



Fusion Data Management and Modeling Techniques in Power Quality Compensation Using SAPF

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Abstract

The development of transportation today encompasses a broad range of technological applications that occasionally present new challenges arising from difficulties that require solutions. The article analyzes the difficulties in electric trains concerning the compensation of electric power quality in a traction system using a parallel active power filter (SAPF). From the literature review of several studies, the test distribution system in a distribution network for an electric train system is analyzed, with a variable load and harmonic content. The estimation and control technique used in the SAPF to compensate for the harmonic content and reduce the reactive power at the output of a traction substation is described. A data fusion management strategy is employed in the analyses, demonstrating the system's effectiveness.

Keywords: active filter; harmonic; fusion; data management; power.

1. Introduction

The train or railway is one of the safest modes of transportation in the world, evidenced by subways, commuter trains, light rail, and trams. The train continues to evolve to remain relevant as one of the best transportation alternatives in many countries and to adjust to the demands and requirements of modern times, an example of this is electric trains, with the advances and challenges they face in their operation and compensation in the quality of electric load.

Currently, with modernity and the increase in technology, there has been an increase in the use of domestic non-linear loads and industrial non-linear loads such as speed drives, rectifiers, converters, etc., that use power electronics. Non-linear loads are generated from sinusoidal waves at the nominal frequency, and other waves with different frequencies create the phenomenon known as harmonics. Harmonics are sinusoidal voltages or currents, with frequencies that are multiples of the nominal frequency of the system (fundamental frequency). Harmonics produce deterioration and degradation of the equipment that makes up a power electrical system such as generators, motors, transformers, cables, etc. Among the main negative effects of the presence of harmonics in the electrical network are the overheating in conductors, particularly in the neutral of installations due to the Skin effect, the reduction of the power factor of the installation, and deterioration of the capacitor banks used for their correction, in addition to the heating and degradation of the insulation of the electrical system components.

DC-powered electric trains play an important role in metropolitan public transport due to their high efficiency, transport capacity, and speed. These are fed by traction substations, which have rectifiers for AC/DC conversion, causing major problems in the quality of the power of the distribution electrical system that feeds them [1]. These problems produce changes in the current and voltage waveform characteristics, the result is the appearance of high harmonic content in the AC supply, changes in reactive power, high fluctuations in voltage levels, flicker, and

equipment heating [2], which can exceed the limits according to the IEEE 519-2014 and IEEE 1453-2015 guidelines [3][4].

Electric power quality is an essential element in the functioning of every electrical system. Electrical energy is a crucial resource for the functioning of contemporary equipment and systems, and its quality can have a substantial impact on their efficiency, dependability, and safety. Electric power quality pertains to the capacity of electrical energy to deliver consistent and undisturbed voltage and current. Consequently, the electrical energy must adhere to specific quality criteria, including frequency, voltage, waveform, and the lack of harmonics and transient disturbances (Figure 1).

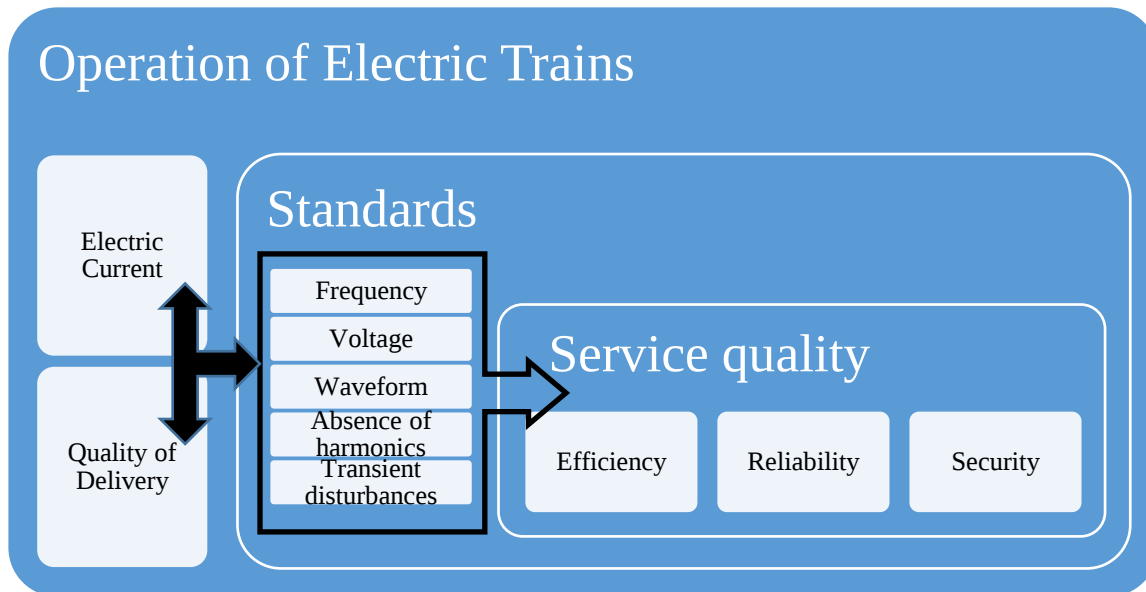


Figure 1: Influence on the quality of operation. Source: own elaboration.

Currently, there are modern ways to compensate for power quality, based on the use of devices that employ power electronics [5], such as active power filters, the D-STATCOM (Distribution-Static synchronous compensator), the DVR (Dynamic Voltage Restorer), UPQC (Unified Power Quality Conditioner), or hybrid power filters resulting from a combination of passive and active filters.

The active power filter emerges as a method with superior compensation performance in both low and high-power systems [6][7]. Reference [8] emphasizes the active filter, which was designed to eliminate harmonics but also has the capability to perform other functions such as reactive power compensation, voltage imbalance compensation, and flicker mitigation. Thus, active filters are shown as an attractive option to improve supply quality and provide a higher degree of reliability [9].

The proper functioning of the service and its system depends on the stability of the power system, seen as the ability of electric power in the system, under a given initial operating condition, to recover an operational equilibrium state after having been subjected to a physical disturbance, with most of the system's variables limited so that practically the entire system remains intact [10].

AC/DC/AC traction converters are widely adopted in the CRH series of EMUs, and the HX D series of AC electric locomotives benefits from their excellent control performance and high-power factor (PF). However, in recent years, a series of harmonic resonance accidents have been caused by high-frequency harmonics, which interfere with the safety and efficient operation of the TPSS [11,12]. Note that the PFC used in the TPSS has poor performance in harmonic compensation [13]. The passive power filter (PPF) and the active power compensation device are frequently used to solve this problem. However, the PPF is more available in terms of cost and reliability. In this regard, the Type C filter has gained attention in the railway field in recent years, as it not only filters the region of high-order harmonics but also compensates for reactive power to improve system performance [14]. Unfortunately, overcompensation caused by the fixed Var capacity of the Type C filters leads to PF deterioration. Therefore, the main challenge is how to compensate for harmonics and PF extensively. Fortunately, power semiconductor switches, such as the thyristor, the metal-oxide-semiconductor field-effect transistor (MOSFET), and the insulated-gate bipolar

transistor (IGBT), have been adopted to control inductance to achieve reactive power compensation since the 1960s; most of the time, the thyristor will be involved when handling high voltage and a simple AC circuit [15]. Therefore, a thyristor-controlled LC coupling structure (TCLC) has been introduced to control the distortion and PF of the three-phase load on the electrical grid [16]. Additionally, a different structure that combines TCLC in series/parallel with active power filters (APF), such as TCLC + APF in [17], and the static var compensator (SVC)/APF in [18], has been proposed. In other words, a new hybrid compensation structure combined with PPF and TCL can be designed to address the above-mentioned problem in railways. However, further research is still needed in the railway field.

Data fusion management is a method that can be employed to assess the challenges that arise in compensating for electrical energy quality. Data fusion is a procedure that entails amalgamating data from several sources in order to generate a more coherent, precise, and valuable collection. This technique is especially applicable in domains characterized by the presence of data originating from several sources and formats. Its implementation allows for the integration of these disparate data sets, resulting in a more comprehensive perspective or the resolution of uncertainties that cannot be adequately handled with a single source of information. Data fusion enhances accuracy by integrating multiple data sources, thereby minimizing errors and improving the precision of the information. It also amplifies complexity and depth by enabling more intricate and comprehensive analysis through the inclusion of diverse data from various perspectives. Additionally, data fusion facilitates decision-making by providing a more robust foundation for this purpose.

The implementation of data fusion strategies in the analyses of compensation in the electrical quality of systems in electric trains proves to be very useful. These strategies consider Data Source Identification, Data Integration, Data Analysis, Decision Automation, Evaluation, and Optimization.

The challenges presented in the quality of electric power in the traction systems for modern trains that make up the current developing transport system, necessitate analyzing the challenges associated with harmonic distortion, voltage fluctuations, and reactive power in these systems. In this sense, the work proposes as its objective to assess the integration of data techniques and models in parallel active filters (SAPF) to improve energy quality, consequently establishing specific objectives:

- Analyze the importance of quality in the delivery of energy in modern electrical systems in critical environments such as traction systems.
- Assess the effectiveness of integrating data and models in parallel active filters to improve energy quality.

2. Materials and Methods.

Historical-logical: This facilitates analyzing the background of railway transportation and the emergence of the use of electricity in traction systems as part of their evolutionary development.

Analysis-synthesis: This allows the evaluation of the main aspects related to electrical systems and the challenges associated with harmonic distortion, voltage fluctuations, and reactive power in these systems.

Literature review: This involves studying the various research efforts that have been conducted on traction systems and the use of parallel active filters aimed at achieving better compensation in electrical quality, as well as exploring conventional and advanced methods for energy quality compensation.

Modeling: The use of electrical system models, including traction substations and electric trains, with the use of parallel active filters, allows for a better assessment of the different proposals and the results of their application in the critical environments of traction systems, to increase service quality and reduce costs.

3. Results and Discussion

For the application of the data fusion strategy in analyzing the system under study for current quality compensation, aspects that must govern the application of each step in the strategy were considered, as analyzed below:

1. Identification of Data Sources:

- **Sensor Data:** Includes real-time voltage and current measurements from critical points in the electrical network.
- **Operational Data:** Information about the schedule and load of electric trains that can affect energy demand.

- Historical Data: Previous records of energy quality, including incidents of harmonics, voltage fluctuations, and other relevant events.
- Meteorological Data: Weather conditions that may influence the operation of the network, such as extreme temperatures affecting the electrical load.

2. Data Integration:

- Data Platform: Utilizes a data integration platform such as Hadoop or a cloud solution to store and process large volumes of data from different sources. Ensures that the platform can handle real-time data streaming along with historical data storage.
- Data Synchronization: Temporally aligns all collected data to ensure that measurements are synchronized in terms of timestamps. This is crucial for accurate analysis and decision-making.

3. Data Analysis:

- Data Processing: Cleans and preprocesses the data to eliminate errors and outliers. This may include data normalization, handling missing values, and noise reduction.
- Predictive Analysis: Uses machine learning techniques to develop predictive models that can anticipate energy quality issues based on historical patterns and current conditions.
- Data Visualization: Implements visualization tools to monitor energy quality and the performance of the SAPF in real-time, facilitating rapid problem detection and assessment of the filter's effectiveness.

4. Decision Automation:

- Automatic Control Systems: Develop control algorithms that automatically adjust the parameters of the SAPF in response to the predictions and alerts generated by the data analysis models.
- Feedback Loop: Establishes a feedback loop where the results of the SAPF are used to continuously improve predictive models and control algorithms, adapting them to changing network conditions.

5. Evaluation and Optimization:

- Testing and Simulations: Conduct regular tests and simulations to evaluate the accuracy of predictive models and the effectiveness of the SAPF under different operational scenarios.
- Continuous Optimization: Uses the results of the tests and operational feedback to fine-tune models and adjust control parameters, always seeking to improve the efficiency and responsiveness of the system.

Implementation:

- For the strategy's implementation, it is important to have collaboration between data experts, electrical engineers, and system operators. It is also essential to have the support of advanced technological tools and possibly invest in IT infrastructure improvements to handle large-scale data integration and analysis.

In this case study, the electrical distribution network that powers the DC traction system is analyzed. It is fed by a 110 kV meshed system, feeding substations with 40/31 MVA transformers with a 110 kV/13.8 kV ratio, aimed at reducing the voltage level and powering two 13.8 kV cable systems which energize the traction substations with their load [19].

Each traction substation converts to a 1500 VDC voltage level and consists of a 3.5 MVA tri-winding transformer with voltage ratios of 13.8 kV/1.22 kV/1.22 kV in a $\Delta/Y/\Delta$ connection. Each transformer winding is connected to a six-pulse rectifier that converts the 1.22 VAC into 1500 VDC, with a phase shift of 30 degrees, to form a 12-pulse converter and reduce the number of 5th and 7th-order harmonics towards the network.

The network segment to be analyzed is shown in Figure 2, where the compensator based on the parallel active filter will address power quality issues in AC, so it is placed at the PCC2 bus at the 13.8 kV voltage level corresponding to the traction transformer input; the upstream network is summarized by an impedance with a short-circuit power of 20.5 MVA. In the system diagram, the measurement points where current, voltage, and power signals are obtained are identified for each of the analyzed elements.

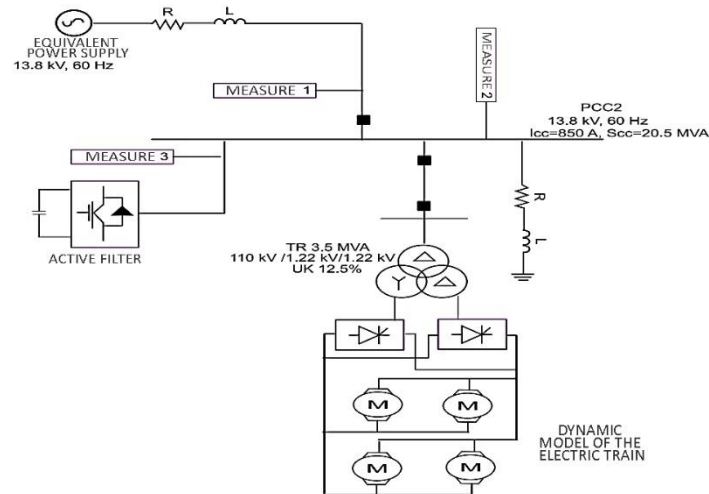


Figure 2: Schematic of the distribution network segment that feeds the DC traction system.

The traction system of the Medellin metro operates at 1500 VDC. The loads connected on the DC side correspond to the electric trains. In [20], a dynamic traction model of an electric train from the Medellin metro is presented, which will be used to identify power quality issues that occur. The traction system employs thyristor control, DC/DC converters, a chopper that operates at a variable frequency and controls the DC voltage, a filter to attenuate current ripple, and other auxiliary components. The traction substation uses 12-pulse rectifiers. A representation of the components required for the operation of the electric train is shown in Figure 3.

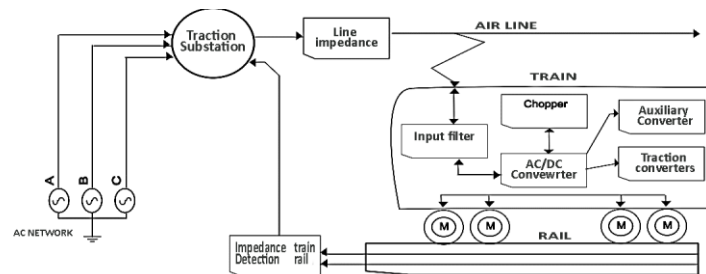


Figure 3: Schematic of the traction substation and components of the electric train charging system.

It is necessary to understand the dynamic behavior of the electric train traction system over a given period. Figure 4 shows the torque and speed profile of the train established between two stations, consisting of acceleration, constant speed, and braking. When the train is in braking mode, the regenerative energy is converted back into the DC line, which can provide a portion of the power required for other trains operating along the track.

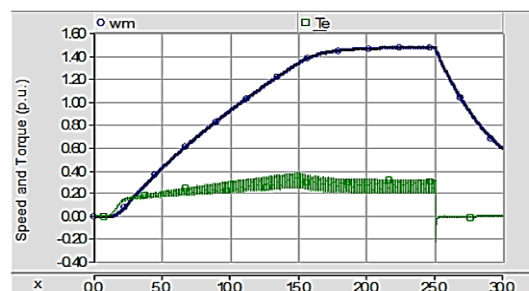


Figure 4: Speed and torque characteristics of the dynamic model of the electric train over time [11].

The system demonstrates that the dynamics of the components on the DC side, as well as the rectifiers, cause power quality issues on the AC side in terms of harmonic content in the output currents, a low initial power factor, and voltage

4. Active Parallel Filter (SAPF) Design

A. Estimation and generation of the reference signal

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \\ I_{L0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (1)$$

Both I_{Ld} and I_{Lq} are further decomposed into two components: a DC component and an oscillating/AC component, which are given by equations (2) and (3). These currents pass through high-pass filters (HPF) with a certain cutoff frequency to decompose into their fundamental components (I_{Ld}^{DC} , I_{Lq}^{DC}) and their oscillating or harmonic components (I_{Ld}^{AC} , I_{Lq}^{AC}).

The control strategy to be used is to compensate for the harmonic content and achieve a unit power factor at the common coupling point. The contribution of the SAPF will be the following compensatory reference currents:

$$I_{Cd_ref} = -I_{Ld}^{AC} + I_{loss} \quad (2)$$

$$I_{Cq_ref} = -I_{Lq}^{AC} - I_{Lq}^{DC} \quad (3)$$

The source, on the other hand, will have to deliver the I_{Ld}^{DC} component to the load for power balance, along with the I_{loss} component to the SAPF itself. The I_{loss} component is an active current component that flows from the grid to the SAPF and represents a small amount of real power required to maintain the DC link capacitor voltage constant and to compensate for losses in the converter; it is obtained from the output of the PI controller of the external DC voltage regulation loop.

Finally, the reference currents (I_{Ca_Ref} , I_{Cb_Ref} , I_{Cc_Ref}), are obtained through the inverse Park transformation in equation (4).

$$\begin{bmatrix} I_{Ca_Ref} \\ I_{Cb_Ref} \\ I_{Cc_Ref} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} I_{Cd_ref} \\ I_{Cq_ref} \\ 0 \end{bmatrix} \quad (4)$$

The complete scheme for the extraction of reference compensating current and the subsequent generation of firing pulses is shown in Figure 6.

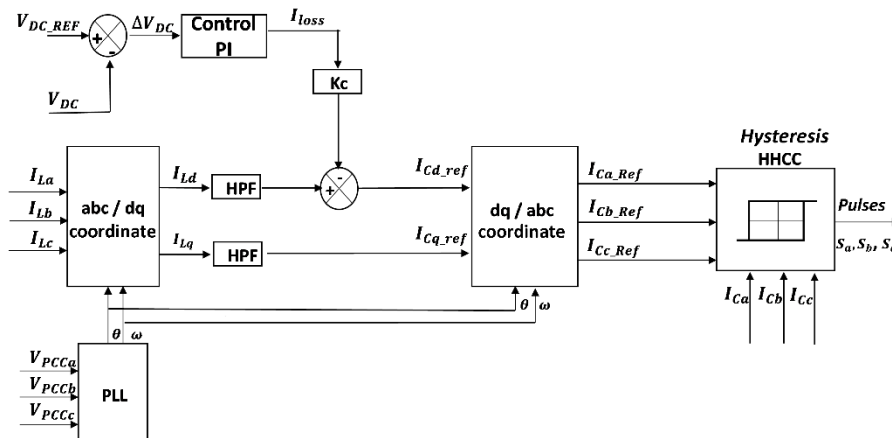


Figure6. Reference signal generation scheme. Source: own elaboration.

B. Trigger signal generation

The compensating currents at the converter output (I_{Ca} , I_{Cb} , I_{Cc}) and the reference currents (I_{Ca_ref} , I_{Cb_ref} , I_{Cc_ref}) are continuously compared one by one. The obtained error passes through the hysteresis controller, which generates the activation signals for the switching devices (S_a , S_b , S_c). The operation of the hysteresis-based control is shown in Figure 7. The hysteresis method requires tolerance limits, called upper and lower error bands, which are defined as follows.

$$\text{Límite Superior} = I_{Cx_Ref} + H \quad (5)$$

$$\text{Límite Inferior} = I_{Cx_Ref} - H \quad (6)$$

Where H is the tolerance value and x represents (a, b, c) for each phase. In the hysteresis method, the switching frequency is not fixed [26][27] and varies according to the error band and system parameters such as the coupling inductance and the instantaneous voltage difference between the grid connection point and the VSI terminals. As a solution to this problem, the output compensating currents I_{Cx} are sampled at a fixed frequency to limit the maximum switching frequency of the inverter. The performance of the SAPF highly depends on the pulse generation technique for the gate of the static converters.

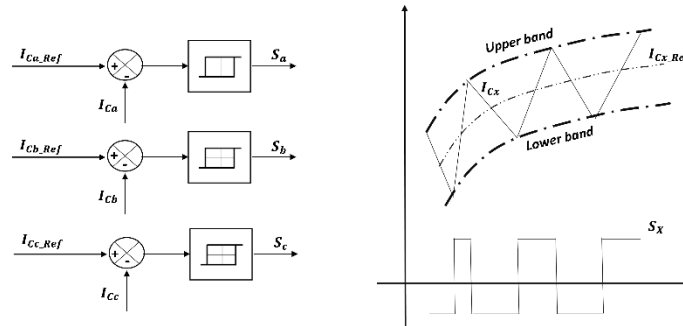


Figure 7: PWM hysteresis for 2-level, 3-branch converter. Source: own elaboration.

C. DC voltage regulator

The VSI type converter uses a capacitor as an energy storage source. The voltage across the capacitor fluctuates as energy is delivered or absorbed by the capacitor. The SAPF voltage control is responsible for maintaining the DC voltage of the capacitor constant. To maintain a certain level of VDC voltage, the error difference between the capacitor voltage and its reference value enters a PI control to generate a signal representing a fundamental active current (I_{d1}) and compensate for SAPF losses.

The output of the PI controller can be expressed as:

$$\frac{I_{loss}}{\Delta V_{DC}} = K_p + \frac{K_i}{s} \quad (7)$$

Where $\Delta V_{DC} = V_{DC_ref} - V_{DC}$. In equation (7), the control constants need to be adjusted. In [3], a controller tuning method is used in which the PI controller gains are obtained by: $K_p = 2\xi\omega_n CDC$ and $K_i = \omega_n/2\xi$, where ξ is the typical damping of 0.707 and ω_n is the angular frequency of the system.

Figure 8 shows the complete closed-loop control system of the SAPF.

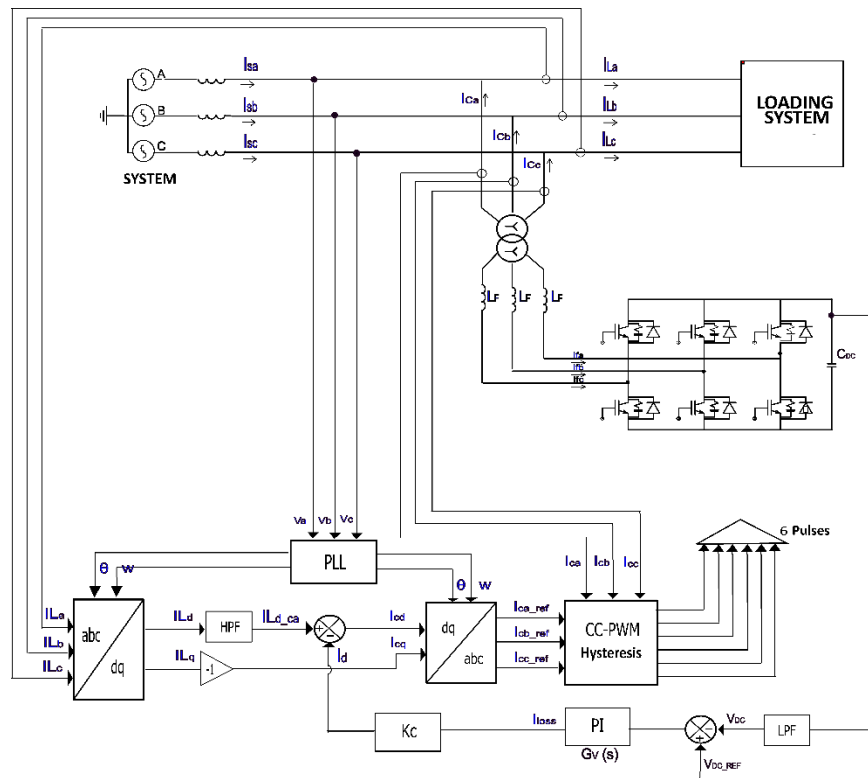


Figure 8: Diagram of the general control system of the active filter. Source: own elaboration.

5. System Parameters and Simulation Results

The simulated model in PSCAD of the proposed system is shown in Figure 9, and the parameters are given in Table 1. The values of the SAPF components and the constants of the closed-loop control system are detailed in Table 2.

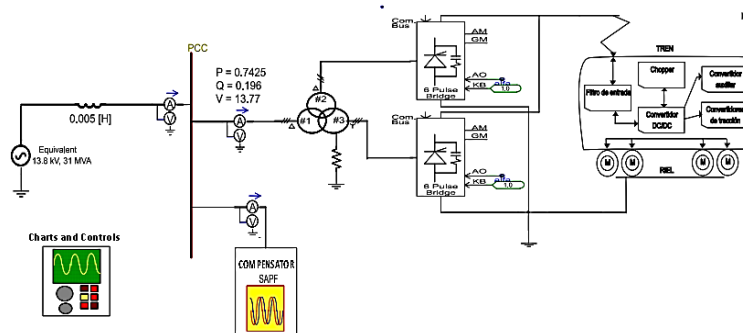


Figure 9: Compensation system based on the SAPF to the tram distribution network.

Table 1: Parameters of the distribution network

Items	Parameters
power network	110kV
	$S_{sc} = 20.5 \text{ MVA}$
Traction system	1(T2), 13.8kV/1.23kV/1.23kV.3.5MVA
Auxiliary services	$R = 0.37 \text{ ohm}$
	$L = 0.1 \text{ H}$

Table 2: Active Parallel filter (SAPF) parameters

Items	Parameters
Investor	VDC =2.9kV
	CDC=1000uF
	Fc=10KHz
Output filter	LF=0.008
Coupling transformer	SCT =1.1MVA
	V1 /V2=13.8kV/1kV
	X (%) =12%
PI Gains	KP=0.9
	KI=0.01

The dynamic system of the electric train starts with acceleration, followed by stable operation, and then braking within a time frame of (0 – 30s). The system is analyzed without the compensator and with the SAPF compensator. Since the load condition is variable, significant harmonic distortion is considered when the train has started or is at its maximum demand. The voltage and current waveforms, as well as their frequency spectrum at the 13.8 kV PCC2 bus feeding the traction substation without any compensation, are shown in Figures 10 and 11; while Figure 12 shows the voltage and current waveforms with SAPF compensation. The severity of the harmonic currents drawn by the railway system depends on the amount of current.

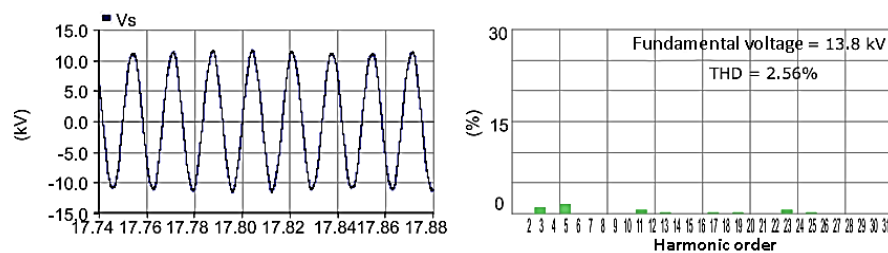


Figure 10: Waveforms per phase of the voltage and its frequency spectrum of the AC system that feeds the DC traction system without compensation

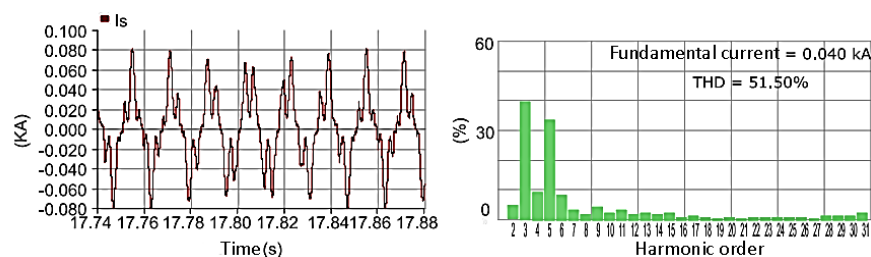


Figure 11: Waveforms per phase of the supply current and its frequency spectrum of the AC system feeding the DC traction system without compensation.

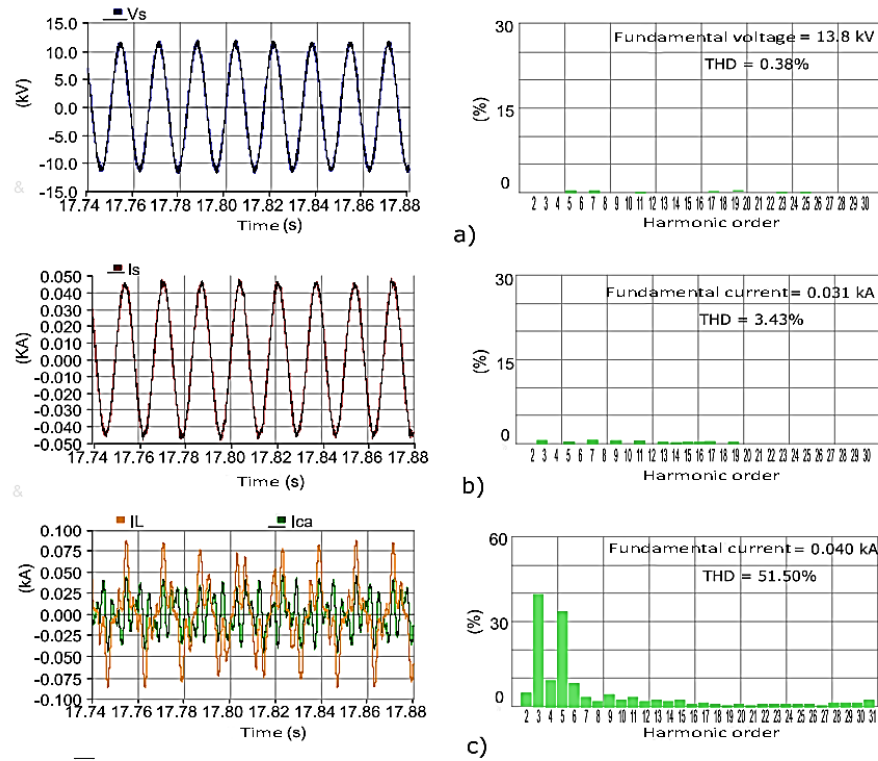


Figure 12: Waveforms per phase and their frequency spectrum of the AC system feeding the DC traction system with SAPF compensation a) Voltage at the PCC; b) Supply current; c) Load and compensation current.

The comparisons between the levels of active power consumption, reactive power, power factor, and voltage variation in the system with and without the SAPF compensator are shown in Figures 13 and 14. The analysis conducted with the different data obtained demonstrates that the SAPF contributes to the improvement in voltage variation reduction as shown in Figure 15. This indicates that the SAPF is capable of performing compensation in dynamic situations, validating the application of the data fusion strategy employed in the study and the implementation of the SAPF in this case. This contributes significantly to solving the difficulties faced by modern trains with electric current quality compensation.

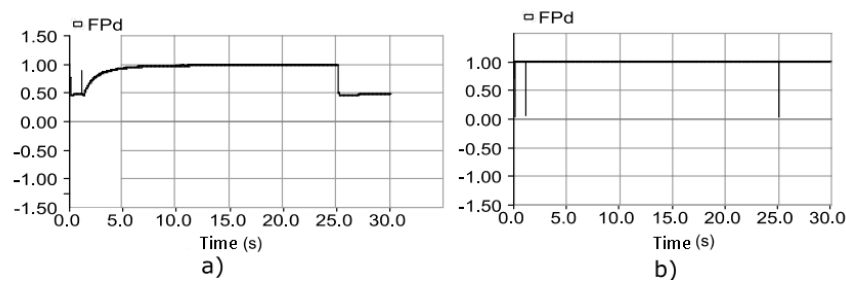


Figure 13: Power factor chart in PCC2. a) Without compensation; b) With compensation

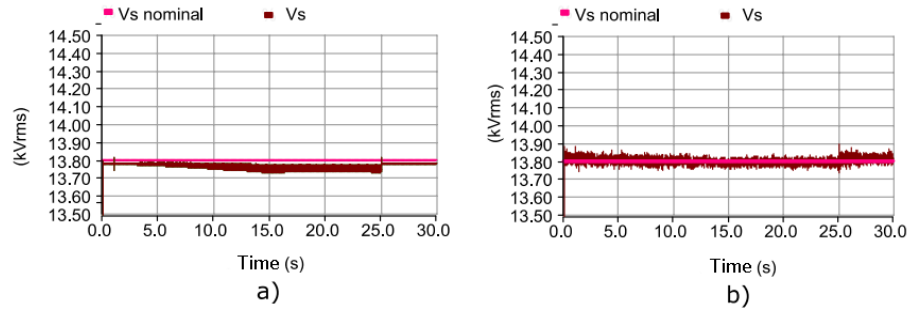


Figure 14: Chart of the voltage variation in PCC2. a) Without compensation; b) With compensation.

The success of SAPF-based compensation lies in the compensatory output signals faithfully following their references. Figure 15a shows the output signal I_c following its reference I^*C , which depends on the relationship between the DC voltage level, the converter's output inductance, the switching frequency, and the delays in signal acquisition. The switching of the thyristors generates a ripple in both the current and the converter's output voltage $VVSC$, as shown in Figure 15b.

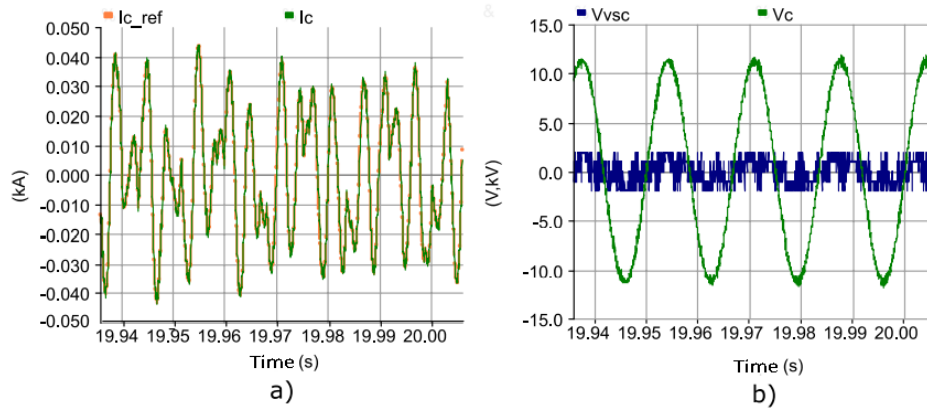


Figure 15: Chart of the voltage variation in PCC2. a) Without compensation; b) With compensation

Comparing the THD results before and after using the SAPF compensator through simulations for the system demonstrates the compensator's efficiency in reducing harmonics, decreasing the current requirement from the source, and improving the voltage level, as shown in Table 3.

Table 3: THD and RMS values of AC supply voltage and current, for the proposed traction system

Parameters	VRMS(kV)	IS_RMS(A)	THD1(%)	THD1(%)
Without Compensation	13.75	40	2.47	51.50
With SAPF Compensation	13.78	31	0.38	3.43

Through the data fusion strategy employed in the analysis, good tracking of the proposed control for the APF was achieved, as it managed the compensation of reactive power, load balancing, and the elimination of neutral current in the system for both cases. In scenarios of higher load requirements, the system will adapt to these needs as long as the APF can obtain sufficient current from the available voltage levels. This voltage level depends on the power that the DC link can supply, which in turn depends on the voltage level that can be obtained through the converter.

Highlighting the computational cost, the time values have a ratio between the execution time of the converter, implying a lower computational cost. The system is sensitive to the passive filter that is in series with the APF, which affects its functionality since it directly impacts the mathematical modeling equation, where these parameters are present.

The structure allows for easier maintenance, and the redundancy provided by the voltage levels increases the system's reliability and flexibility in response to higher demands. This results in better performance and the introduction of new

harmonic elimination methods, though it does not completely solve the problem, indicating a need for further research. Science and technology are advancing rapidly, and with that, the technologies applied to compensate for electric quality require new solutions.

Data fusion management in this context helps make the compensation system more adaptive and efficient, reducing response times to power quality issues and improving the reliability and efficiency of power supply. Additionally, it allows for more precise management of energy consumption and quality, which can result in longer equipment life and lower operating costs. This data fusion management strategy not only enhances power quality management through the SAPF but also facilitates a more efficient and adaptable operation of the electrical grid, leading to better responsiveness to dynamic needs and more proactive maintenance of critical systems.

6. Conclusions

The rapid development in transportation through electric trains makes the control strategy of the active filter play the most important role when defining the compensation capabilities for harmonic distortion, reactive power, voltage regulation, or all together. Therefore, the control is what differentiates passive filters from other modern line conditioners with similar topologies such as D-STATCOM, DVR, SVC, and others. In practice, the demand for reactive power in a traction system is very variable. The SAPF compensator, in addition to almost entirely reducing harmonic distortion, can perform dynamic and variable compensation of reactive power. Simulation results prove the efficiency of the parallel active filter structure in reducing current harmonics, compensating reactive power, and improving the power factor. The techniques applied in electrical systems for transportation operations necessitate new research aimed at eliminating the effects of harmonics, reactive power, and fluctuations, which achieve reduced transmission losses, increased reliability, and the possibility of connecting various additional loads at the common coupling point to the AC grid.

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References

- [1] S. H. Hosseini, F. Shahnia, M. Sarhangzadeh, and E. Babaei, “Power quality improvement of DC electrified railway distribution systems using hybrid filters,” *ICEMS 2005 Proc. Eighth Int. Conf. Electr. Mach. Syst.*, vol. 2, pp. 1273–1277, 2005, doi: 10.1109/ICEMS.2005.202752.
- [2] R. E. Morrison, “Parameters that influence power quality on industrial frequency AC traction systems,” in *2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262)*, 2001, vol. 1, pp. 204–209 vol.1, doi: 10.1109/PESS.2001.970013.
- [3] “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems,” *IEEE Std 519-2014 (Revision of IEEE Std 519-1992)*, pp. 1–29, 2014, doi: 10.1109/IEEESTD.2014.6826459.
- [4] “IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems,” *IEEE Std 1453-2015 (Revision of IEEE Std 1453-2011)*, pp. 1–74, 2015, doi: 10.1109/IEEESTD.2015.7317469.
- [5] *Power Electronic Control in Electrical Systems*. 2002.
- [6] IEEE, “IEEE Publication Services and Products Board Operations Manual 2023,” no. February 2002, 2023.
- [7] H. Akagi, “Active Harmonic Filters,” *Proc. IEEE*, vol. 93, no. 12, pp. 2128–2141, 2005, doi: 10.1109/JPROC.2005.859603.
- [8] M. Torabian Esfahani, S. H. Hosseinian, and B. Vahidi, “A new optimal approach for improvement of active power filter using FPSO for enhancing power quality,” *Int. J. Electr. Power Energy Syst.*, vol. 69, pp. 188–199, 2015, doi: 10.1016/j.ijepes.2014.12.078.
- [9] W. U. Tareen, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, “Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system,” *Renew. Sustain. Energy Rev.*, vol. 70, pp. 635–655, 2017, doi: <https://doi.org/10.1016/j.rser.2016.11.091>.
- [10] Hatziaargyriou, N., Milanovic, J., Rahmann, C., Ajjarapu, V., Canizares, C., Erlich, I., ... & Vournas, C. (2020). Definition and classification of power system stability–revisited & extended. *IEEE Transactions on Power Systems*, 36(4), 3271-3281.

- [11] Chen, M.; Roberts, C.; Weston, P.; Hillmansen, S.; Zhao, N.; Han, X. Harmonic modeling and prediction of high-speed electric trains based on non-parametric confidence interval estimation method. *En t. J. Electr. Electrical power system.* **2017** , 87 , 176–186.
- [12] Zhang, R.; Lin, F.; Yang, Z.; Cao, H.; Liu, Y. A Harmonic Resonance Suppression Strategy for a High-Speed Railway Traction Power Supply System with a SHE-PWM Four-Quadrant Converter Based on Active Set Secondary Optimization. *Energies* **2017** , 10 , 1567.
- [13] Kalair, A.; Abas, N.; Kalair, AR; Saleem, Z.; Khan, N. Review of harmonic analysis, modeling and mitigation techniques. *Renew. Hold. Energy Rev.* **2017**, 78, 1152–1187.
- [14] Lamlom, A.; Ibrahim, A.; Balci, ME; Karadeniz, A.; Aleem, SHA Optimal design and analysis of type C anti-resonance high-pass filters. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering y IEEE Industrial and Commercial Power Systems Europe 2017 (EEEIC/I&CPS Europe), Milán, Italia, 6 a 9 de junio de 2017; págs. 1–6.
- [15] Iwamuro, N.; Laska, T. History, state of the art and future perspectives of IGBTs. *IEEE Translation. Electron. Devices.* **2017** , 64 , 741–752.
- [16] Wang, L.; Lam, C.; Wong, M. Design of a thyristor-controlled LC compensator for dynamic reactive power compensation in smart grids. *Traducción IEEE. Red inteligente* **2017** , 8 , 409–417.
- [17] Wang, L.; Lam, C.; Wong, M. Selective distortion, reactive and unbalanced power compensation of a thyristor-controlled LC-coupled hybrid active power filter (TCLC-HAPF). *Traducción IEEE. power electron.* **2017** , 32 , 9065–9077.
- [18] Wang, L.; Lam, C.; Wong, M. Hybrid structure of static Var compensator and hybrid active power filter (SVC//HAPF) for medium voltage heavy load compensation. *Traducción IEEE. Indiana electrón.* **2018** , 65 , 4432–4442.
- [19] J. Lara L., J. González S., L. Castrillón A., I. Isaac M., H. Cardona R., and G. López J., “Modelo digital de tracción del Metro de Medellín para análisis de cortocircuitos,” *Sci. Tech.*, vol. 18, no. 1, pp. 285–292, Sep. 2013, [Online]. Available: <https://www.redalyc.org/articulo.oa?id=84927487042>.
- [20] A. E. Diaz, M. F. Carrillo, J. A. Velásquez, A. Armstorfer, and E. M. Álvarez Cano, “Simulación del sistema de tracción del metro de Medellín,” no. December 2011, 2015.
- [21] M. Popescu, A. Bitoleanu, and M. Dobricianu, “Harmonic current reduction in railway systems,” *WSEAS Trans. Syst.*, vol. 7, no. 7, pp. 689–698, 2008.
- [22] J. N. Castillo, V. F. Resabala, L. O. Freire, and B. P. Corrales, “Modeling and sensitivity analysis of the building energy consumption using the Monte Carlo method,” *Energy Reports*, vol. 8, 2022, doi: 10.1016/j.egyr.2022.10.198.
- [23] J. N. Castillo, G. G. Carrillo, L. O. Freire, and B. P. Corrales, “Energy modeling and simulation of a building to perform sensitivity analysis of energy consumption,” *Energy Reports*, vol. 8, 2022, doi: 10.1016/j.egyr.2022.10.197.
- [24] S. Bhattacharya, T. M. Frank, D. M. Divan, and B. Banerjee, “Active filter system implementation,” *IEEE Ind. Appl. Mag.*, vol. 4, no. 5, pp. 47–63, 1998, doi: 10.1109/2943.715508.
- [25] S. H. Qazi and M. W. Mustafa, “Review on active filters and its performance with grid connected fixed and variable speed wind turbine generator,” *Renew. Sustain. Energy Rev.*, vol. 57, pp. 420–438, 2016, doi: <https://doi.org/10.1016/j.rser.2015.12.049>.
- [26] V. D. Yurkevich, “PWM Controller Design based on Singular Perturbation Technique: A Case Study of Buck-Boost DC-DC Converter,” *IFAC Proc. Vol.*, vol. 44, no. 1, pp. 9739–9744, 2011, doi: <https://doi.org/10.3182/20110828-6-IT-1002.00963>.
- [27] G. A. Ramos Fuentes, J. A. Cifuentes Quintero, and I. D. Melo Lagos, “High performance control of a three-phase PWM rectifier using odd harmonic high order repetitive control,” *Dyna*, vol. 83, no. 198, pp. 27–36, 2016, doi: 10.15446/dyna.v83n198.53276.