International Journal of Electrical and Electronics Engineers
Vol. No. 9, Issue No. 02, July - December 2017
ISSN (O) 2321-2055
ISSN (P) 2321-2045

Harmonic and Unbalance Compensation Based on Direct Power Control for Traction Systems

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ABSTRACT

This paper presents a general filtering and unbalance compensation scheme for electric traction systems using a direct power control-based algorithm. For a balanced three-phase three-wire system, the proposed method is able to control the power flow exchange between the grid and the load so that the instanta-neous complex power is maintained constant. As a consequence, any nonlinear unbalanced load is seen by the three-phase sup-ply as a balanced linear load. The proposed filter is evaluated on power substations with open delta (V-V) and Scott transformer feeders, and for two-level and dual converter in the power stage. The scheme has been simulated and experimentally validated. The results from experimental and simulation tests show the controller advantages and the applicability of the proposed method in railway systems.

Index Terms: Active filters, harmonics distortion, power control, rail transportation power system.

I. INTRODUCTION

LECTRIC traction systems for passengers and freight use Evarious power transformer configurations, in order to feed single-phase systems from the three-phase supply. In general, three-phase to two single-phase conversion schemes use transformers connected in open delta (V-V), Scott or Le Blanc configurations [1], to improve the power system balance. However, in practical applications these transformer connections do not solve the unbalance problem seen from the three-phase side, due to the variable demands in the transport system and railroad line profile. Also, the use of uncontrolled rectification to feed the traction load contribute to the total unbalance seen from the three-phase supply. For balanced loads, this unbalance is due to the injection of current harmonics by the railroad converter to the main three-phase system, depending on the transformer connec-tion and harmonic order [2]. Filters and unbalance compensators are therefore required to ensure proper system operation and to improve the power quality [3]. These problems are usually addressed, in practice, with the use of passive power quality compensators such as reactive power compensation capacitors and passive filters, and they are single-phase equipment installed in each feeder from the traction substation. Usually, the coupling factor between two feeders is negligible due to the independent operation of each passive compensator [4]. Moreover, passive equipment does not have the dynamic capability to adjust to changes in load, where over and under compensation happen frequently as a result of continuous changes in load conditions. There are different active power quality compensators proposed in the literature [5]–[10], to solve the unbalance problem, but they neglect the sequence components introduced by har-monics. Also, all of them employ two single-phase converters that have a common dc bus, but they cannot provide simultane-ous compensation of unbalance and harmonic content. However, for the compensation made 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 traction system under study is similar to the stage 1 railway Ezequiel Zamora in Venezuela. It draws power using a Scott transformer (115/25 kV, 60 Hz, 40 MVA). This transformer provides two single-phase lines with a 90◦ phase shift between them. One of the single-phase lines feeds both ways of the Charallave–Caracas section (24 km), with a ramp of 3.125%. The other single-phase line feeds both ways of the Charallave– Cua section (17.5 km), with less traffic and a ramp of 0.6%, resulting in less load for this phase. For this configuration, the Scott transformer has an unbalance in the range of 12–20% in normal operation, and 40% for emergency operation. The railway system uses eight four-wagon trains, with half of the wagons powered. Each powered wagon has four 600 kW induc-tion machines fed with DTC controlled VSCs and single-phase PWM in the rectifier front end. The average current total demand distortion for normal operation of the system is about 20%. Only a balanced electric system without current and voltage harmonics will produce constant instantaneous power (s) [13], [15], [18], [19], as shown below in Section II-D. With this in mind, a compensation scheme based on direct power control (DPC) [20]–[25] is proposed to provide simultaneous correction of harmonic content and load unbalance, commonly found in railroad systems with different transformer connection schemes in the power substation.

The control strategies are simulated using a state variable model representation and experimentally validated using a DSP-based modular power electronic system able to emulate the electric traction system operating conditions, the open delta and Scott transformer connection schemes, the filtering and the load balancing power converters [26].

The power range for the railroad application in this paper is around 10 MVA, and its implementation using multilevel con-verters have several advantages. Multilevel converters continue to be a topic of intense research and there are several modulation techniques, reported in the literature [27]–[29], with several ad-vantages over conventional two-level converters [30], [31]. An important advantage of multilevel converters is the possibility to improve harmonic content of the synthesized voltage with a re-duced amount of commutation. Another advantage of multilevel converters is the possibility to reach higher voltage levels and higher power ratings with power devices having lower break-down voltages [30]. The increase in components in multilevel converters results in a corresponding increase in the number of valid commutation states, and thus in smoother changes in the state variables of the system and its consequent reduction in *dv/dt* of the output voltage.

Among many existing multilevel topologies, the dual con-verter has the advantage that two standard two-level converters can produce multilevel operation. However, the main disadvan-tage of the dual-converter topology is the need for a coupling transformer, not needed in other multilevel topologies for the same range of power and voltage.

The generality of the proposed filtering technique using instantaneous active and reactive power can be applied to any transformer configuration scheme in the power substation. Multilevel converter technology can facilitate the industrial im-plementation because it reduces the specifications of the power electronics switches and the voltagestress *dv/dt* on the magnetic components like coupling transformers and/or inductors [27].

II. HARMONIC AND UNBALANCE COMPENSATION SYSTEM

On balanced three-phase systems feeding balanced linear loads, the instantaneous active and reactive terms of the com-plex power are constant and equal to $p(t) = 3VI\cos(\varphi)$ and $q(t) = 3VI\sin(\varphi)$ [13], [32], whereas for

International Journal of Electrical and Electronics Engineers
Vol. No. 9, Issue No. 02, July - December 2017
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similar balanced three-phase systems, the instantaneous active and reactive power with unbalanced nonlinear loads contains average and oscillat-ing terms. To compensate for load imbalance and reduce har-monic injection from the load to the supply system, the proposed controller, shown in Fig. 1, is aimed at keeping constant the in-stantaneous active and reactive power exchange with the supply. In this paper, this is achieved with a shunt active filter directly connected to the power system using a voltage step-up filter transformer. For the railway application, the power stage in the filter is a three-phase voltage source converter (VSC) with a rat-ing between 10% and 15% of the distribution transformer rated power.

The controller computes the total instantaneous active and reactive power taken by the combination of traction system and filter. In the proposed compensation scheme, the controller selects the converter voltage *vr* required to keep constant the total instantaneous active and reactive power drawn from the grid, acting in this way as a three-phase current balancer and harmonic filter.

The *p*re f consign is used to reduce the variations in the dc link of the filter's power stage. This will adjust automatically the power taken by the traction system plus the filter losses. The reactive power reference *q*re f provides an additional degree of freedom that can be used to adjust the system's power factor.

Fig. 2 shows the open delta (V-V) and Scott transformers used frequently to connect a traction substation to the electric grid. These connection schemes generate two single-phase networks from the three-phase power system. Each single-phase circuit is used to feed a 60–100 km rail track.

The simulation of the steady state and dynamic behavior for the traction system under unbalance conditions and with harmonic current injection uses a space vector model of the open delta and Scott transformer, uncoupling the differential equations in the transformer model [11]. Additionally, the fil-ter and its control have been modeled using a space vector representation [22].

The power invariant space vector transformation is defined as [11]

$$x = \sqrt{\frac{2}{3}}\left(x_a(t) + \alpha x_b(t) + \alpha^2 x_c(t)\right); \quad \alpha = e^{j\frac{2\pi}{3}} \qquad (1)$$

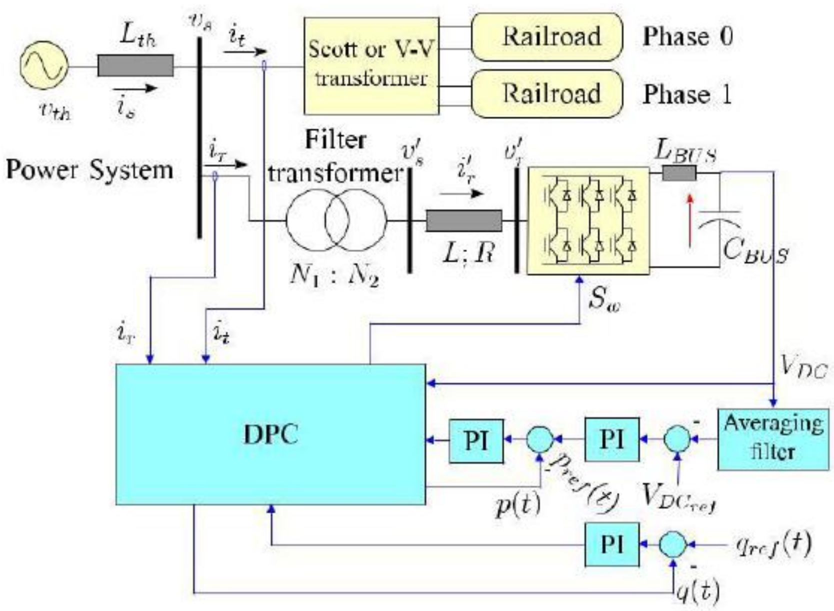

Fig. 1. Proposed compensation scheme.

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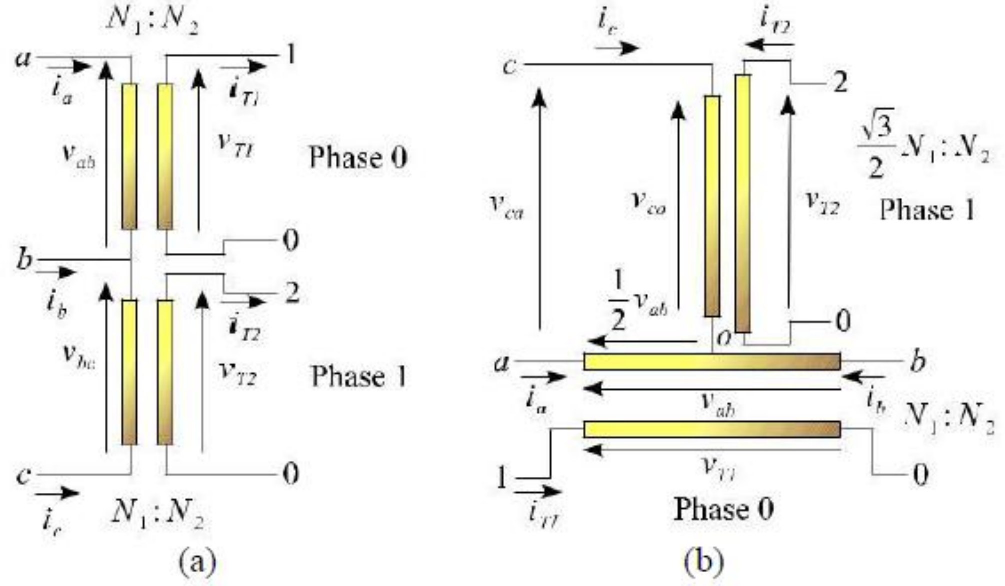

Fig. 2. Traction transformer schemes. (a) V-V transformer. (b) Scott transformer.

A. V-V Transformer Space Vector Model

For the ideal V-V transformer configuration shown in Fig. 2, its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws [1]

$$v_{ab} = \frac{N_1}{N_2} v_{T1}\,;\; v_{bc} = \frac{N_1}{N_2} v_{T2}$$
$$i_a = \frac{N_2}{N_1} i_{T1}\,;\; i_c = \frac{N_2}{N_1} i_{T2}. \tag{2}$$

The voltage and current space vectors calculated in the transformer's primary winding as function of the secondary winding voltages and currents are

$$v_s = \sqrt{\frac{2}{3}}\frac{N_1}{N_2}\left(v_{T1} - \alpha^2 v_{T2}\right)$$
$$i_t = \sqrt{\frac{2}{3}}\frac{N_2}{N_1}\left((1-\alpha)\, i_{T1} + \left(\alpha - \alpha^2\right) i_{T2}\right). \tag{3}$$

B. Scott Transformer Space Vector Model

For the ideal Scott transformer shown in Fig. 2, its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws [1]:

$$v_{ab} = \frac{N_1}{N_2} v_{T1}\,;\; v_{co} = \frac{\sqrt{3}}{2}\frac{N_1}{N_2} v_{T2}\,;$$
$$\frac{\sqrt{3}}{2}\frac{N_1}{N_2} i_c = i_{T2}\,;\; \frac{1}{2}\frac{N_1}{N_2}\left(i_a - i_b\right) = i_{T1}. \tag{4}$$

The voltage and current space vectors calculated in the transformer's primary winding as function of the secondary winding voltages and currents are

$$v_s = \sqrt{\frac{3}{2}}\frac{N_1}{N_2}\frac{1}{1-\alpha^2}\left(v_{T1} - j v_{T2}\right)$$
$$i_t = \sqrt{\frac{2}{3}}\frac{N_2}{N_1}\left((1-\alpha)\, i_{T1} + \sqrt{3}\,\alpha^2 i_{T2}\right). \tag{5}$$

discrete time k. Also, the algorithm for balancing and compensating the harmonics content, in the three-phase system, sets up the value for the wanted apparent power $s_{ref}(k)$. With these two values for the apparent power, $s(k)$ and $s_{ref}(k)$, any of the DPC controllers described in the literature [20]–[25], [34] can be used with the compensating converter to produce the proper rectifier voltage $v(k)$, i.e., for a given reference in active and reactive power, the change in power for proper compensation depends on the converter voltage $v(k)$. The apparent power variation needed to change from the uncompensated to the compensated state, gives the rectifier voltage $v_r(k)$ as follows:

$$v_r(k) = \frac{L}{T_s}\,\frac{s_0(k) - s(k)}{v(k)e^{j\omega T_s}} \tag{11}$$

where T_s is the control period, $s_0(k)$ is the change in the apparent power due to a null vector in the rectifier voltage, and $s(k)$ is defined as follows. Reference [22] shows a detailed development of this expression, for the DPC implementation used in this paper

$$s(k) = p_{ref}(k) - \Re e\{s(k)\} + j\left(q_{ref}(k) - \Im m\{s(k)\}\right). \tag{12}$$

The rectifier voltage v_r is synthesized in the converter using standard space vector modulation. As with other DPC algorithms, the reactor parameters are required for computing the estimated value of the power system voltages, the active and reactive power values and the updated value for the converter voltage indicated in (11).

The proposed algorithm has low computational demands, provides instantaneous correction of the active and reactive power in the point 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.

D. Harmonics Filtering and Balance Using DPC

In a power system with a high short-circuit ratio ($I_{SC}/I_L \geq$

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B. Scott Transformer Space Vector Model

For the ideal Scott transformer shown in Fig. 2, its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws [1]:

$$v_{ab} = \frac{N_1}{N_2} v_{T1}\ ;\ v_{co} = \frac{\sqrt{3}}{2}\frac{N_1}{N_2} v_{T2}\ ;$$

$$\frac{\sqrt{3}}{2}\frac{N_1}{N_2} i_c = i_{T2}\ ;\ \frac{1}{2}\frac{N_1}{N_2}(i_a - i_b) = i_{T1}\ . \quad (4)$$

The voltage and current space vectors calculated in the transformer's primary winding as function of the secondary winding voltages and currents are

$$v_s = \frac{\sqrt{3}}{2}\frac{N_1}{N_2}\frac{1}{1-\alpha^2}(v_{T1} - j v_{T2})$$

$$i_t = \frac{2N_2}{\sqrt{3}N_1}\left((1-\alpha) i_{T1} + \sqrt{3}\,\alpha^2 i_{T2}\right) . \quad (5)$$

C. Active and Reactive Power Control

The DPC controller is based on the instantaneous apparent power from the current and voltage space vectors definitions culated with the measured variables $v_s(k)$ and $i_s(k)$, in any

$$s(k) = p_{ref} - \Re e\{s(k)\} + j\, q_{ref} - \Im m\{s(k)\} . \quad (12)$$

The rectifier voltage v_r is synthesized in the converter using standard space vector modulation. As with other DPC algorithms, the reactor parameters are required for computing the estimated value of the power system voltages, the active and reactive power values and the updated value for the converter voltage indicated in (11).

The proposed algorithm has low computational demands, provides instantaneous correction of the active and reactive power in the point 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.

D. Harmonics Filtering and Balance Using DPC

In a power system with a high short-circuit ratio ($I_{SC}/I_L \geq$ 20), the voltage distortion produced by harmonic or unbalanced currents can be neglected [35], [36]. The unbalance is defined using the ratio between negative V_2 and positive V_1 sequence V_2/V_1 [37]. For three-phase voltage and current, a general expression including harmonics and unbalance is obtained with

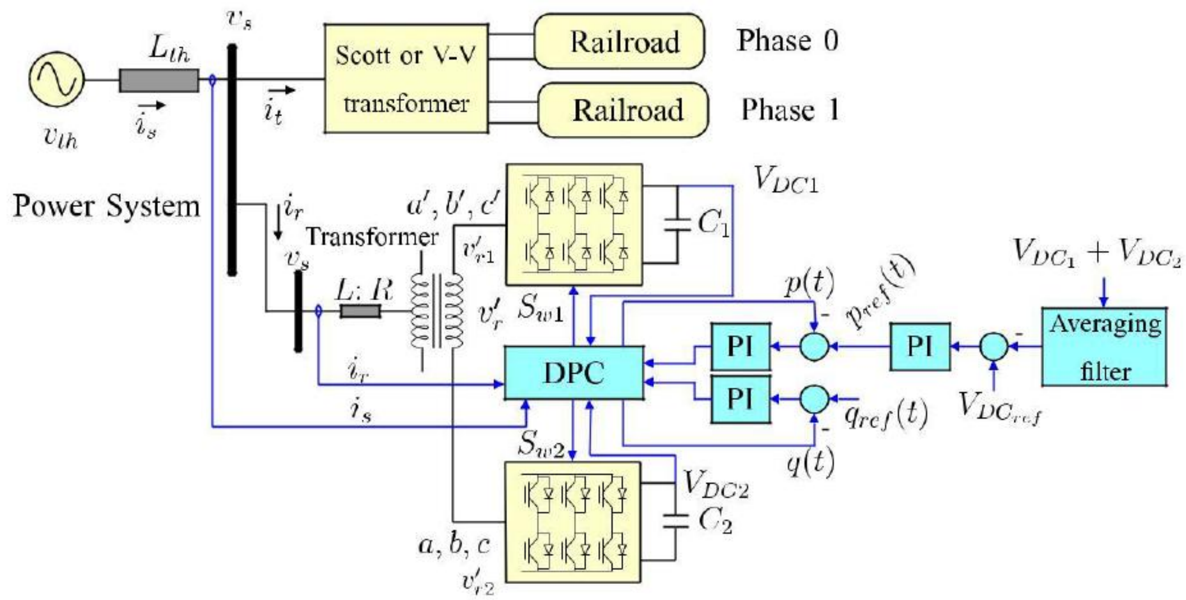

Fig. 3. Proposed multilevel compensation scheme.

and the instantaneous power ($s = v_s \cdot i_s^*$) becomes [13]

$$s = 3\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} V_{n1} I_{m1} e^{j((n-m)\omega t + \alpha_{n1} - \beta_{m1})} + \cdots$$

$$+ V_{n1} I_{m2} e^{j((n+m)\omega t + \alpha_{n1} + \beta_{m2})} + \cdots$$

$$+ V_{n2} I_{m1} e^{-j((n+m)\omega t + \alpha_{n2} + \beta_{m1})} + \cdots$$

$$+ V_{n2} I_{m2} e^{-j((n-m)\omega t + \alpha_{n2} - \beta_{m2})} . \quad (16)$$

TABLE I
PARAMETERS OF THE FILTER SCHEME MODEL

V_{th}	L_{th}	R_{trx}	L_{trx}	$C_{\{1,2\}}$	$V_{DC\{1,2\}}$
$208\,V$	$0.1\,mH$	$1\,m\Omega$	$10.0\,mH$	$1100\,\mu F$	$200 \sim 600V$

the compensation system keeps a constant instantaneous power, the harmonic current distortion THD_I can be improved up to the harmonic voltage distortion THD_V value [35], [37], [38].

E. Multilevel Compensation

Fig. 3 shows the open delta transformer (V-V) used to connect a traction substation to the electric grid, while the voltage space vector calculated in (11) is synthesized with the

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Enforcing a constant instantaneous complex power s, eliminates the time dependence in (16) for a strong voltage supply. Hence, the first and fourth terms in (16) are constant when $n = m$, corresponding to harmonic filtering in the current sequence with strong voltage supply. The second and third terms for ($n = m$) in (16) are zero for instantaneous constant complex power s, leading to the following expression:

$$\sum_{n=1}^{\infty} V_{n1} I_{n2} e^{j(2n\omega t+\alpha_{n1}-\beta_{n2})} + \cdots$$

$$+ V_{n2} I_{n1} e^{-j(2n\omega t+\alpha_{n2}-\beta_{n1})} = 0. \quad (17)$$

To obtain zero in (17) the following relations need to be satisfied:

$$V_{n1} I_{n2} = 0, \text{ and } \quad V_{n2} I_{n1} = 0. \quad (18)$$

To obtain zero in (17) the following relations need to be satisfied:

$$V_{n1} I_{n2} = 0, \text{ and } \quad V_{n2} I_{n1} = 0. \quad (18)$$

As the positive sequence voltage V_{n1} and current I_{n1} are different from zero ($V_{n1} = 0 \wedge I_{n1} = 0$), the negative sequence voltage V_{n2} and current I_{n2} should be zero in other to obtain a constant instantaneous power. According to (18), for constant instantaneous power ($s = P + jQ$) unbalance is eliminated and voltage and current have similar harmonic composition. The power system voltage normally has a $THD_V \leq 3\%$, so that when dual converter modulation technique presented in [34].

III. Simulation Results

The scheme 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 included in these simulations. The railroad system is represented using the measured harmonic currents distribution, injected to the power system in the secondary side of each transformer [39]. 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.

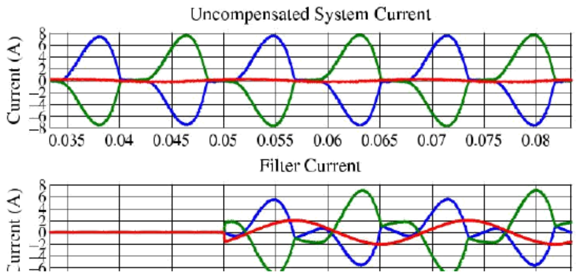
Table II shows the current total harmonic distortion (THD) and the unbalance relation between positive and negative se-quences

shown in Table I.

Table II shows the current total harmonic distortion (THD) and the unbalance relation between positive and negative se-quences I_2/I_1 [35], for uncompensated and compensated cases using V-V and Scott transformers. The rectifier case uses a single-phase rectifier bridge-based load in one secondary of the main transformer. For the railroad case, the measured har-monic current spectrum is injected in one secondary phase [39]. The simulation uses maximum unbalance by operating on one

TABLE II
Simulated THD and Unbalance

	Uncompensated		Compensated	
Simulated Cases	THD	I_2/I_1	THD	I_2/I_1
$V-V$: rectifier case	.4022	.9494	.0067	.0024
$V-V$: rail road case	.2074	.9239	.0068	.0018
Scott: rectifier case	.4061	.9236	.0070	.0014
Scott: rail road case	.1226	.8754	.0051	.0014



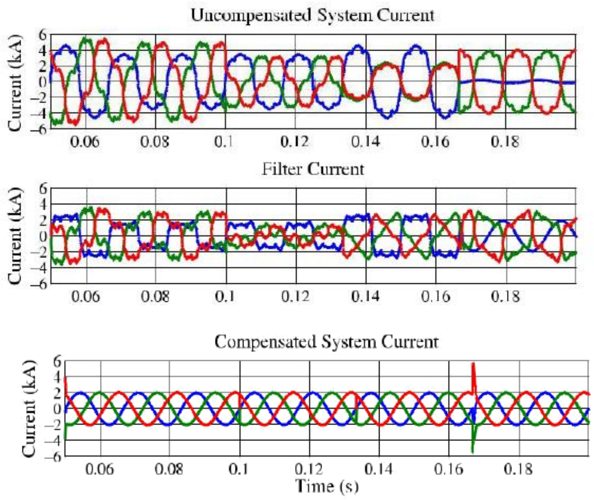


Fig. 5. Simulated waveforms for the Scott transformer connection for different railroad load profiles.

International Journal of Electrical and Electronics Engineers
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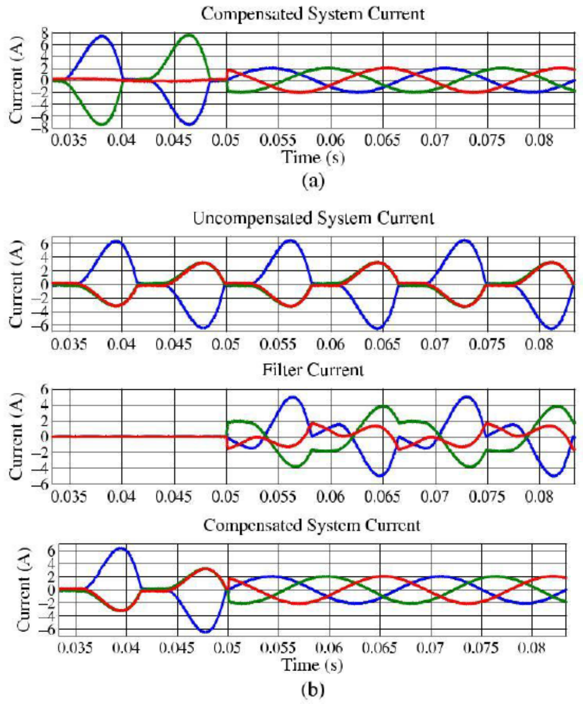


Fig. 4. Simulated active filter effect on the power system currents feeding a single phase rectifier load for the Scott and V–V connections. (a) V–V. (b) Scott.

single-phase circuit with the other under no load, which is the most demanding operating condition. The active filter injects the harmonic content used by the single-phase railroad load. The proposed control scheme reduces by more than 96% the THD for both transformer connections.

Fig. 4 shows the simulated instantaneous currents flowing into the power system without compensation and with the proposed

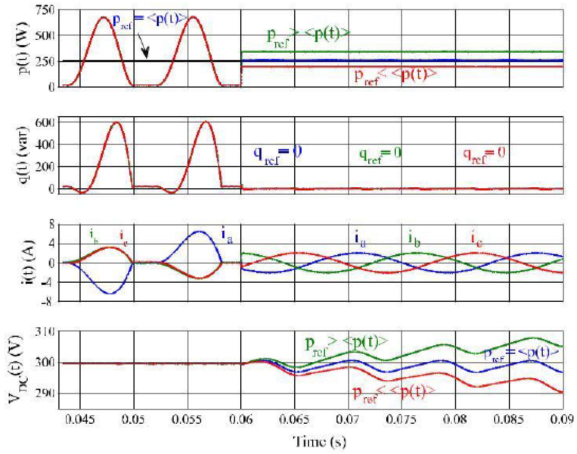


Fig. 6. Effect on dc voltage due to p_{ref} variation.

active and reactive compensation. The simulations show the balancing effect on the power system current as well as the THD reduction obtained with the active filter controlled by the instantaneous active and reactive power. Both transformers (V-V and Scott) have a similar current behavior when a single-phase rectifier load is connected in one secondary.

Fig. 5 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. This load profiles was selected from the Ezequiel–Zamora railroad system and the harmonic content from [39].

Fig. 6 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 minimum

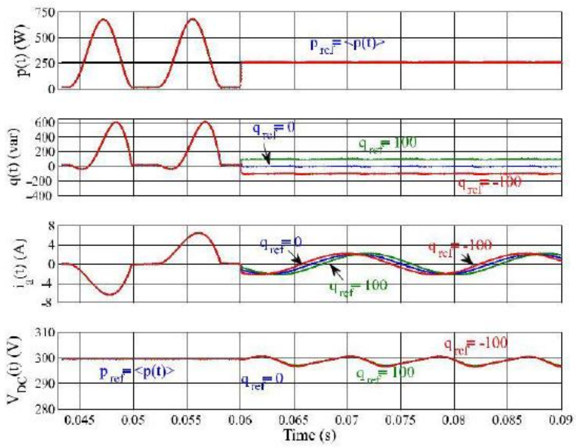
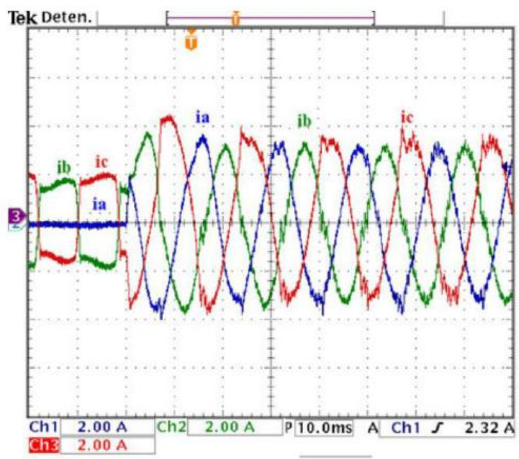


Fig. 7. Effect on the line current's phase shift due to q_{ref} variation.



(a)

International Journal of Electrical and Electronics Engineers
Vol. No. 9, Issue No. 02, July - December 2017
ISSN (O) 2321-2055
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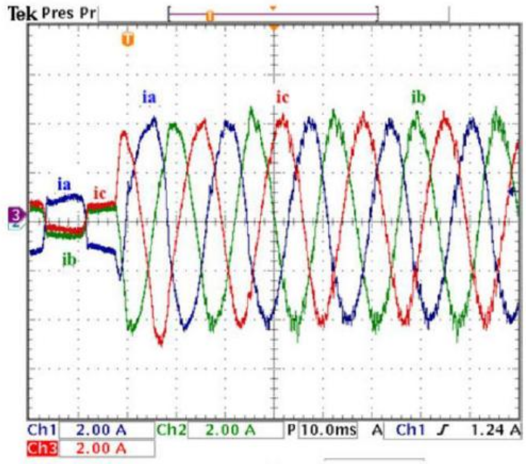
effect on the instantaneous reactive power and phase currents. Nevertheless, V_{dc} voltage changes when the reference power p_{ref} is different than the average power $p(t)$. A greater power reference p_{ref} with respect to the average power inject power in the dc bus and this energy is stored in the converter capacitor C. When the p_{ref} is lower than $p(t)$, energy flows from the capacitor to the power system and the dc voltage decreases.

Fig. 7 shows how for p_{ref} constant, changes in q_{ref} affect the system variables. In this case, the main effect of the reactive power reference variation is on the system's power factor, and can be observed in the relative current phase. On the other hand, the dc-link voltage V_{dc} is barely influenced by changes in the reactive power reference.



(b)

Fig. 8. Balance and harmonic current compensation in two-level converter. (a) V-V transformer. (b) Scott transformer.

IV. EXPERIMENTAL RESULTS

For the experimental test, the proposed algorithm is imple-mented on a custom built floating point DSP (ADSP-21369-330 MHz)-based test-rig. The power stage uses six 50 A, 1200 V, IGBTs with two 2200 μF 400 V series connected capacitors in the dc link. The input inductors have 7 mH and its resistive component have been neglected; the PWM signals are pro-vided by a Xilinx FPGA with a 10 kHz carrier. The railroad load is implemented in only one single-phase circuit using a single-phase rectifier bridge with an R–L (50–200 Ω, 40 mH) load on the dc side. The sampling frequency is synchronized by the coprocessor at the beginning of each PWM cycle. The electrical parameters for the power circuit in the experimental tests are the same as those used in the simulations and shown in Table I. The V-V and Scott transformer connections are built us-ing two single-phase 480–240: 240–120 V, 1 kVA transformers. The Scott transformer's ratio is adjusted using two additional single-phase variable transformers.

Fig. 8(a) and (b) shows the current waveform on a three-phase V-V and Scott transformers test bench feeding a nonlinear load, with and without the proposed compensation method. The average load power $p(t)$ was 115.36 W with power factor 96% and the reference power p_{ref} was chosen as 300 W and $q_{ref} = 0$ var. Comparing the compensated and uncompensated results, it can be observed that the compensator activated at t = 20 ms reduces unbalance and harmonic distortion in the system in both transformer connections.

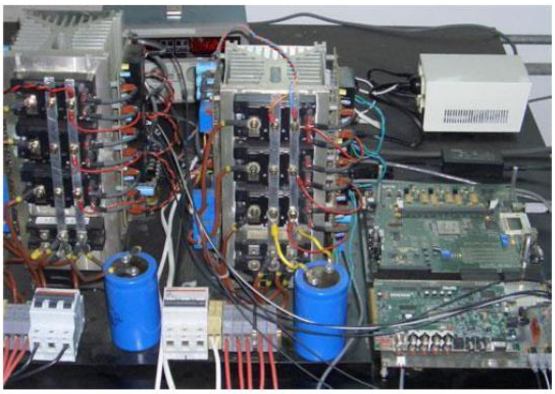


Fig. 9. Dual converter test-rig.

Fig. 9 shows the dual converter test-rig used in the multilevel experimental setup.

Fig. 10(a) and (b) shows the compensated currents waveforms in steady state for two dual-converter test setups, one with a three-phase V-V transformer and the other with a Scott trans-former, feeding a nonlinear load. The average load power $p(t)$ was 115.36 W with power factor 96% and the reference power p_{ref} was chosen as 300 W and $q_{ref} = 0$ var. The uncompensated results are the same observed in the two-level converter. The compensator reduces unbalance and harmonic distortion in the system for both transformer connections.

Table III shows the current total harmonic distortion (THD) and unbalance relation between positive and negative sequences (I_2/I_1), for uncompensated and compensated cases using V-V

TABLE III
EXPERIMENTAL RESULTS THD AND UNBALANCE

	Uncompensated		Compensated 2 Level		Compensated Dual	
	THD	I_2/I_1	THD	I_2/I_1	THD	I_2/I_1
$V-V$	.469	0.988	.108	.0267	.092	.0336
Scott	.456	0.986	.096	.0157	.087	.0178

and Scott transformer for both converter configurations. The load uses a single-phase rectifier bridge-based load in one secondary of the main transformer. The proposed control scheme reduces the unbalance from 98% to less than 3.4% in both transformer connections. Also the THD is reduced from 47% around 10%. The two-level scheme has better performance for unbalance compensation and the dual converter improve the THD obtained.

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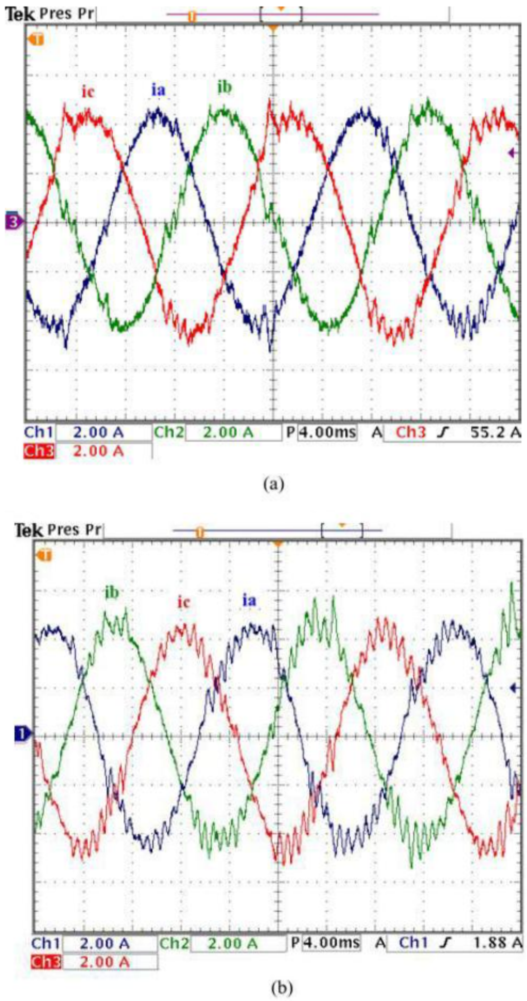

Fig. 10. Balance and harmonic current compensation using a dual converter. (a) V-V transformer. (b) Scott transformer.

V. CONCLUSION

The proposed DPC-based compensation scheme reduces negative sequence currents injected by an uncompensated electric traction system using any power transformer connection. This technique can be used to reduce the current THD to values complying with international regulations, and additionally regulates the power factor observed in the common coupling point between the traction substation and the grid. Also, the compensation method based on the instantaneous power control algorithm with direct space vector representation, reduces the system's current THD to allowable ranges (< 20%) and reduces the overall unbalance from 97% to 18% for worse-case operation. The compensation algorithm is able to control the power factor measured at the common coupling point under all considered conditions, with a very short transient thanks to the fast dynamic response of DPC. The distortion that remains in the compensated current is mainly due to the distortion in the grid voltage and the limitations of the switched nature of the filter's power stage, that is, unable to compensate very fast transients present in the traction current.

Finally, a previously unreported space vector model for the Scott and open delta transformer connection, has been introduced in this paper.

The dual converter compensation scheme using an instantaneous power control algorithm with direct space vector computation reduces the unbalanced currents to allowable ranges (< 10%) and reduces the overall unbalance from 42.8% to 3.8%. The dual converter's topology has been tested as an active fil-ter, for increased power conversion employing lower voltage switching devices. The algorithm used in the control of the dual converter was an optimized version of the DPC. *dv/dt* is re-duced by the increased number of levels generated by the dual converter topology.

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