converter feeding single-phase circuit and controlling feeder voltage with fixed power factor method for Shinkansen, *IEEE Transactions on Power Electronics*, Vol.27, No.9, (2012), pp. 3888-3896.
- [19] A. Steimel, Power-electronic grid supply of AC railway systems, 2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Brasov, (2012), pp.16-25.
- [20] M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmann, D. Soerangr, HVDC plus–Basics and Principle of Operation, In Special Edition for Cigré Exposition, (2008).
- [21] Q. Xu, F. Ma, Z. He, Y. Chen, J.M. Guerrero, A. Luo, Y. Li, Y. Yue, Analysis and Comparison of Modular Railway Power Conditioner for High-Speed Railway Traction System, in *IEEE Transactions on Power Electronics*, Vol.32, No.8, (2017), pp.6031-6048.
- [22] M. Hagiwara, H. Akagi, PWM Control and Experiment of Modular Multilevel Converters, *PESC 2008, Conf. Proc.*, Rhodes, (2008).