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AN INNOVATIVE TOPOLOGY FOR HARMONICS AND UNBALANCE COMPENSATION IN ELECTRIC TRACTION SYSTEM USING DIRECT POWER CONTROL TECHNIQUE

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ABSTRACT

Power quality problems in power systems have been improved due to nonlinear loads. To compensate these problems Direct Power Compensator was suggested in this paper. A Direct Power Compensator (DPC) is proposed in this paper to reduce the harmonic currents, compensate power factor and voltage unbalance problems generated by the nonlinear loads present in three phase systems. A DPC contains back to back converter by sharing the same dc link power and v/v transformer to provide a voltage balance in transmission line. Hysteresis harmonic current regulator is used to create pulse for back to back converter. A controller maintains the dc-link voltage and compensates the power factor, harmonic currents. A comparative analysis for traction system with and without DPC was performed using MATLAB Simulink. Simulation results show the controller advantages and the applicability of the proposed method in railway systems.

KEY TERMS - Active filters, harmonics distortion, power control, rail transportation power system, Direct Power Compensator (DPC).

INTRODUCTION

Electric traction systems for customers and goods use different power transformation schemes in order to convert the three phase supply system into two single-phase methods. The more common three-phase to two single phase conversion schemes use transformers connected in open delta (V –V), Scott configurations [1]. In a real-world application, the load associated with each single-phase circuit does not recompense each other, due to the variable stress in the transport system and railroad line profile. Also, the use of uncontrolled variation to feed the traction load contribute to the total unbalance seen form the three phase supply. Injects current harmonics into the single-phase supply system and those harmonics transmit into the main three-phase system depending on the transformer connections and the harmonic order. The harmonic content inserted into the main three-phase system contributes to the total system unbalance [2]. It is then essential to use of filters and unbalance compensation to ensure proper system operation and raise the electric service quality [3].

These problems are usually addressed, in reality, with the use of passive power quality compensators such as reactive power compensation capacitors and reactive filters, and they are single-phase apparatus installed in each feeder from the traction substation. Usually, the blend factor between two feeders is negligible due to the independent process of each passive compensator [4]. Moreover, passive equipment does not have the dynamic capability to adjust to changes in freight, where over and below compensation happen frequently as a result of continuous changes in load situations. Unlike active power quality compensators are proposed in [4-6] to solve the unbalance problem. All of them utilize two single-phase converters that have a common dc bus. The harmonic and negative sequence currents can be compensated successfully. In addition, these active power quality compensators use the instantaneous active and reactive power means to determine the compensating currents, which is not appropriate for single-phase traction power systems [7].

There are different active power quality compensators proposed in the literature [5]–[10], to solve the unbalance problem, but they neglect the sequence modules introduced by harmonics. Also, all of them occupy two single-phase converters that have a common dc bus, but they cannot deliver simultaneous compensation of unbalance and harmonic content. However, for the compensation done from the three-phase side, the use of the instantaneous active and reactive power definition [11]–[17] provides a way for simultaneous compensation of unbalance and harmonics. The overview of the proposed filtering method using instantaneous active and reactive power can be applied to any transformer configuration scheme in the power substation. Multilevel converter technology can make possible the industrial implementation because it reduces the specifications of the power electronics switches and the voltage stress dv/dt on the magnetic components like coupling transformers and/or inductors.

This work proposes a compensation scheme that provides simultaneous correction of harmonic content and load unbalance for railroad systems using an open delta connection in the power substation. This method is based on the instantaneous power description of the scheme, using space vector representation of the state variables, and the use of direct power control (DPC) to attain the required correction by minimizing a cost function achieved from the instantaneous active and reactive mismatch [8].The control strategies presented in this work are experimentally legalized using a DSP based modular power electronic system able to emulate the electric traction system operating conditions, the open delta transformer and the filtering and load balancing converters [9].

HARMONICS AND UNBALNCE COMPENSATION SYSTEM

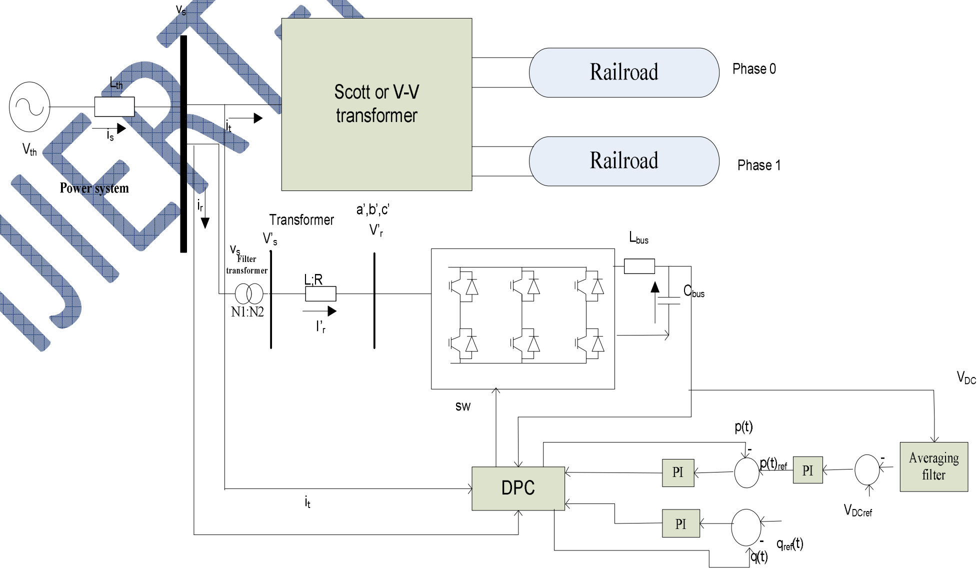


Fig. 1 Proposed Compensation Scheme

Figure 1 shows the proposed control design. A parallel active filter is used, indirectly connected to the power system using a voltage expanding transformer. The active filter uses a power converter configured as an active three-phase PWM rectifier, connected to the three-phase side.

The instantaneous active and reactive terms of the complex power are constant and equal to p (t) = 3VI cos (Φ) and q (t) = 3VI sin (□) [13], [32], other than the analogous balanced three-phase systems, the instantaneous active and reactive power with unbalanced nonlinear loads contains middling and oscillating terms to compensate for load inequality and cuts harmonic injection from the load to the supply system. This is designed by keeping constant the instantaneous active and reactive power replace with the supply. This is achieved with a shunt active filter directly connected to the power system using a voltage step-up filter transformer. The controller computes the total instantaneous active and reactive power taken by the arrangement of traction system and filter. In the projected compensation scheme, the controller selects the converter voltage V_r required to keep constant the total instantaneous active and reactive power drawn from the grid.

The power invariant space vector conversion is definite as [11]

$$\vec{x} = \sqrt{\frac{2}{3}}\left(x_a(t) + \alpha x_b(t) + \alpha^2 x_c(t)\right); where\ \alpha = e^{\frac{j2\pi}{3}} \quad \ldots. (1)$$

V-V TRANSFORMER SPACE VECTOR MODEL

Figure (2) shows the V –V transformer used to joins a traction sub-station to the electric lattice. This connection generates two single-phase networks from the three-phase power system. Every single-phase circuit is used to feed a train of 60 to 100 km. The transformer model obtained by using transformer ration and using ampere and faraday laws[2].

$$v_{ab} = \frac{N1}{N2} v_{T1};\ v_{bc} = \frac{N1}{N2} v_{T2}$$

$$i_a - \frac{N2}{N1} i_{T1};\ i_c - \frac{N2}{N1} i_{T2}$$

Calculated voltage and current space vectors in the transformer's primary winding as function of secondary windings voltage and currents are:

$$\vec{v_s} = \sqrt{\frac{2}{3}}\frac{N1}{N2}\left(v_{T1} - a^2 v_{T2}\right)$$

$$\vec{i_t} - \sqrt{\frac{2}{3}}\frac{N2}{N1}\left[(1-\alpha) i_{T1} + (\alpha - \alpha^2) i_{T2}\right]$$

SCOTT TRANSFORMER SPACE VECTOR MODEL

In support of the ideal Scott transformer shown in Fig. 2, its representation can be obtained by considering the transformer ratio and using Ampere and Faraday Laws [1]

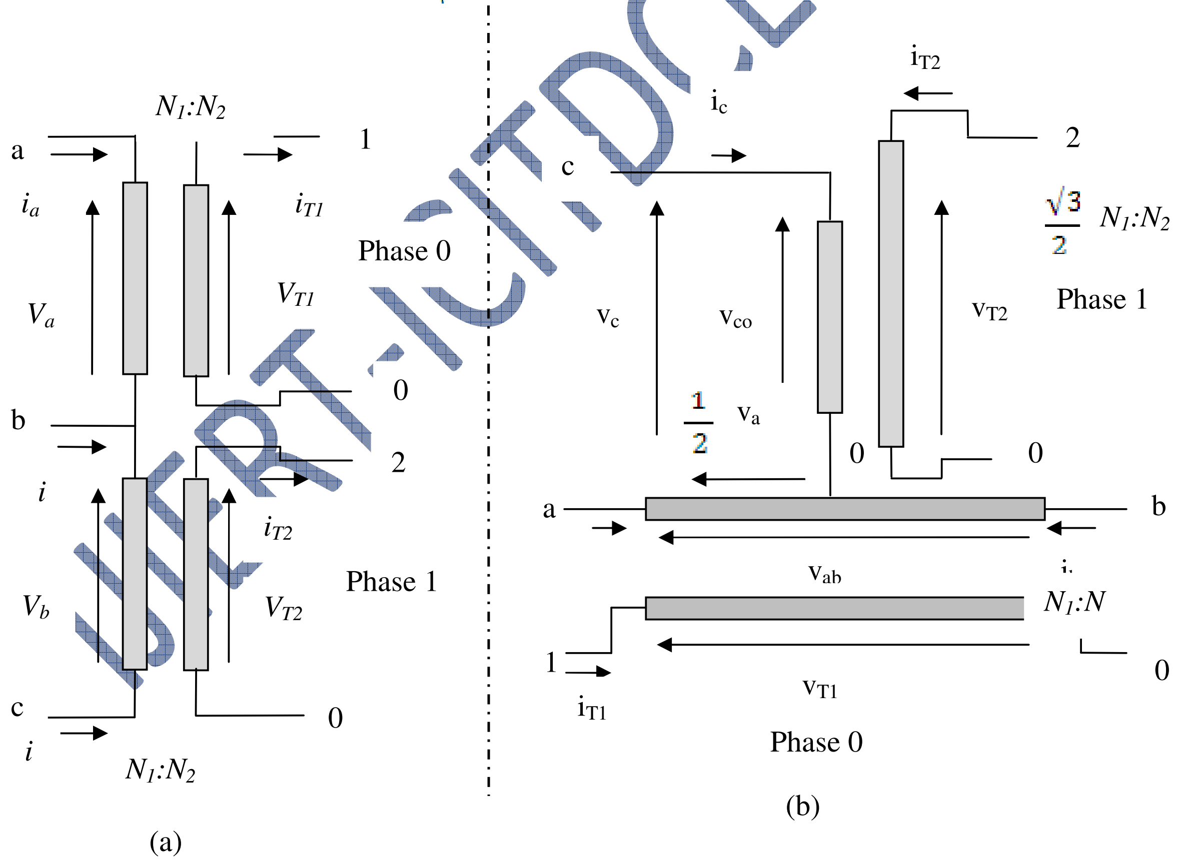
$$v_{ab} - \frac{N1}{N2} v_{T1}; v_{co} - \frac{\sqrt{3}}{2}\frac{N1}{N2} v_{T2}$$

$$\frac{\sqrt{3}}{2}\frac{N1}{N2} i_c = i_{T2}; \frac{1}{2}\frac{N1}{N2}(i_a - i_b) = i_{T1}$$

The voltage and current space vectors designed in the transformers primary winding is a purpose of the secondary winding voltages and currents are

$$\vec{v_s} = \sqrt{\frac{3}{2}\frac{N1}{N2}}\,\frac{1}{1 \quad \alpha^2}\,(v_{T1} - j v_{T2})$$

$$\vec{i_i} = \sqrt{\frac{2}{3}\frac{N2}{N1}}\,((1-\alpha) i_{T1} - \sqrt{3}\alpha^2 i_{T2}$$



ACTIVE AND REACTIVE POWER CONTROL

The Direct Power controller is based on the instant apparent power from the current and voltage space vectors definitions [11-13]

$$s = \overrightarrow{v_s} * \overrightarrow{i_s^*} = p + jq$$

From fig.1 active filter modelled as

$$\overrightarrow{v'_s} = \overrightarrow{v'_r} + R\overrightarrow{i'_r} + L\frac{d\overrightarrow{i'_r}}{dt}$$

Where

$$v_s' = \frac{N1}{N2}\overrightarrow{v'_s}\ ;\ v_r' = \frac{N1}{N2}\overrightarrow{v'_r}\ ;\ \vec{i_r} = \frac{N2}{N1}\overrightarrow{i'_r}$$

$$R = \left(\frac{N1}{N2}\right)^2 R_r\ ; L = \left(\frac{N1}{N2}\right)^2 L_r$$

For a given orientation in active and reactive power, the change in power for suitable compensation becomes a role of the converter voltage $\widehat{v_{rk}}$. The apparent power variation Δsk = Δpk + jΔqk needed to change from the real to the demanded value in the following sampling time, p_{ref} and q_{ref}, are given by the following expressions:

$$\epsilon_{sk} = \left(p_{refk+1} - p_k\right) + j\left(q_{refk+1} - q_k\right)$$

$$= \Delta p_k + j\Delta q_k = \epsilon_{qk} + j\,\epsilon_{qk}$$

for a given reference in active and reactive power, the change in power for proper compensation depends on the converter voltage $\overrightarrow{v_r}(k)$

$$v'_r(k) = \frac{L}{T_s}\left[\frac{\Delta\overrightarrow{s_0}(k) - \Delta\overrightarrow{\epsilon_s}(k)}{\overrightarrow{v r_s}(k) * e^{jwT_s}}\right]^*$$

The proposed algorithm has low computational stress, provides instantaneous modification of the active and reactive power in the tip of common coupling, and reduces the ripple in the instantaneous power and currents. This produces low harmonic distortion and balances the load seen from the grid.

MULTILEVEL COMPENSATION

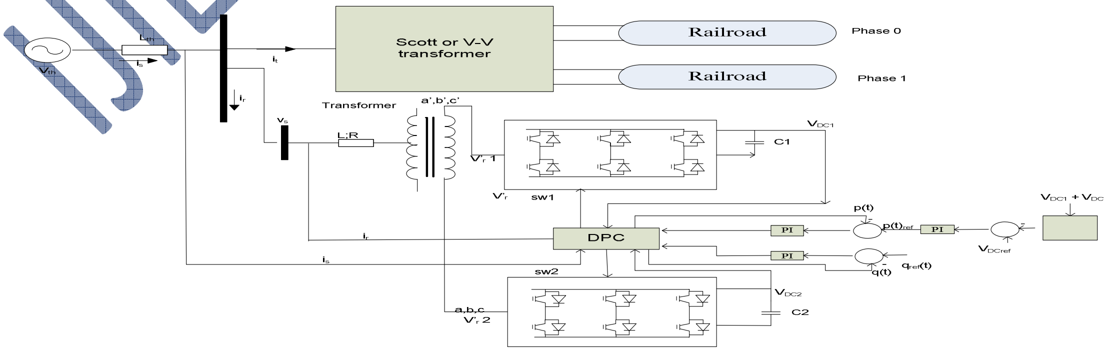


Fig.4 Circuit diagram of proposed multilevel compensation scheme

Figure 4 shows the open delta transformer (V-V) used to tie a traction substation to the electric grid, whereas the voltage space vector calculated in (11) is synthesized with the dual converter modulation method.

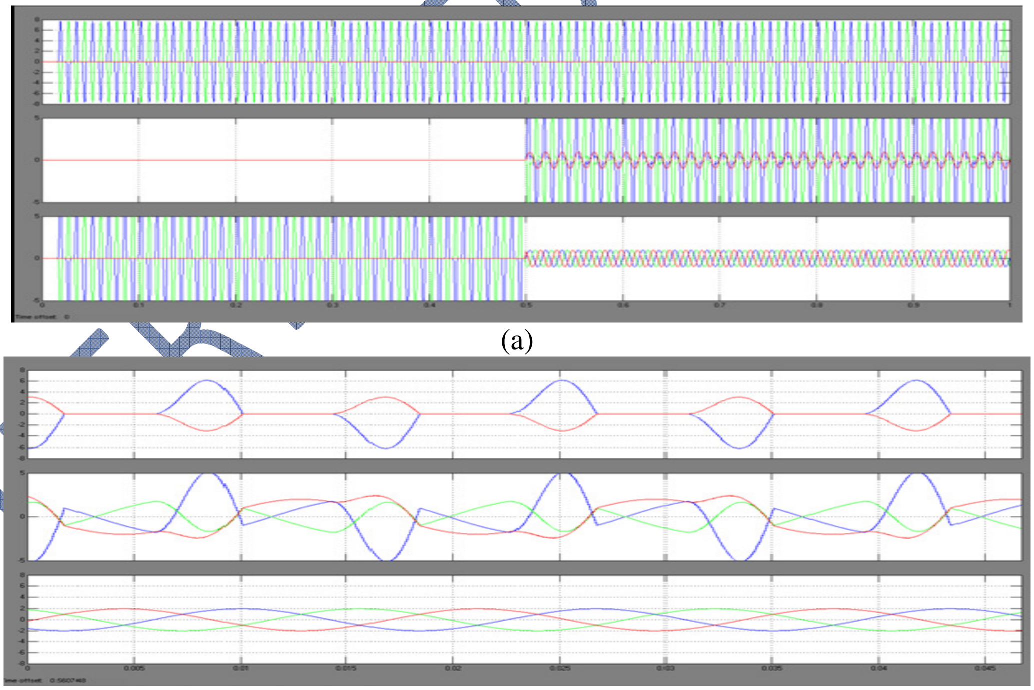
SIMULATION RESULTS

The system shown in Fig. 1 is modeled using the space vector representation of the state variables [11], at a 10 kHz sampling rate. Both, the V-V and Scott transformers are built-in these simulations. The railroad system is represented using the calculated harmonic currents distribution, injected to the power system in the secondary side of each transformer [16].The three-phase power system is modeled using a space vector Thevenin equivalent. Also, space vector representations of the power transformer (V-V or Scott), three-phase (VSC), and the filter are used in the simulation. The parameters used in the simulations are shown in Table I. The rectifier case uses a single-phase rectifier bridge-based load in one secondary of the key transformer. For the railroad case, the measured harmonic current range is injected in one secondary phase [16].

Table I.
THE FILTER SCHEME MODEL

V_{th}	L_{th}	R_{trx}	L_{trx}	C{1,2}	V_{DC}\{1,2\}
208v	0.1mH	1mΩ	10.0mH	1100µF	200~600V

The simulation uses highest unbalance by working on one single-phase circuit with the other in no load condition, which is the most difficult operating condition. The active filter injects the harmonic content used by the single-phase railroad load. The planned control scheme reduces by more than 96% the THD for both transformer connections.



(a)

(b)

Fig. 5 Simulated active filter effect on the power system currents feeding a single phase rectifier load for the Scott and V–V connections (a) V–V (b) Scott.

Figure 5 Shows the simulated instantaneous currents flow into the power system not including compensation and with including active and reactive compensation. The simulations show the balancing result on the power system current and the THD reduction obtained with the active filter controlled by the instantaneous active and reactive power. Both transformers (V-V and Scott) have a related current behavior when a single-phase rectifier load is connected in one secondary.

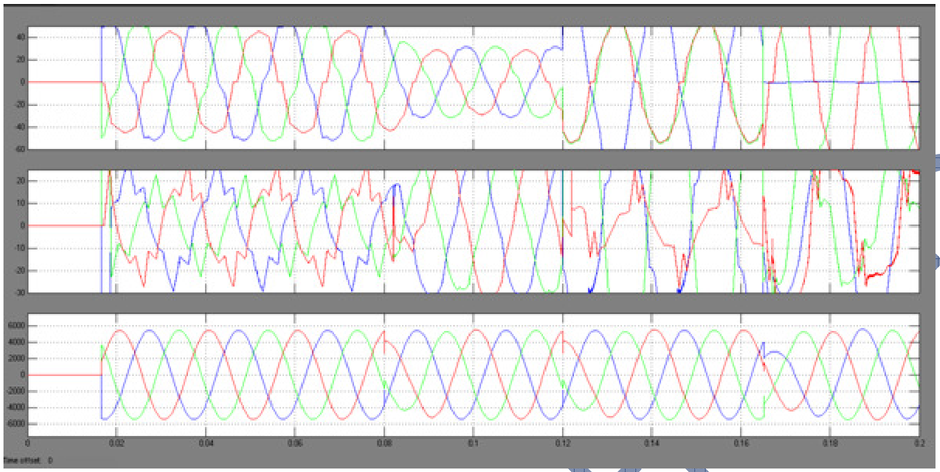


Fig.6 Simulated waveforms for the Scott transformer connection for different Railroad load profiles.

Figure 6 shows the waveforms in the simulated railroad system for four different load profiles: first a maximum load profile is applied before t = 0.1 s; then a minimum operating load profile is applied from t = 0.1 s to t = 0.132 s; after this, an emergency condition with the full load is applied only to phase 1 from t= 0.132 s to t = 0.164 s; after this the emergency condition is changed to full load applied only to phase 0.

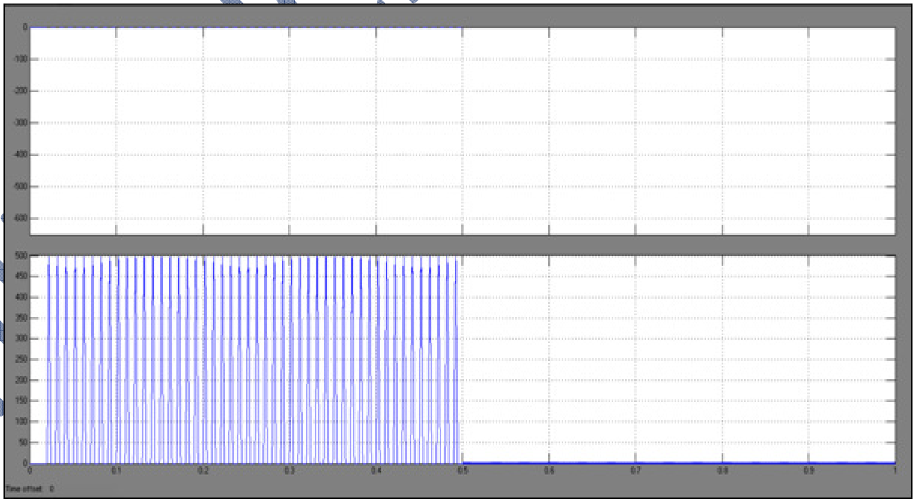


Fig.7 Effect on dc voltage due to p_{ref} variation

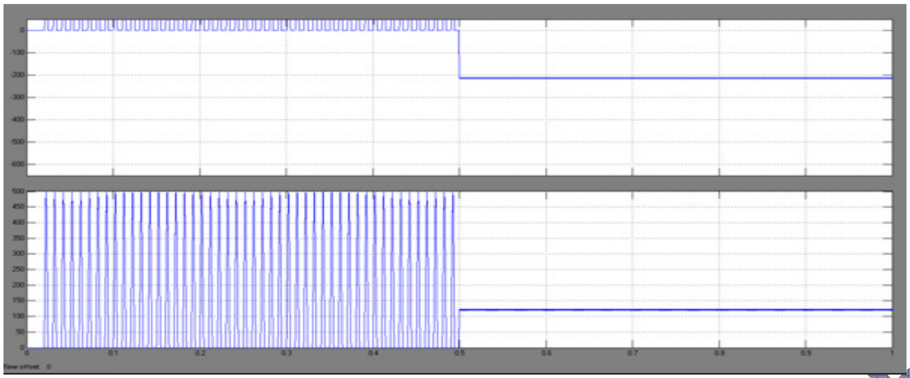


Fig.8 Effect on the line current's phase shift due to q_{ref} variation

Figure 7 shows how changes in p_{ref} affect the system variables for unity power factor operation ($q_{ref} = 0$). The compensation control starts at t = 0.06 s and changes in p_{ref} have a least effect on the instantaneous reactive power and phase currents. However, V_{dc} voltage changes when the reference power pref is dissimilar than the average power p(t). A larger power reference p_{ref} with respect to the average power inject power in the dc bus and this power is stored in the converter capacitor C. When the p_{ref} is lesser than p(t), power flows from the capacitor to the power system and the dc voltage decreases. Fig.8 shows for p_{ref} constant, changes in q_{ref} influence the system variables.

CONCLUSION

The planned DPC-based compensation system reduces negative sequence currents injected by an uncompensated electric traction system using several power transformer connections. This method can be used to decrease the current THD to values complying with worldwide regulations, and also regulates the power factor observed in the common coupling point among the traction substation and the grid. Also, the compensation technique based on the instantaneous power control algorithm with direct space vector representation, decreases the system's current THD to permissible ranges (<20%) and reduces the generally unbalance from 97% to 18% for bad-case operation. The compensation algorithm is capable to control the power factor calculated at the common coupling point in all measured conditions, with a very short transient merit to the fast dynamic response of DPC. The distortion that leftovers in the compensated current is mostly due to the distortion in the grid voltage and the restrictions of the switched nature of the filter's power stage, that is, incapable to compensate very fast transients existing in the traction current. The dual converter compensation method using an instantaneous power control algorithm with direct space vector calculation reduces the unbalanced currents to acceptable ranges (<10%) and reduces the overall unbalance from 42.8%to 3.8%. The dual converter's topology has been tested as an active filter, for improved power conversion employing lower voltage switching devices. The algorithm used in the control of the dual converter was an optimized edition of the DPC.

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