Harmonic and Balance Compensation using Instantaneous Active and Reactive Power Control on Electric Railway Systems

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***Abstract*—This work presents a general filtering and unbalance compensation scheme for electric traction systems. The proposed method uses an active filter controlled with the instantaneous active and reactive power, to reduce the harmonic current distortion and the negative sequence obtained by the system under unbalanced operation in steady state. The proposed filter is evaluated using open delta (V-V) and Scott transformers in the power substation. The scheme has been simulated and experimentally validated. Experimental and simulation results show the controller advantages and the applicability of the proposed method in railway systems .**

***Index Terms*—Harmonics, Active filter, Transformer, Locomotive, Traction application.**

I. Introduction

Electric traction systems for passengers and goods use different 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]. In a practical application, the load associated with each single-phase circuit does not compensate each other, 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. This unbalance is due mainly to the injection of current harmonics to the main three-phase system depending on the transformer connection and harmonic order [2].

It is then required the use of filters and unbalance compensators to ensure proper system operation and to raise 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 of the traction substation. Usually, the coupling factor between two feeders is negligible due to the independent operation of each passive compensator. 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 change in load conditions.

Different active power quality compensators have been proposed in [4]–[6] to solve the unbalance problem. All of them employ two single-phase converters that have a common DC bus and the simultaneous compensation of harmonic content and unbalance can not be achieved with these schemes. Also, when the compensation is made from the single phase side, the instantaneous active and reactive power definition is difficult to use in the compensation of harmonics and power unbalance [7] [8].

In this work a compensation scheme is proposed to provide simultaneous correction of harmonic content and load unbalance for railroad systems using open delta or Scott transformers in the power substation. This scheme is based on the instantaneous active and reactive power description of the system [9], using space vector representation of the state variables, and the application of direct power control (DPC) to attain the required correction by minimizing a cost function obtained from the instantaneous active and reactive mismatch [10]–[12].

The control strategies presented in this work are both, simulated using a state variables 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, the Scott transformer, the filtering and the load balancing converters [13].

The generality of the proposed filtering technique using instantaneous active and reactive power can be extended to any other transformer configuration in the power substation. Multilevel converter technology can facilitate the industrial implementation because reduces the specifications of the power electronics switches and the voltage stress ($\frac{dv}{dt}$) on the magnetic components like coupling transformers and/or inductors [14].

II. Harmonic and unbalance compensation system

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

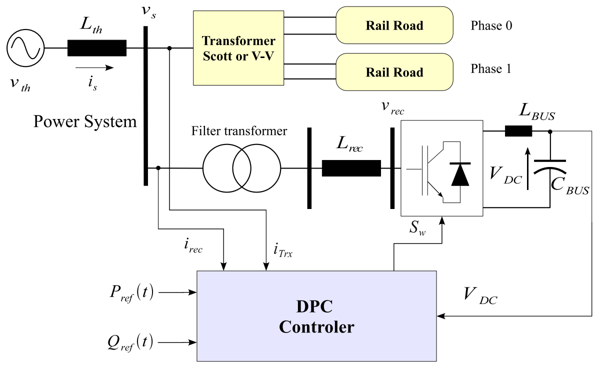
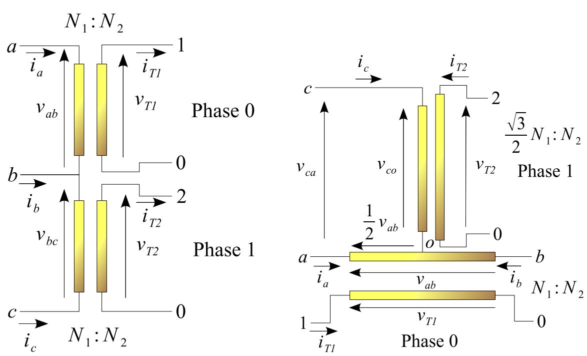


Figure 1: Proposed compensation scheme



(a) V-V Transformer (b) Scott Transformer

Figure 2: Proposed compensation scheme.

Figure 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 to 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 [7]. Additionally, the filter and its control have been modeled using a space vector representation [15].

The power invariant space vector transformation is defined as,

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

A. V-V Transformer space vector model

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

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

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

$$\begin{array}{c} \vec{v}_s = \sqrt{\tfrac{2}{3}}\, \tfrac{N_1}{N_2} \left(v_{T1} - \alpha^2 v_{T2} \right) \\ \vec{i}_s = \sqrt{\tfrac{2}{3}}\, \tfrac{N_2}{N_1} \left[(1-\alpha)\, i_{T1} + \left(\alpha - \alpha^2\right) i_{T2} \right] \end{array} \tag{3}$$

B. Scott Transformer space vector model

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

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

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

$$\begin{array}{c} \vec{v}_s = \sqrt{\tfrac{3}{2}}\, \tfrac{N_1}{N_2}\, \tfrac{1}{1-\alpha^2} \left(v_{T1} - j v_{T2} \right) \\ \vec{i}_s = \sqrt{\tfrac{2}{3}}\, \tfrac{N_2}{N_1} \left((1-\alpha) i_{T1} + \sqrt{3}\alpha^2 i_{T2} \right) \end{array} \tag{5}$$

C. Active and reactive power control

The DPC controller is based in the instantaneous apparent power from the current and voltage space vectors definitions [7]:

$$\vec{s} = \vec{v}_s \cdot \vec{i}_s^{\,*} = \left(v_{s\alpha} + j\, v_{s\beta} \right) \cdot \left(i_{s\alpha} + j\, i_{s\beta} \right)^* = p + jq \tag{6}$$

From Fig. 1, the active filter can be modeled as,

$$\vec{v}_s = \vec{v}_r + R\,\vec{i}_s + L\frac{d\vec{i}_s}{dt} \tag{7}$$

A discrete time version of this equation is obtained by replacing the derivative with a first order Euler approximation, and the estimated supply current for the next control cycle becomes

$$\widehat{\vec{i}}_s(k+1) = \vec{i}_s(k) + \Delta\widehat{\vec{i}}_s(k) \tag{8}$$

where

$$\Delta\widehat{\vec{i}}_s(k) = \frac{T_s}{\hat{L}} \left[\widehat{\vec{v}}_s(k) - \widehat{\vec{v}}_r(k) - \hat{R}\,\vec{i}_s(k) \right] \tag{9}$$

From (6), the estimated active and reactive power for the next sampling period can be written as,

$$\begin{array}{l} \vec{s}(k+1) = \vec{s}(k) + \Delta\vec{s}(k) = \vec{s}(k) + \Delta p(k) + j\Delta q(k) = \\ = \vec{v}_s(k) \cdot \vec{i}_s(k)^* + \Delta\widehat{\vec{v}}_s(k) \cdot \vec{i}_s(k)^* + \widehat{\vec{v}}_s(k+1) \cdot \Delta\widehat{\vec{i}}_s(k)^* \end{array} \tag{10}$$

Replacing (9) in (10), the change in apparent power is:

$$\begin{array}{rcl} \Delta\vec{s}(k) & = & \Delta\widehat{\vec{v}}_s(k) \cdot \vec{i}_s(k)^* + \cdots \\ \cdots & + & \widehat{\vec{v}}_s(k+1) \cdot \dfrac{T_s}{\hat{L}} \left[\widehat{\vec{v}}_s(k) - \widehat{\vec{v}}_r(k) - \hat{R}\,\vec{i}_s(k) \right]^* \end{array} \tag{11}$$

For a sinusoidal voltage source power supply, the estimated $\widehat{\vec{v}}_s(k+1)$ is obtained by rotating in $\Delta\theta = \omega T_s$ rads.

$$\widehat{\vec{v}}_s(k+1) = \vec{v}_s(k) \cdot e^{j\omega T_s} \quad (12)$$

$$\Delta\widehat{\vec{v}}_s(k) = \vec{v}_s(k) \left(e^{j\omega T_s} - 1\right) \quad (13)$$

The complex apparent power $\vec{s}(k)$ is a function of the supply voltage, and also changes with the rectifier voltage $\widehat{\vec{v}}_r(k)$ that can be manipulated to obtain the commanded value $p_{ref} + j\, q_{ref}$. Defining $\Delta\vec{s}_0(k)$ as an independent voltage vector term in $\widehat{\vec{v}}_r(k)$, the following change in active and reactive power is obtained

$$\begin{aligned} \Delta\vec{s}_0(k) \quad &= \quad \frac{T_s}{\hat{L}} \left|\vec{v}_s(k)\right|^2 \cdot e^{j\omega T_s} + \cdots \quad (14) \\ \cdots \quad &+ \vec{v}_s(k) \cdot \vec{i}_s(k)^* \left[\left(1 - \frac{T_s \hat{R}}{\hat{L}}\right) e^{j\omega T_s} - 1 \right] \end{aligned}$$

For a given reference in active and reactive power the change in power for proper compensation becomes a function of the converter voltage $\widehat{\vec{v}}_r(k)$. The apparent power variation needed to change from the actual to the demanded value in the following sampling period, p_{ref} and q_{ref}, are given by the following expressions

$$\Delta\vec{s}(k) = \Delta\vec{s}_0(k) - \frac{T_s}{\hat{L}} \left[\widehat{\vec{v}}_s(k+1) \cdot \widehat{\vec{v}}_r(k)^*\right] \quad (15)$$

$$\vec{\epsilon}_s(k) = \underbrace{p_{ref} - \Re e\{\vec{s}(k)\}}_{\epsilon_p(k)} + j\, \underbrace{q_{ref} - \Im m\{\vec{s}(k)\}}_{\epsilon_q(k)} \quad (16)$$

In the OVSS algorithm, also known as predictive direct power control, a cost function is evaluated for a set of the converter voltages $\vec{v}_r$, and the value of this voltage providing the minimum value for the cost function is employed in the next control cycle [16]–[18]. In this case the cost function is

$$J(k) = \eta_p \left(\epsilon_p(k) - \Re e\, |\Delta\vec{s}(k)|\right)^2 + \eta_q \left(\epsilon_q(k) - \Im m\, |\Delta\vec{s}(k)|\right)^2 \quad (17)$$

where η_p and η_q control the relative importance of the active and reactive parts in the system.

The proposed control technique is based in the selection of the voltage vector that minimized the cost function (17) expressed by the active and reactive power errors. However, since zero is the global minimum for the cost function, instead of testing among several candidate vectors for the best choice, the proposed techniques computes with a closed form formula, the voltage vector for this minimum. Forcing to zero the cost function (17), $J(k) = 0$,

$$\vec{\epsilon_s}(k) - \Delta\vec{s}(k) = \mathbf{0} \quad (18)$$

Replacing (15) and (16) in (18)

$$\Delta\vec{s}_0(k) - \frac{T_s}{\hat{L}} \left[\widehat{\vec{v}}_s(k+1) \cdot \widehat{\vec{v}}_r(k)^*\right] = \epsilon_p(k) + j\epsilon_q(k) \quad (19)$$

Finally, replacing (12) into (19), the absolute optimum converter voltage required to attain the commanded active and reactive power becomes

$$\widehat{\vec{v}}_r(k) = \widehat{v}_{r\alpha}(k) + j\, \widehat{v}_{r\beta}(k) = \frac{\hat{L}}{T_s} \left[\frac{\Delta\vec{s}_0(k) - \vec{\epsilon}_s(k)}{\vec{v}_s(k) \cdot e^{j\omega T_s}}\right]^* \quad (20)$$

This voltage is synthesized in the converter using standard space vector modulation (SVM) [19]. 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 and the update value for the converter voltage indicated in (20).

The proposed algorithm has many advantages over existing methods, among them it provides an instantaneous correction of the active and reactive power flowing into the converter, reduces the ripple in the instantaneous power and currents, resulting in a low harmonic distortion and have low computational demands.

III. Simulation Results

The scheme shown in Fig. 1 has been modeled using the space vector representation of the state variables [7]. Both, the $V-V$ and Scott transformers have been included in these simulations. The rail road system is represented using the measured harmonic currents distribution, injected to the power system in the secondary side of each transformer [20]. 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), IGBT converter and the filter inductor are used in the simulation. The per unit parameter used in simulations are shown in Table I.

Table I: Parameters of the filter scheme model

L_{th}	R_{Trx}	L_{Trx}	R_{trx}	L_{trx}	R_{rec}	L_{rec}	V_{DC}
0.037	0.01	0.1	0.01	0.1	0.005	0.05	3

Table II shows the current Total Harmonic Distortion (THD) and the unbalance relation between positive and negative sequences (I_2/I_1) [21], for uncompensated and compensated cases using $V-V$ and Scott transformer. The simulation uses maximum unbalance by operating on one 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 rail road load. The proposed control scheme reduces by more than 50% the THD for both transformer connections.

Table II: Simulated total harmonic distortion and unbalance

	Uncompesated		Compensated	
Simulated Cases	THD	I_2/I_1	THD	I_2/I_1
$V-V$ rectifier	.4065	.9238	.1804	.0835
$V-V$ rail road	.2054	.9216	.1110	.0732
Scott rectifier	.4015	.9235	.1228	.0838
Scott rail road	.2264	.9384	.0747	.0813

Figure 3 shows the simulated instantaneous currents flowing into the power system without compensation and with the proposed 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.

IV. Experimental results

For the experimental test, the proposed algorithm was implemented on a custom build floating point DSP (ADSP-21061-40 MHz) based test-rig. The power stage uses six 50A, 1200V, IGBTs with two 2200 μF 400 V series connected capacitors in the DC link. The input inductors have an 7mH; the PWM signals are provided by a motion co-processor ADMC-201 operating at 10 kHz. The rail road load was implemented in only one single phase circuit using a single phase rectifier bridge with an R-L (50-200 Ω, 40 mH) load in the DC side. The sampling frequency is synchronized by the motion co-processor at the beginning of each PWM cycle. Fig. 4 shows the power module and the DSP based processing unit. The electrical parameters for the power circuit in the experimental tests are the same to those used in the simulations, and shown in Table III. The $V-V$ and Scott transformer connections were built using two single-phase – 480 : 240 – 120 V, 1 kVA transformers. The Scott transformer was built with two additional single phase variable transformers.

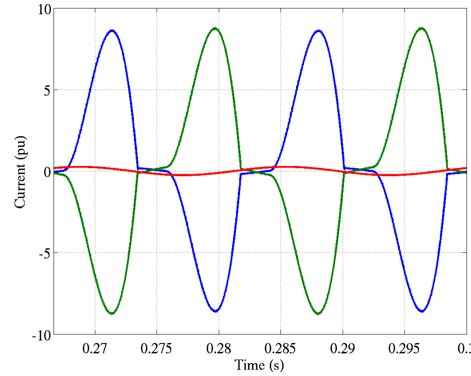
Table III: Parameter test-rig

R_{rec}	L_{rec}	C	V_{DC}	T_s	V
$20\,m\Omega$	$7.0\,mH$	$1100\,\mu F$	$200 \sim 600V$	$100\,\mu s$	$208\,V$

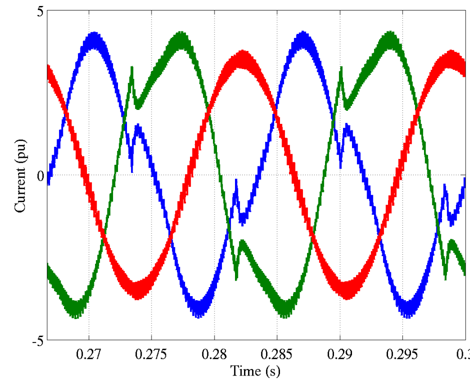
f	f_s	R_{LOAD}	C_{LOAD}	L_{LOAD}
$60\,Hz$	$100\,kHz$	$50\,\Omega$	$2200\,\mu F$	$17\,mH$

A. $V-V$ Transformer

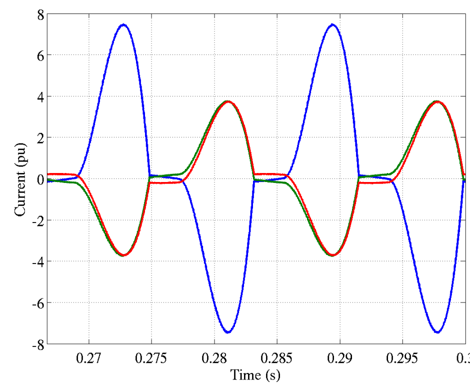
Figures 5a to 5d show the current waveforms and spectrums measured on a three phase $V-V$ transformer test bench feeding a non-linear load, with and without the proposed compensation scheme. The measurements were obtained using a power quality analyzer type “B” [22]. Comparing the compensated and the uncompensated results, it can be observed that the compensator reduces unbalance and harmonic distortion in the system. The unbalance is reduced from 94.7% (uncompensated value) to 16.8% (compensated value), and the system's current THD to values below 18.4% in all phases, with a significant reduction in the third and seventh harmonics which are the more significant components present in the harmonic spectra generated by vector controlled converters used in locomotives.



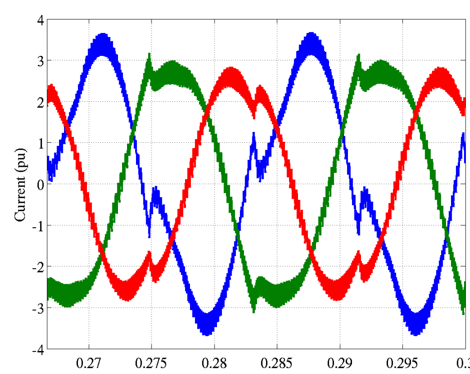
(a) Uncompensated ($V-V$ transformer)



(b) Compensated ($V-V$ transformer)



(c) Uncompensated (Scott transformer)



(d) Compensated (Scott transformer)

Figure 3: Simulated active filter effect on power system currents feeding a single phase rectifier load

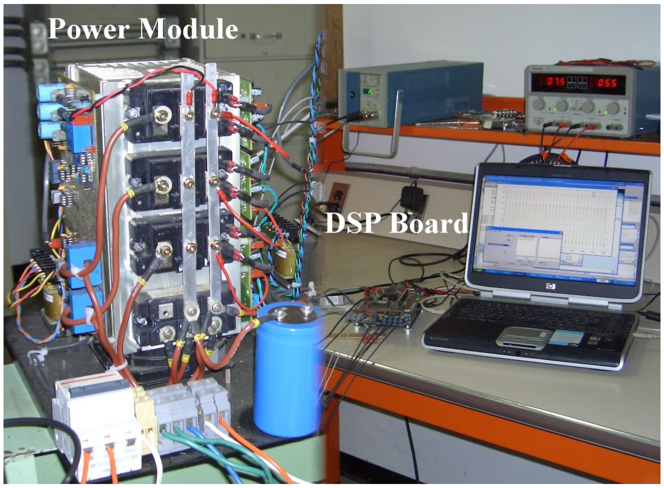


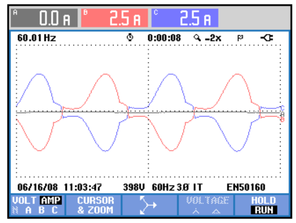
Figure 4: Experimental rig

B. Scott Transformer

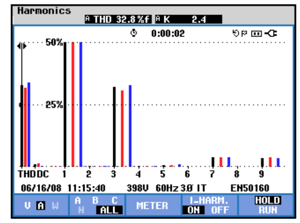
Figures 5e to 5h show the current waveforms and the harmonic spectrum, measured on a three phase Scott transformer test bench feeding a non-linear load, with and without the proposed compensation scheme. The non-linear load was the same used in the $V-V$ transformer case. Comparing the compensated and the uncompensated results, it can be observed that the compensator reduces harmonic content and balance the three phase load. The compensator reduces the current unbalance from 94.7% (uncompensated value) to 16.8% (compensated value), and the system's current THD to values below 18.4% in all phases, with a significant reduction in the third and seventh harmonics which are the more significant components present in the harmonic spectra generated by vector controlled converters used in locomotives.

V. Conclusions

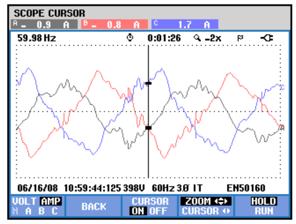
The proposed compensation scheme reduces negative sequence currents that circulate in the uncompensated system feeding an electric traction system using a power system transformer connected in $V-V$ or Scott configuration. The scheme reduces the current THD to values allowed by international regulations, and regulates the power factor observed in the common coupling point between the traction substation and the power system. The proposed compensation scheme implementation using an 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 coupling point under all considered conditions. From the simulation and experimental results it is found that there is a compromise between the amount of unbalance correction and harmonic reduction that can be achieved. This is due to the finite amount of energy stored by the active filter in its input inductance and dc-link capacitor.



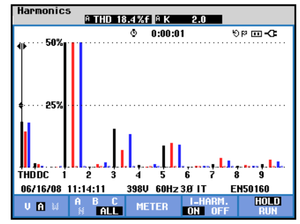
(a) Uncompensated ($V-V$)



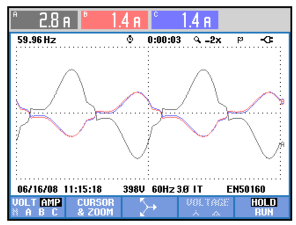
(b) Harmonics uncompensated ($V-V$)



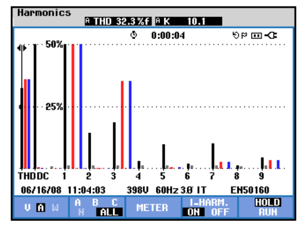
(c) Compensated ($V-V$)



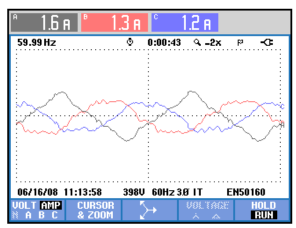
(d) Harmonics compensated ($V-V$)



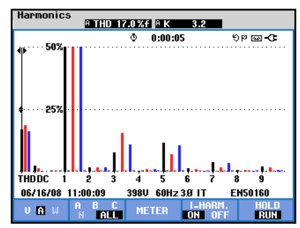
(e) Uncompensated (Scott)



(f) Harmonics uncompensated (Scott)



(g) Compensated (Scott)



(h) Harmonics compensated (Scott)

Figure 5: Experimental active filter effects on power system currents feeding a single phase rectifier load

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References

[1] B.-K. Chen and B.-S. Guo, “Three phase models of specially connected transformers,” *Power Delivery, IEEE Transactions on*, vol. 11, no. 1, pp. 323–330, 1996.

[2] G. W. Chang, H.-W. Lin, and S.-K. Chen, “Modeling characteristics of harmonic currents generated by high-speed railway traction drive converters,” *IEEE Transactions on Power Delivery*, vol. 19, pp. 766–733, apr 2004.

[3] R. E. Morrison, "Power quality issues on ac traction systems," in *Proceedings Ninth International Conference on Harmonics and Quality of Power, 2000*, vol. 2, pp. 709–714, 2000.

[4] S. T. Senini and P. J. Wolfs, "Novel topology for correction of unbalanced load in single phase electric traction systems," in *IEEE 33rd Annual Power Electronics Specialists Conference, 2002. pesc 02. 2002*, vol. 3, pp. 1208–1212, 2002.

[5] M. Goto, T. Nakamura, Y. Mochinaga, and Y. Ishii, "Static negative-phase-sequence current compensator for railwaypower supply system," in *International Conference on Electric Railways in a United Europe, 1995.*, pp. 78–82, mar 1995.

[6] R. Cutri and L. M. Jr, "Reference currents determination techniques for load unbalance compensation," Tech. Rep. 11, 2005.

[7] J. M. Aller, A. Bueno, and T. Pagá, "Power system analysis using space vector transformation," *IEEE Transaction on Power System*, vol. 17, no. 4, pp. 957–965, 2002.

[8] H. Li, F. Zhuo, L. Wu, W. Lei, J. Liu, and Z. Wang, "A novel current detection algorithm for shunt active power filters in harmonic elimination, reactive power compensation and three-phase balancing," in *IEEE 35th Annual Power Electronics Specialists Conference, 2004. PESC 04. 2004*, vol. 2, pp. 1017–1023, jun 2004.

[9] J. M. Aller, A. Bueno, J. Restrepo, M. I. Giménez, and V. Guzmán, "Advantages of instantaneous reactive power definition in three phase system meausrements," *IEEE Power Engineering Review*, vol. 19, no. 6, pp. 49–50, 1999.

[10] S. A. Larrinaga, M. A. R. Vidal, E. Oyarbide, and J. R. T. Apraiz, "Predictive control strategy for DC/AC converters based on direct power control," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 54, pp. 1261–1271, June 2007.

[11] P. Antoniewicz, M. P. Kazmierkowski, S. Aurtenechea, and M. A. Rodriguez, "Comparative study of two predictive direct power control algorithms for three-phase AC/DC converters," in *Power Electronics and Applications, 2007 European Conference on*, (Aalborg), pp. 1–10, Sept. 2007.

[12] P. Cortés, J. Rodríguez, P. Antoniewicz, and M. Kazmierkowski, "Direct power control of an AFE using predictive control," *IEEE Transactions on Power Electronics*, vol. 23, pp. 2516–2523, Sept. 2008.

[13] M. Giménez, V. Guzmán, J. Restrepo, J. Aller, A. Bueno, J. Viola, A. Millán, and A. Cabello, "Plataforma: Development of an integrated dynamic test system for power electronics systems performance analysis," *Revista de la Facultad de Ingeniería – UCV*, vol. 23, no. 3, pp. 91–92, 2008.

[14] Y. Cheng, C. Qian, M. L. Crow, S. Pekarek, and S. Atcitty, "A comparison of diode-clamped and cascaded multilevel converters for a statcom with energy storage," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 53, pp. 1512–1521, Oct. 2006.

[15] J. A. Restrepo, J. M. Aller, J. C. Viola, A. Bueno, and T. G. Habetler, "Optimum space vector computation technique for direct power control," *IEEE Transactions on Power Electronics*, vol. 24, pp. 1637–1645, June 2009.

[16] J. Restrepo, J. Viola, J. M. Aller, and A. Bueno, "A simple switch selection state for svm direct power control," in *Proceedings of the 2006 IEEE International Symposium on Industrial Electronics, ISIE 2006*, pp. 1112–1116, July 2006.

[17] S. Larrinaga, M. Rodríguez, E. Oyarbide, and J. Torrealday, "Predictive control strategy for DC/AC converters based on direct power control," *IEEE Trans. Ind. Electron.*, vol. 54, pp. 1261–1271, June 2007.

[18] P. Antoniewicz, M. P. Kazmierkowski, S. Aurtenechea, and M. A. Rodriguez, "Comparative study of two predictive direct power control algorithms for three-phase AC/DC converters," in *Proceedings of the 2007 European Conference on Power Electronics and Applications, EPE 2007*, pp. P1–P10, Sept. 2007.

[19] M. Malinowski, "Adaptive modulator for three-phase pwm rectifier/inverter," in *Proceedings of the 9th International conference on power electronics and motion control EPE-PEMC 2000*, vol. 1, (Kosice, Slovak Republic), pp. 35–41, Sept. 2000.

[20] S. R. Huang and B. N. Chen, "Harmonic study of the le blanc transformer for taiwan railway's electrif ication system - power delivery, ieee transactions on," *IEEE TRANSACTIONS ON POWER DELIVERY*, vol. 17, no. 2, pp. 495–499, 2002.

[21] IEEE, *IEEE 519-1992 Recommended practices and requirements for harmonic control in electrical power systems*. pub-IEEE-STD:adr: IEEE Standards Coordinating Committee, 1992.

[22] IEC, *IEC 61000-4-15 Testing and measurement techniques – Flickermeter Functional and Desing Specifications*. International Electrotechnical Commission Standard, 1997.