

An Active Railway Power Quality Compensator for 2×25kV High-Speed Railway Lines

Hamed Jafari Kaleybar*, Hossein
Madadi Kojabadi
Department of Electrical Engineering
Sahand University of Technology
Tabriz, Iran
jafarik.hamed@gmail.com
hmadadi64@yahoo.ca

Morris Brenna, Federica Foiadelli
Department of Energy
Polytechnic University of Milan
Milan, Italy
morris.brenna@polimi.it
federica.foiadelli@polimi.it

Seyed Saeed Fazel
School of Railway Engineering
Iran University of Science and
Technology
Tehran, Iran
fazel@iust.ac.ir

Abstract— The AC 2×25 kV power supply system is a widespread solution in high-speed railway networks. Owing to the operation of high-power trains in these systems, the 4Q converter generates a high amount and wide spectrum of harmonic currents, which may interface with the signaling systems, communication devices and utility power systems. In this paper, a new Active Railway Power Quality Compensator (ARPQC) based on two-phase, three-wire converter is proposed to suppress harmonics and improve the displacement factor of the system. In order to have an accurate analysis, a suitable model of 4Q converter and eight-conductor based Overhead Catenary System (OCS) together with autotransformers have been developed. The precise simulation results have been provided to verify the effectiveness of the proposed compensator.

Keywords— railway system; power quality; four quadrant converter; active railway power quality compensator.

I. INTRODUCTION

Single-phase electrical railway networks, especially High-Speed Railway (HSR), commonly adopts the 2×25 kV AC power supply system. The reduced number of Traction Power Substations (TPSS), the longer distance between TPSSs, the high efficiency due to the high voltages and low currents, the reduction of electromagnetic interference between traction converters, adjacent telecommunication circuits and interfacing with signaling systems of interconnection point of different supply systems as well as the reduction of voltage drops are the main advantages of these systems [1-3]. The Power Quality (PQ) problems in such a network are one of the critical concerns of experts for the correct operation of the railway service. In addition, the control systems, auxiliary equipment and local consumptions of railway network are supplied directly by feeder wire. The measurement results of Italian and French 2×25 kV lines have demonstrated that the harmonic spectra and displacement factor (DF) are among the most important PQ indexes [4]. The four quadrant converter (4Q), pantograph sliding contact, uninterruptible power supply for the feeding of on-board auxiliary services, induction traction motors and inductive parameters of lines are the main source of harmonic injection and DF deficiency [5, 6]. In recent years, numerous researchers have studied various methods for PQ improvement in the railway system. Owing to

the simple overhead catenary system (the low number of conductors) and using of balanced traction transformers, the majority of these studies have been concentrated on 1×25 kV power supply system [7, 8]. However, the electromagnetic behavior of multi-conductor based OCS, operation of autotransformers during lines and different distances of TPSS in 2×25 kV systems are effective in PQ analysis. Despite the fact that numerous articles about the PQ problems of 2×25 kV networks have been published, presenting of solutions to these problems has been paid less attention. A few researches about using of flexible alternating current transmission system (FACTS), passive and active filter in 2×25 kV are introduced which have certain shortcomings [9-11]. In fact, the installation of equipment in the primary high-voltage side makes it not to be affordable. In this paper, an Active Railway Power Quality Compensator (ARPQC) based on two-phase, three-wire converter is proposed. The proposed converter is formed by two step-down transformers and three switch legs connecting to the two contact wire, feeder wire and to the common grounded rail. To demonstrate the high ability of this compensator, the study has been carried out in two cases considering the dedicated single-phase transformers in TPSS (Italian railway as a case study) and two train translocations. The paper is structured as follows. In section II the proposed system details together with OCS model and load 4Q model is presented. Then in section III, the proposed ARPQC has been studied in details including control strategies. In section V, the simulation results and analysis are presented and compared and finally, section VI summarizes the paper and draws conclusions.

II. PROPOSED SYSTEM DESCRIPTION

Fig.1 demonstrates the model of a 25 km long section of an Italian HSR line. The ARPQC installed in TPSS is composed of a three-leg converter, three switching inductances and two single-phase step-down transformers. Each leg has two power switches which are connected together through a DC-link capacitor. A step-down transformer with a secondary winding ground connected central tap feeds the contact line and the feeder line. In practical, it is also connected to the rails through inductive connections.

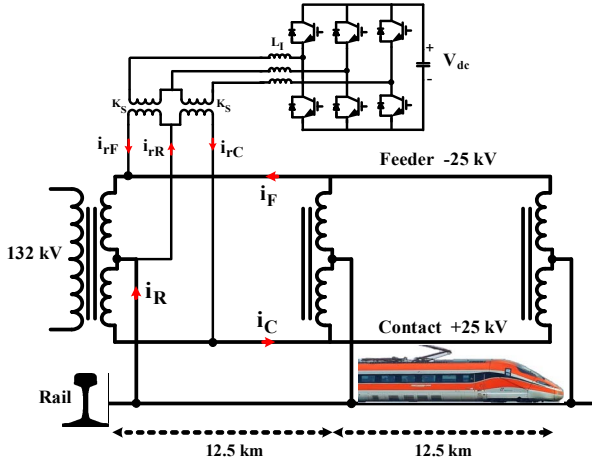


Fig. 1. HSR standard configuration of 2×25 kV–50 Hz power supply system with single-phase traction transformer and proposed ARPQC

Along the track, the 50/25 kV autotransformers, with central taps connected to the rail, distribute the current absorbed by the trains between the feeder and the contact line. The main advantages of these ATs are compensating the voltage drops and avoiding the electromagnetic induction failures.

A. OCS Modeling

The OCS is constituted by the contact wire, feeder wire and rails. The wire arrangement of eight conductor line is illustrated in Fig. 2. The self and mutual impedances of each conductor are computed using Neumann formulas in [12] as follows:

$$Z_{ii} = \left((R_{i-int} + \Delta R_{ii}) + j \left(\omega \frac{\mu_0}{2\pi} \ln \frac{2h_i}{r_i} + X_{i-int} + \Delta X_{ii} \right) \right) \quad (1)$$

$$Z_{ik} = Z_{ki} = \Delta R_{ik} + j \left(\omega \frac{\mu_0}{2\pi} \ln \frac{D_{ik}}{d_{ik}} + \Delta X_{ik} \right) \quad (2)$$

The line parameters of rails have been adopted from the extracted results in [1] through FEM analysis. The complete line model has been built in SIMULINK using self and mutual inductances and resistances illustrated in Fig. 3.

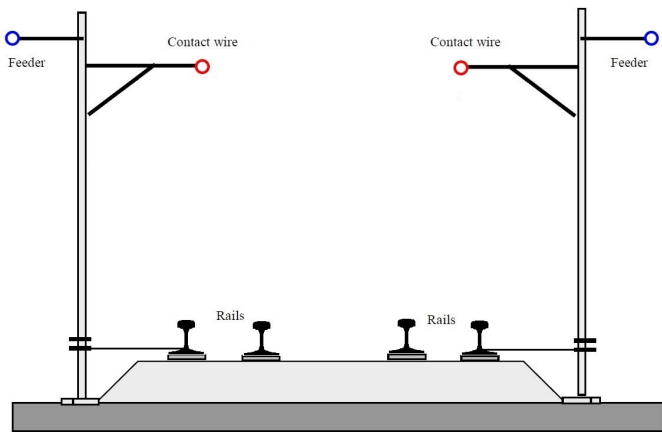


Fig. 2. Transversal section and wire arrangement of 2×25 kV–50 Hz power supply system.

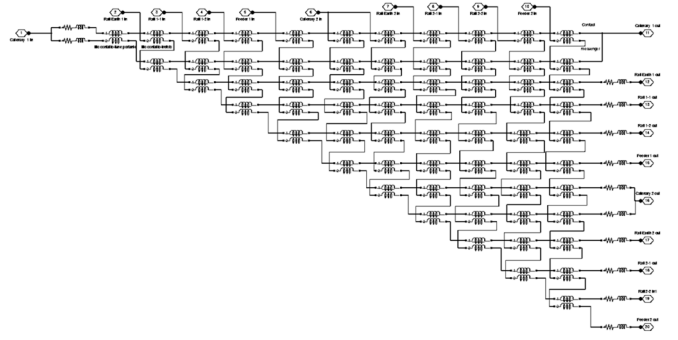


Fig. 3. Simulated model of OCS elementary cell.

B. Load Modeling With 4Q Converter

Since the PWM converter contains a quick response and can also provide high power to the traction loads, in most of HSR trains, a traction drive consists of a single-phase PWM ac-to-dc converter known as 4Q converter, a second harmonic passive filter, a dc link capacitor and a three-phase PWM dc-to-ac inverter. However, the 4Q converters which are input stages of HSR trains generate a high amount of harmonic currents [13, 14]. This amount can trespass the PQ standards in most cases. In order to evaluate an accurate harmonic current distribution, the suitable model of 4Q converter in both of interleaved and independent situation has been adopted.

III. ARPQC DESCRIPTION

Over the last years, experts have concerns about the PQ problems, especially the ones caused by railway networks. Extensive research and studies in this field led to introduce of particular compensator for railway networks [15-19]. The main duty of these compensators is transferring of active power from the lightly-loaded section to eliminate the negative sequence currents, transferring the reactive power from leading-section to the lagging-section in order to improve PF and injecting the compensating currents to eliminate harmonic components of currents in power grid [20]. These compensators are assigned for 1×25 kV networks. The ARPQC presented in this paper is adapted based on these compensators and modified in order to be able to work in 2×25 kV networks.

A. Configuration

The configuration of ARPQC in 2×25kV HSR TPSS in case of single-phase based traction transformer with central tap is illustrated in Fig. 1. The proposed ARPQC is composed of three-leg power switches with a DC-link capacitor. The legs are connected to feeder, contact and rail through two step-down transformers and three switching inductances. The compensating performance in this configuration has been shared for legs. In ideal condition the current distribution in feeder line and contact line are same and in rail is zero. However, in practical field the distributed currents have a little unbalanced condition which can affect the performance of the system and causes problems to the nearby systems [12].

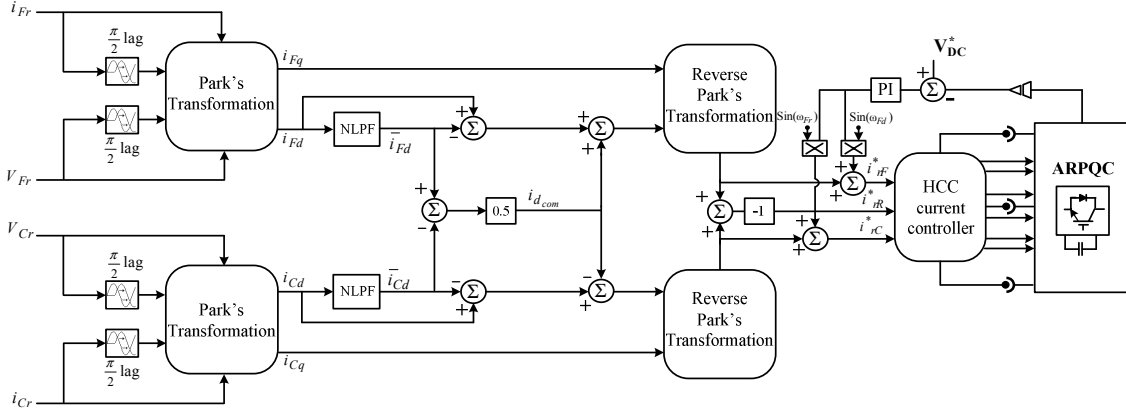


Fig. 4. Block diagram of control system for proposed system.

B. Control System

The proposed control system for ARPQC is illustrated in Fig. 4. Considering the difference between two main theories for implementing in proposed two phases system, SRF based theory has been implemented [21, 22]. Accordingly, a modified SRF based control system has been developed to improve the ARPQC capability in 2×25kV HSR.

Using the Phase Locked Loop (PLL) and making $\pi/2$ lag in instantaneous voltages and currents, the obtained system can be represented in $\alpha\beta$ -coordinate system as (3)-(7).

$$\begin{pmatrix} V_{\alpha F}(t) \\ V_{\beta F}(t) \end{pmatrix} = \begin{pmatrix} V'_{FR}(t) \\ V'_{FR}(t) \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} V_{\alpha C}(t) \\ V_{\beta C}(t) \end{pmatrix} = \begin{pmatrix} V'_{CR}(t) \\ V'_{CL}(t) \end{pmatrix} \quad (4)$$

$$\begin{pmatrix} V_{\alpha C}(t) \\ V_{\beta C}(t) \end{pmatrix} = \begin{pmatrix} V'_{CR}(t) \\ V'_{CL}(t) \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} i_{\alpha F}(t) \\ i_{\beta F}(t) \end{pmatrix} = \begin{pmatrix} i'_{FR}(t) \\ i'_{FR}(t) \end{pmatrix} \quad (6)$$

$$\begin{pmatrix} i_{\alpha C}(t) \\ i_{\beta C}(t) \end{pmatrix} = \begin{pmatrix} i'_{Cr}(t) \\ i'_{Cr}(t) \end{pmatrix} \quad (7)$$

Implementing Park transformation the currents in d-q frame can be calculated as:

$$\begin{pmatrix} i_{Fd}(t) \\ i_{Fq}(t) \end{pmatrix} = \begin{pmatrix} \cos \omega_f t & \sin \omega_f t \\ -\sin \omega_f t & \cos \omega_f t \end{pmatrix} \begin{pmatrix} i_{\alpha F}(t) \\ i_{\beta F}(t) \end{pmatrix} \quad (8)$$

$$\begin{pmatrix} i_{Cd}(t) \\ i_{Cq}(t) \end{pmatrix} = \begin{pmatrix} \cos \omega_c t & \sin \omega_c t \\ -\sin \omega_c t & \cos \omega_c t \end{pmatrix} \begin{pmatrix} i_{\alpha C}(t) \\ i_{\beta C}(t) \end{pmatrix} \quad (9)$$

A numerical LPF (NLPF) based on VFF-RLS is used to separate dc parts and ac parts of currents. The required currents for producing the reference compensation currents can be calculated as:

$$\begin{pmatrix} i'_{Fd}(t) \\ i'_{Fq}(t) \\ i'_{Cd}(t) \\ i'_{Cq}(t) \end{pmatrix} = \begin{pmatrix} \tilde{i}_{Fd}(t) + \Delta \bar{i} \\ i_{Fq}(t) \\ \tilde{i}_{Cd}(t) - \Delta \bar{i} \\ i_{Cq}(t) \end{pmatrix} \quad (10)$$

Where, $\Delta \bar{i}$ is the difference of fundamental current in two phases, $\tilde{i}_{Fd}(t)$ and $\tilde{i}_{Cd}(t)$ are the ac parts of feeder and contact currents in d axis. Similarly, i_{Fq} and i_{Cq} are the reactive components in q axis. The primary reference compensating currents can be calculated using the reverse Park transformation.

$$\begin{pmatrix} i'_{\alpha F}(t) \\ i'_{\beta F}(t) \end{pmatrix} = \begin{pmatrix} \cos \omega_f t & \sin \omega_f t \\ -\sin \omega_f t & \cos \omega_f t \end{pmatrix}^{-1} \begin{pmatrix} i'_{Fd}(t) \\ i'_{Fq}(t) \end{pmatrix} \quad (11)$$

$$\begin{pmatrix} i'_{\alpha C}(t) \\ i'_{\beta C}(t) \end{pmatrix} = \begin{pmatrix} \cos \omega_c t & \sin \omega_c t \\ -\sin \omega_c t & \cos \omega_c t \end{pmatrix}^{-1} \begin{pmatrix} i'_{Cd}(t) \\ i'_{Cq}(t) \end{pmatrix} \quad (12)$$

C. DC-Link Voltage Control System

Regarding to ARPQC topology and compensating of harmonic currents and reactive power, the DC-link capacitor faces with voltage changing. To stabilize this voltage, a conventional dual PI controller has been employed. This controller compares the reference voltage and DC-link voltage and produces the proper signals to make the charging and discharging of capacitor balanced. The final reference currents can be extracted as:

$$\begin{cases} i_{rF}^* = i'_{\alpha F} + i_{Floss} \\ i_{rC}^* = i'_{\alpha C} + i_{Closs} \\ i_{rR}^* = -(i_{rF}^* + i_{rC}^*) \end{cases} \quad (13)$$

Where, i_{Floss} and i_{Closs} are the loss currents proportional to the DC-link capacitor losses determined by PI controller.

IV. SIMULATION RESULTS

In order to verify the effectiveness of the proposed strategy, simulations based on MATLAB/Simulink software have been carried out in two different cases for two load translocation. In case 1, the train is assumed with four interleaved 4Q converter.

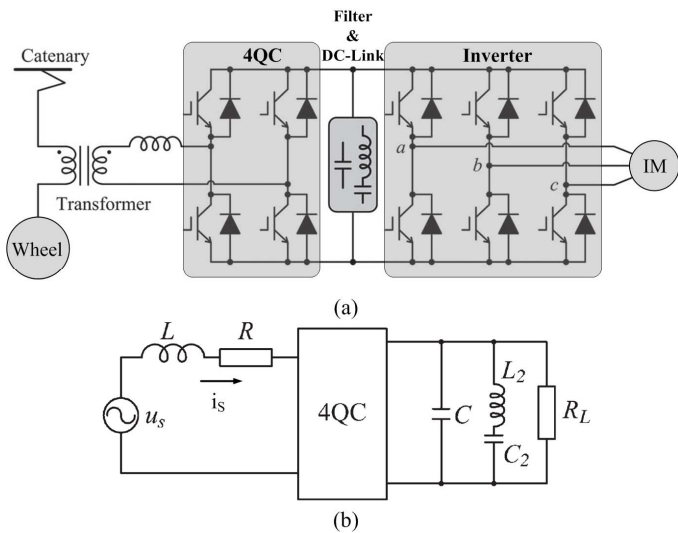


Fig. 5. Traction drives System in AC HSR. a) Typical configuration b) Equivalent simulated model

In case 2, the train is assumed with one 4Q converter to simulate the worst harmonic situation. The typical traction drive system and equivalent simulated model are illustrated in Fig. 5. In case 1, it is considered the train with four interleaved 4Q converters with power level of 4.4 MW based on HS train normal working mode. In this case, the harmonic content of current absorbed by train is reduced. Fig. 6.a. and Fig. 6.b. demonstrate the current distribution of the three conductors in right and left section of the TPSS.

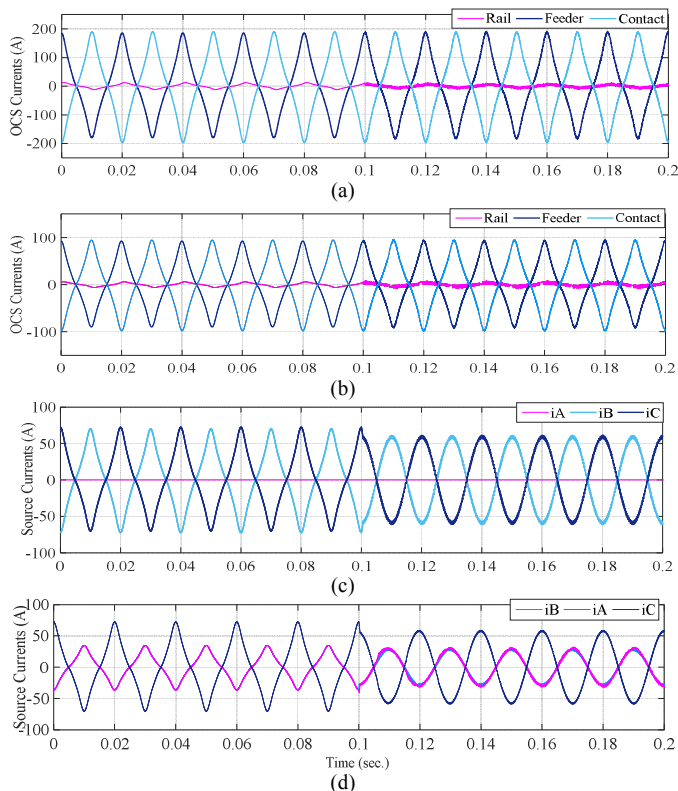


Fig. 6. Current waveforms of 2×25 kV-50 Hz HSR (case 1). a) OCS conductor currents in right section b) OCS conductor currents in left section c) The network-side three-phase currents for LBR=0 d) The network-side three-phase currents for LBR=0.5.

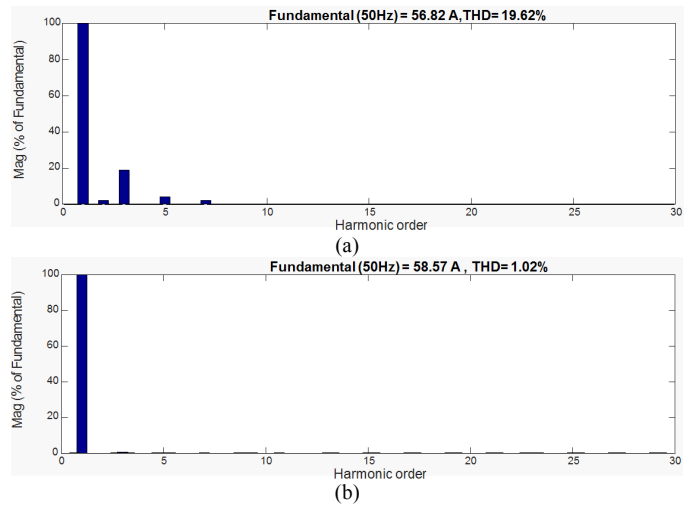


Fig. 7. Fourier analysis of network-side currents (Case 1). a) before compensation b) after compensation

In Fig. 6.c and Fig. 6.d the network-side three-phase currents for Load Balanced Ratio (LBR= 0) and LBR=0.5 are illustrated respectively. The ARPQC is switched on in $t = 0.1$ s. It can be seen from the Fourier analysis of these currents reported in Fig. 7 and the simulation results shown in Table I that THD% of network-side three-phase currents which exceeds 19% has been reduced significantly. In case 2, it is considered the train with one 4Q converter with a power level of 4.4 MW based on HS train normal working mode.

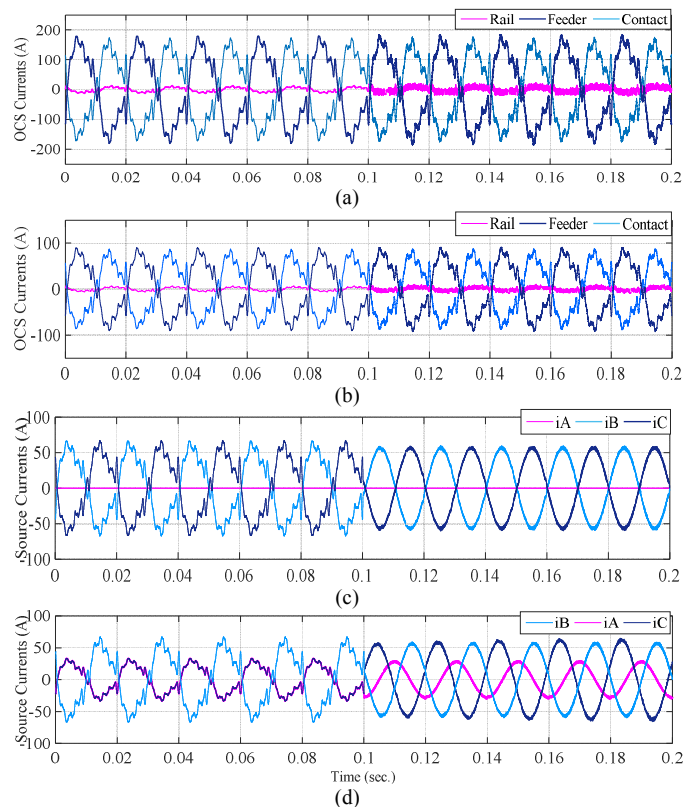


Fig. 8. Current waveforms of 2×25 kV-50 Hz HSR (case 2). a) OCS conductor currents in right section b) OCS conductor currents in left section c) The network-side three-phase currents for LBR=0 d) The network-side three-phase currents for LBR=0.5.

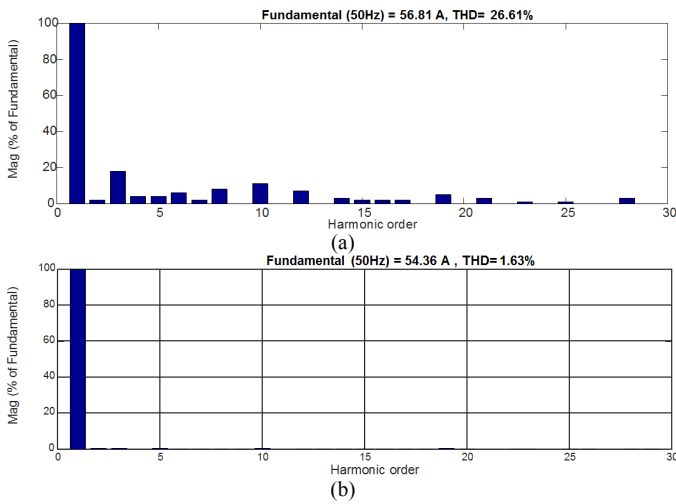


Fig. 9. Fourier analysis of network-side currents (Case 2). a) before compensation b) after compensation

Fig. 8.a and Fig. 8.b depicted the current distribution of the three conductors in right and left section of the TPSS. In Fig. 8.c. and Fig. 8.d. the network-side three-phase currents for LBR= 0 and LBR=0.5 are reported. The Fourier analysis demonstrated in Fig. 9.a shows the high spectrum of ten-order harmonic, which is related to the switching frequency. At $t=0.1$ s the ARPQC is switched on. It can be seen from the simulation results shown in Table I and Fourier analysis demonstrated in Fig. 9.b that THD% of network-side three-phase currents which exceeds 26% has been reduced significantly for acceptable compliance with the IEEE std-519 standard. On the other hand, a considerable amount of reactive power consumed by traction loads makes the low DF in the power grid. However, as Table I illustrates, after compensation, DF has improved from the approximate value of 0.92 and 0.94 to the 0.99. It is worth noting that because of dedicated single-phase transformers in TPSS the three-phase currents in the primary side of transformers can not be balanced completely [23]. However, in case of using intelligent cooperation based control strategy they can be balanced from the point of the upstream utility grid [24].

The DC-link capacitor voltage is represented in Fig.10. The initial voltage of the capacitor is selected as 2000 V. It is noted that, after applying ARPQC at $t = 0.1$ s, the control strategy regulates capacitor voltage and it tends to a constant average voltage. It should be mentioned that, the 100 Hz ripple voltage is due to the single-phase absorption and transferring of active power. This figure confirms the high dynamic and accurate of the controller.

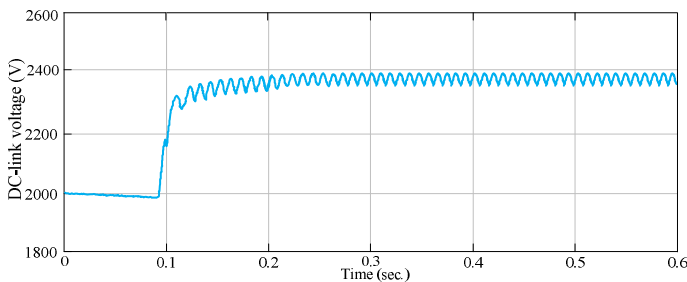


Fig. 9. DC-link capacitor voltage.

TABLE I. SIMULATION RESULTS

		Power quality parameters			
		THD _i %			DF
		A	B	C	
Case 1: four 4QC	before compensation	19.31	19.62	19.20	0.94
	after compensation	1.22	1.24	1.02	0.99
Case 2: one 4QC	before compensation	26.21	26.61	25.92	0.92
	after compensation	1.83	1.63	1.62	0.99

V. CONCLUSION

In this paper, a new two-phase, three-wire based compensator has been presented to suppress harmonic currents and improve DF in 2×25 kV railway networks. To have a precise analysis the eight-conductors based OCS was modeled using the calculated line parameters of self and mutual inductances and resistors. The simulated model represents a 25 km long section of an Italian HSR considering 4Q converters as a harmonic source generation. The simulation results showed that the proposed compensator can be helpful in suppressing harmonics and improving DF factor. Even though the proposed compensator is capable of balancing the active power from one leg to the other, due to the dedicated single-phase transformers in TPSS it is not possible to compensate the current unbalance in the primary side. Replacing these transformers with balanced transformers, the current unbalance can be eliminated.

REFERENCES

- [1] M. Brenna, F. Foiadelli and D. Zaninelli, "Electromagnetic Model of High Speed Railway Lines for Power Quality Studies," *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1301-1308, Aug. 2010.
- [2] F. Caracciolo, A. Fumi and E. Cinieri, "Managing the Italian High-Speed Railway Network: Provisions for Reducing Interference Between Electric Traction Systems," *IEEE Electrific. Mag.*, vol. 4, no. 3, pp. 42-47, Sept. 2016.
- [3] M. Brenna and F. Foiadelli, "Analysis of the Filters Installed in the Interconnection Points Between Different Railway Supply Systems," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 551-558, Mar. 2012.
- [4] A. Mariscotti, "Results on the Power Quality of French and Italian 2×25 kV 50 Hz railways," in *Proc. IEEE Inter. Instrument. and Measur. Tech. Conf.*, Graz, 2012, pp. 1400-1405.
- [5] A. Dolara, M. Gualdoni and S. Leva, "Impact of High-Voltage Primary Supply Lines in the 2×25 kV-50 Hz Railway System on the Equivalent Impedance at Pantograph Terminals," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 164-175, Jan. 2012.
- [6] M. Brenna, F. Foiadelli and D. Zaninelli, "New Stability Analysis for Tuning PI Controller of Power Converters in Railway Application," *IEEE Trans. Ind. Electron.*, vol. 58, no. 2, pp. 533-543, Feb. 2011.
- [7] S. Hu *et al.*, "A New Integrated Hybrid Power Quality Control System for Electrical Railway," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6222-6232, Oct. 2015.
- [8] F. Ma *et al.*, "A Railway Traction Power Conditioner Using Modular Multilevel Converter and Its Control Strategy for High-Speed Railway System," *IEEE Trans. Transport. Electrific.*, vol. 2, no. 1, pp. 96-109, Mar. 2016.
- [9] R. Grunbaum, "FACTS for power quality improvement in grids feeding high speed rail traction," in *Proc. IEEE Inter. Electric Machines & Drives Conf.*, Antalya, 2007, pp. 618-623.
- [10] P. Ladoux, G. Raimondo, H. Caron and P. Marino, "Chopper-Controlled Steinmetz Circuit for Voltage Balancing in Railway Substations," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5813-5822, Dec. 2013.
- [11] Kyoung-Min Kwon, Young-Shin Song and Jaeho Choi, "6MVA single-phase APF for high speed train line in Korea," in *Proc. IEEE Conf.*

Power Engin. and Renewable Energy (ICPERE) 2014, Bali, 2014, pp. 31-36.

- [12] M. Brenna and F. Foiadelli, "Sensitivity Analysis of the Constructive Parameters for the 2×25-kV High-Speed Railway Lines Planning," in *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1923-1931, Jul. 2010.
- [13] F. Foiadelli, G. C. Lazaroiu and D. Zaninelli, "Probabilistic method for harmonic analysis in railway system," in *Proc. IEEE Power Engin. Society General Meet.*, , 2005, pp. 2397-2401 Vol. 3.
- [14] G. W. Chang, Hsin-Wei Lin and Shin-Kuan Chen, "Modeling characteristics of harmonic currents generated by high-speed railway traction drive converters," *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 766-773, Apr. 2004.
- [15] H. Hafezi, G. D'Antona, A. Dedè, D. Della Giustina, R. Faranda and G. Massa, "Power Quality Conditioning in LV Distribution Networks: Results by Field Demonstration," *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 418-427, Jan. 2017.
- [16] G. D'Antona, R. Faranda, H. Hafezi, and M. Bugliesi, "Experiment on Bidirectional Single Phase Converter Applying Model Predictive Current Controller," *Energies*, vol. 9, no. 9, pp. 13, 24 Mar., 2016.
- [17] H. J. Kaleybar, S. Farshad, M. Asadi, and A. Jalilian, "Multifunctional control strategy of half-bridge based railway power quality conditioner for traction system," in *Proc. IEEE 13th Int. Conf. Environ. and Elec. Eng. (EEEIC)*, pp. 207-212, 2013.
- [18] A. Ghassemi, S.S. Fazel, I. Maghsoud and S. Farshad, "Comprehensive study on the power rating of a railway power conditioner using thyristor switched capacitor," *IET Elec. Systems in Transport.*, vol. 4, no. 4, pp.97-106, Dec. 2014.
- [19] Z. Sun, X. Jiang, D. Zhu, and G. Zhang, "A novel active power quality compensator topology for electrified railway," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1036-1042, Jul. 2004.
- [20] H. J. Kaleybar, S. Farshad, "A comprehensive control strategy of railway power quality compensator for AC traction power supply systems," *Turk. J. Elec. Eng. & Comp. Sci.*, vol. 24, no. 6, 4582-4603, 2016.
- [21] H. Hafezi, E. Akpinar and A. Balikci, "Assessment of two different reactive power estimation methods on single phase loads," in *Proc. IEEE 16th Inter. Power Elec. and Motion Cont. Conf. and Expos.*, Antalya, 2014, pp. 82-87.
- [22] A. Javadi, A. Hamadi and K. Al-Haddad, "Three-phase power quality device for weak Systems based on SRF and p-q theory controller," in *Proc. IEEE 41st Ann. Conf. Indust. Electron. Society (IECON)*, Yokohama, 2015, pp. 000345-000350.
- [23] H. J. Kaleybar, H. M. Kojabadi, M. Fallah, S. S. Fazel and Liuchen Chang, "Impacts of traction transformers on power rating of Railway Power Quality Compensator," in *Proc. IEEE 8th Inter. Power Elec. and Motion Control Conf. (IPEMC-ECCE Asia)*, Hefei, 2016, pp. 2229-2236.
- [24] H. M. Kojabadi, H. J. Kaleybar, M. Fallah, S. S. Fazel and Liuchen Chang, "Capacity diminution of railway power conditioner using a new smart control system," in *Proc. IEEE 8th Inter. Power Elec. and Motion Control Conf. (IPEMC-ECCE Asia)*, Hefei, 2016, pp. 2097-2102.