Study of Harmonics generated in Rectifier Substation of Railway System

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Abstract: - The rectifiers that feed electric trains can cause undesirable effects on substation feeding systems, as to increase electrical losses, equipment malfunction and harmonic overvoltage. This research analysis a real case at railway substation and uses a tool in the ATP software (Alternative Transients Program), with the presentation of the results obtained by simulations and the analysis of these results with proposals for solutions, supporting electric engineering maintenance work teams.

Key-Words: - maintenance, software for engineering applications, software simulation, harmonics, railway systems

1 Introduction

The electric railway systems are composed with complex equipments combinations and subsystems, since the main supplier, transformers, power transmission between the substations and power distribution for the compositions or the trains themselves. The electrified railways have primary substations, which receive power directly from the local electric power utility and secondary substations, which receive the energy from the primary substations.

This system specificity is that as a train moves physically from two substations, load provided by these substations for the composition is proportional to the proximity of this train the same. As the train moves away from a substation, the load will be progressively decreasing, increasing at the same rate in the nearest substation where the train will go.

The major part of railways uses trains with DC motors, since this is best suited for electric traction, due to feature high torque at low speeds and to support constant changes of engine speed with relatively simple methods. To feed DC motors is required to use rectifiers (AC-DC converters).

The paper will present a study case covering the modeling of power supply trains circuit since the delivery connect point by the concessionaire until the train DC motor circuit. The Modeling is developed through the ATP program (Alternative Transients Program) [1], [2] where are made simulations for rectifier harmonic behavior. In addition to compromising the equipment useful life, high harmonics levels can compromise the system operation through the low performance of protective devices [3].

The use of software tools to support harmonic knowledge is applied for several years. In special, there is a paper [4] that describes a tutorial to evaluate harmonic in microwaves circuits using SPICE as software. In this case, there is an example of ATP software used in studies for power supply to railway systems is the harmonic analysis and demand impact presented in [5]. Researches concerning the impact of converters use in railway power systems and the importance of this analysis and comparison between theoretical and measurements results is presented in [6].

Studies with other simulation software present contributions to drives harmonic analysis in railway systems. MATLAB software evaluations are presented in [7] for double stage drives and support tool to choose better filters configuration in [8]. There are others software's to support electric system analysis and projects. An example is the software PSCAD/EMTDC in [9] where a distribution power system is project. The application of this software for harmonic analysis railway systems can be found in [10]. Measurement techniques and comparison of the results are presented in [11], [12].

In Federal Fluminense University (UFF) there are several simulation activities to support researches and theoretical disciplines as: energy conservation avoiding losses [13], thermodynamic models applied to electric transformers [14] and induction motor parameters estimation [15].

2 Types of Rail Systems Loads

2.1 Linear Load

A linear load can be defined as one in which there is a linear relationship (linear differential equation with constant factors) between current and voltage. In resume, a linear load absorbs sinusoidal current when it is supplied by a sinusoidal voltage, taking into account the homogeneity and additivity.principles. Linear loads consist of passive elements, which are the inductive, capacitive and resistive loads.

As an example, the circuit shown in Fig. 1 presents the modeling of a 220 Volts voltage source supplying a 10 ohms resistive load. Arrows 1 and 2 indicate, respectively, the current and voltage measuring points. The waveforms corresponding to phase-earth voltage and current measurements in the resistive load are represented in the graph of Fig. 2 indicated by green curve (current) and red curve (voltage).

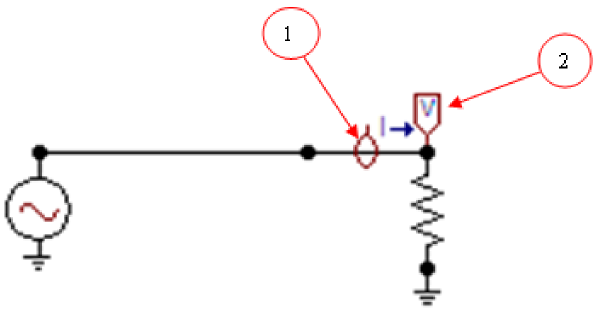

Fig. 1 – ATP Model for a 220 V voltage source feeding a 10 ohms resistive load

2.2 Non Linear Load

In the situation where the relationship between current and voltage in a component is not described by a linear equation, this component is called non-linear load. It absorbs a non sinusoidal current and therefore harmonic currents, even when it is supplied by a sinusoidal voltage. These loads have linear and non-linear components such as diodes, transistors and thyristors. Thus, this load can operate in conduction condition, corresponding to a closed switch, where the current through the component can get high values, but with practically zero voltage and minimum power dissipation or result in blocking state, corresponding to an open switch, where the current through the device is virtually zero, but the voltage is high and, therefore, the power dissipation is also low.

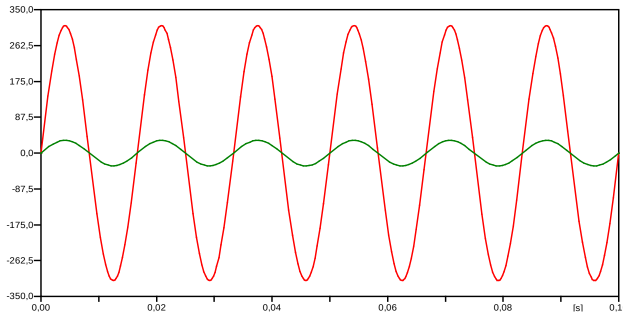

Fig. 2 – Waveform of voltage and current in a resistive load

Due to conduction semiconductor points to be controlled, these devices controlling the voltage and current circuit supplying a particular linear load, deform the waveforms of voltage and current load.

2.3 Characteristics of Loads in Railway Systems

The load characteristics applied to a railway substation is specific, as well as, in according that the train starts and goes physically until another substation; the power supplied to the train is proportional to the proximity between train and substation. The energy supplied for a departure substation decrease progressively, and the energy supplied for final substation where the train will go increase at the same rate. In [16] are presented equipment descriptions and operational characteristics for train traction systems.

Some features can be cited.

- Abrupt load changes due to departures, braking and train ramp efforts;
- Non-sinusoidal request due to rectifier;
- Unbalanced load imposed by power supply;

Due the load requests may arise in railway systems problems such as:

- Voltage fluctuation;
- Harmonics;
- Current imbalance;

These problems cause disruption and failures in power supply systems, mainly due to harmonics, in special because the transmission and distribution lines are so longer. The four main disturbance characteristics are:

- Interference in communication Systems;
- Capacitors overvoltages' or overcurrents';
- Energy loss by Joule effect in transformers and transmission lines;
- Vibration and heating in motors and generators;

3 Rectifier Substation Power Circuit ATP Modeling

This item presents the models used on the main component studies. The values presented are real and have been collected to format the case truthfully.

3.1 Power Transformer

The transformer data used in this study are presented in Table 1.

Table 1. Characteristics of Substation Power Transformer

POWER TRANSFORMER	
PHASES NUMBER	3
FREQUENCY (HZ)	60
CONNECTION GROUP	DELTA-Y
VOLTAGE RATE (KV)	138/44
APPARENT POWER (MVA)	30
IMPEDANCE (%)	7.79

The Power transformer modeling at the ATP program was performed considering the transformer characteristics showed at Table I. The transformer model used in ATP is the BCTRAN and their details are illustrated in Fig. 3 [17].

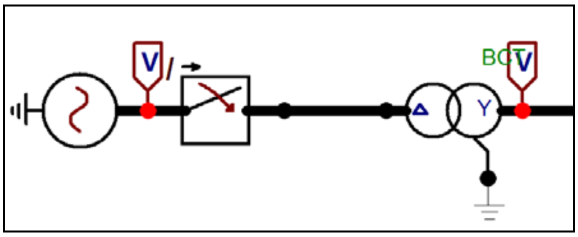

Fig. 3 – ATP Model for a Power Transformer

3.2 Rectifier Transformer

This substation equipment has three-phase windings, one in its primary side and the secondary side with two windings. Therefore this transformer has a six-phase output to supply a six-phase substation rectifier. The transformer used in the rectifier is feeder by power transformer substation in 44 kV and reduces the voltage level for 2,410 V phase-phase or 1,390 V phase-to-ground.

The table 2 and Fig. 4 present the data and the dual secondary winding rectifier model.

Table 2. Rectifier Transformer Characteristics

RECTIFIER TRANSFORMER	
PHASE NUMBERS	PRIMARY=3 AND SECONDARY=6
FREQUENCY (HZ)	60
CONNECTION TYPE	Y-Y-Y
NOMINAL VOLTAGE RATE (KV)	44/2.41
APPARENT POWER (MVA)	3.4
IMPEDANCE (%)	4.84

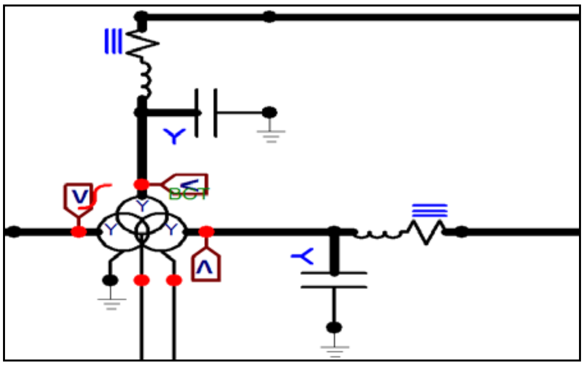

Fig. 4 – ATP Model for a Substation Rectifier Transformer

The capacitor, inductor and resistor in the output circuit of both secondary transformers configure the model "π" for the purpose to define the shielded cable electrical parameters that connects this transformer and rectifier substation.

The values of the cable parameters (resistance, inductance and capacitance) used in the model were calculated according to the length and the manufacturer's manual data and these data are summarized in Table 3.

Table 3. Transformer to Rectifier data cable

SHIELDED CABLE 240 mm^2 - VOLTAGE CATEGORY 3,6/6 KV – MANUFACTURY-FICAP	
CAPACITIVE REACTANCE (Ω.Km)	3700
INDUCTIVE REACTANCE (Ω/Km)	0.10206
RESISTANCE (Ω/Km)	0.09967

When the research team visited the local to inspect the installation, they identified that cable had approximately 50 meters, and therefore, all its parameters can be calculated and inserted in the full model.

3.3 Six Phase Rectifier

The substation rectifier is a six-phase model and it has two rectifier bridges connected in series, each one of bridge supply 1,500 DC output voltage totaling 3,000 VDC between the positive and negative output rectifier terminal.
The rectifier particularity is in their power supply, because both rectifiers inputs are connected by secondary transformer and each output rectifier connected to the neutral secondary transformer that feed the rectifier. This description can be displayed in Fig. 5 that represent the ATP rectifier modeling. In this modeling were considered only six diodes, with three in each bridge rectifier. However the rectifier substation studied in this paper has a total of 72 diodes.
The fact of considering only a diode as a replacement to a group of 12 diodes, configured in mixed connection (series-parallel) does not influence the simulations results, because the diodes guarantee a security voltage level between its terminals. The older manufactured rectifiers had several diodes connected in parallel with resistors, capacitors and inductors. This connection was necessary to ensure a better voltage balance between its terminals (snubber's circuits).

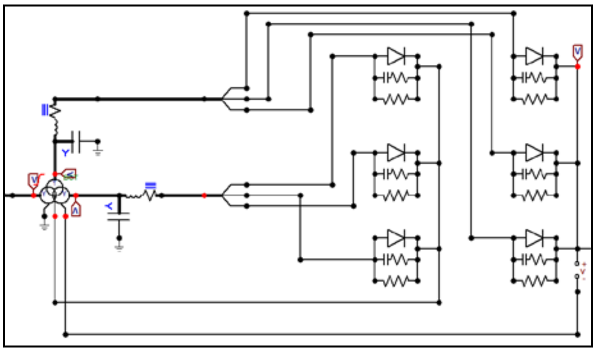

Fig 5. – ATP Model for a controlled half bridge

Each diode in the bridge rectifier is connected in parallel with two loads; the first being comprised of a 12 Ω resistor and a capacitor of 1 μF, and the second a resistive load with 25 kΩ.

3.4 Tuned Filter

The tuned Filter must be connected to the train power circuit so as to provide a low impedance way for Harmonic frequencies, thus avoiding their insertion into the load supply circuit. The filter present in the substation is a shunt filter, it provides a way for harmonic currents flowing through a branch with capacitor and inductor connected in series and tuned to a specific frequency.
In the study case the frequencies for which filters are tuned are: 360 Hz, 720 Hz, 1,080 Hz and 1,440 Hz, this means an adjustment to the harmonics of order 6, 12, 18 and 24 respectively.
The ATP filter modeling is performed through the connection of inductors and capacitors, where each branch has a different inductor and capacitor values adjusted in according to harmonic frequency that the filter you eliminate using the frequency resonance principle .
The components (capacitors and inductors) are adjusted to obtain the correct frequency to get the relation $X_L = X_C$.
In the case of substation filter, the calculated values satisfy this condition and are summarized in Table 4.

3.5 DC Motor

It is considered in the train model that it have four engines, two engines in series at truck-1 and two truck series engines at truck-2. Initially the four motors are connected in series. After the departure of the train, the truck-1 motors are connected in parallel with truck-2 motors.

For the modeling of this system was considered the values of field and armature resistance determined by measurement. These values have difference and depend of the train manufactory. In this part of the study uses a steady state DC motor model, learned by the undergraduate student on the initials class of electrical engineer course. Table 5 presents the values of the field and DC motor armature resistance of an engine trains manufacturer.

Table 4 – Tuned Harmonic Filter Characteristics

TUNED HARMONIC FILTER			
BRANCH	TUNED FREQUENCY (Hz)	INDUCTANCE (mH)	CAPACITANCE (μF)
1º	360	2.92	64
2º	720	2.92	16
3º	1,080	2.92	8
4º	1,440	2.92	4

Table 5 – Internal Resistance values of electric traction DC Motors

TYPICAL DC MOTORS OF RAILWAY		
SERIE	ARMATURE RESISTANCE (Ω)	FIELD RESISTANCE (Ω)
500	0.192	0.061
700	0.1339	0.073
8000	0.225	0.1155
900	0.22	0.0985
90000	0.22	0.0895

The model of DC motor in series configuration, i.e. on condition of departure is illustrated in Fig. 6.

In this model are present four DC voltage sources representing the armature voltage of each motor, eight resistors representing the armature and field resistance for each motor and two inductances, each one represents a group of truck engines.

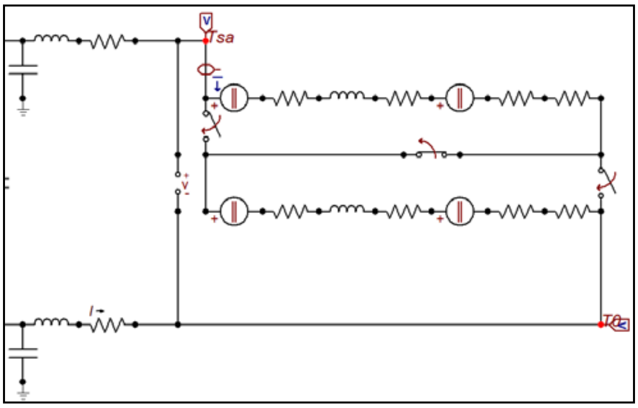

Fig 6. – ATP Model for Serie DC Motor Circuit

In according with the manufacturer´s manual, the inductive reactance of the traction motor is 0.0829 (60 Hz). So, for this reactance has a corresponding 0.22 mH inductance

As ATP modeling circuit of Fig.6 is represented only an inductance in the branch with 2 motors, the value entered for this inductance was twice the value of the individual motor inductance, i.e. L = 0.44 mH.

It is observed by modeling circuit that the central branch switch is in the closed position while the side switches are in the open position. This configuration represents the engine series once the current that runs through the four motors are the same.

Whereas the value of rectifier output current is approximately 1,000 A. This value was measured by the substation ammeter and it helps to calculate the approximate value of the train DC motor armature voltage in steady condition, when each truck train is connected in parallel.

The voltage in the catenaries for motors power supply is 3,000 VDC, so parallel configuration it is possible to write the Equation (1):

$$V_{Arm} = \frac{3000}{2} - 2.(R_A + R_S).500 \quad (1)$$

This equation can be inferred through the circuit analysis at parallel configuration ATP modeling, as represented by Fig. 7.

It is observed by modeling circuit that the central switch is in the open position, while the side switches are in the closed position, featuring parallel configuration of engines between trucks.

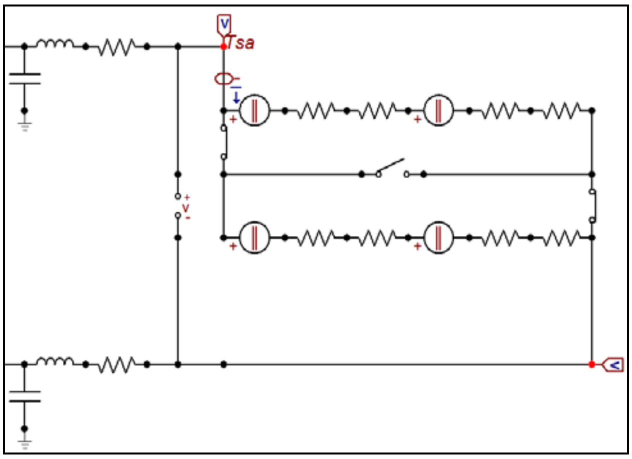

Fig 7. – ATP Model for Shunt DC Motor Circuit

By the circuit it should be noted that the terminals voltage of each engines group of the same truck is 1,500 V, once the circuit of "trucks" are in parallel. In addition, as it was considered that the rectifier output current is approximately 1,000 A, the current flowing in each truck train is 500 A, because all motors of this circuit are the same. Thus, by Equation (1) is possible to determine the armature voltage, substituting the field and armature resistance values. The calculated value is $V_{Arm} = 1{,}330\ V$.

The "π" model showed in the motor circuit represents the electrical parameters effect of the shielded cable between the rectifier and the catenaries to supply trains. The parameters calculation is determined similarly to the calculation performed for the cable that connects the transformer and rectifier.

On local measurement realized by team work was found that this cable is a three-pole type and has 30 meters in length. Its main features provided by the manufacturer are: 500 mm^2 shielded cable, voltage class 3.6/6 kV, X_c = 3,276 Ω.km, X_l = 0.0963Ω/km and 0.05387 Ω/km.resistance.

Therefore, the total resistance for this cable is 1.62 mΩ, X_l 2,889 mΩ, L = 0.00766 mH, X_c = 109.200 Ω and C = 0.0243 µF.

4 Simulations for Harmonic Analysis

In a Rectifier System there are two types of harmonic distortion to consider:

- The Harmonic distortion or ripple on the DC side, which affects the equipment to be powered. The DC shunt or compound motors are little affected by voltage harmonics, but are really affected by current that cause vibrations and heating unnecessary;
- The AC side harmonic distortion, which compromises the energy quality to other equipment connected to the electric grid. In addition, these harmonics cause the overheating of the transformer rectifier requiring a larger core.

4.1 Output Rectifier Voltage Harmonic Analysis

This analysis aims to evaluate the output rectifier voltage harmonic, before the tuned filter acts. Figure 8 represents the voltage waveform graph between the positive and negative terminals on the rectifier output.

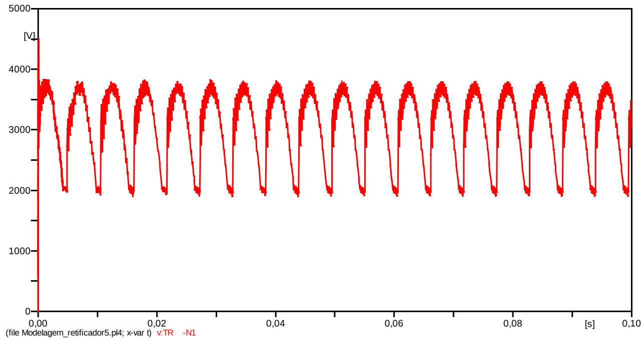

Fig 8. – Waveform of rectifier output voltage

In the Fig. 8 graph appears that the DC output voltage is characterized by oscillation amplitudes of high harmonics present. The frequency spectrum with the DC rectifier output voltage harmonics orders is shown in Fig. 9. The upper part of this spectrum corresponds to the harmonic module graph and the bottom corresponds to the angle of each respective harmonic.

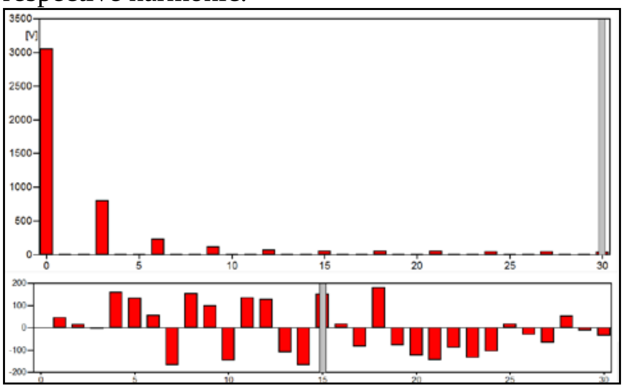
Fig 9. – Frequency Harmonic spectrum of rectifier output voltage

Observe the chart the presence of harmonics multiple of 3 orders, i.e. orders 3, 6, 9, 12, 15, 18, etc. Thus, it is concluded that it is essential to use tuned circuit filter for harmonic mitigation. It is possible to verify that the continuous voltage component has a value of approximately 3,000 Volts that is the supply voltage to the trains.

4.2 Output Rectifier Current Harmonic Analysis

This analysis aims to verify current harmonics that are generated as a function AC substation rectifier. The Fig. 10 shows the output current rectifier waveform.

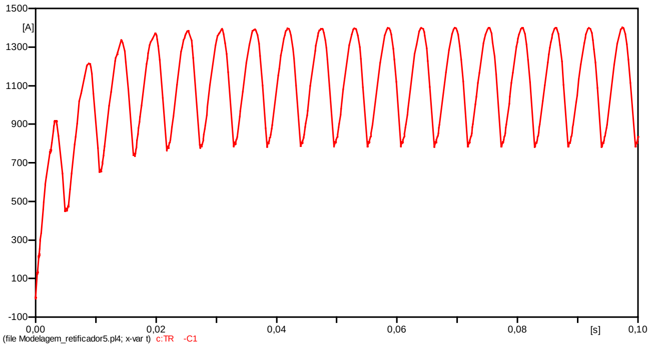

Fig 10. – Waveform of rectifier output current

In the graph is observed that there are high oscillating, demonstrating the presence of harmonics in rectifier output. The frequency spectrum in Fig. 11 illustrates these harmonics.

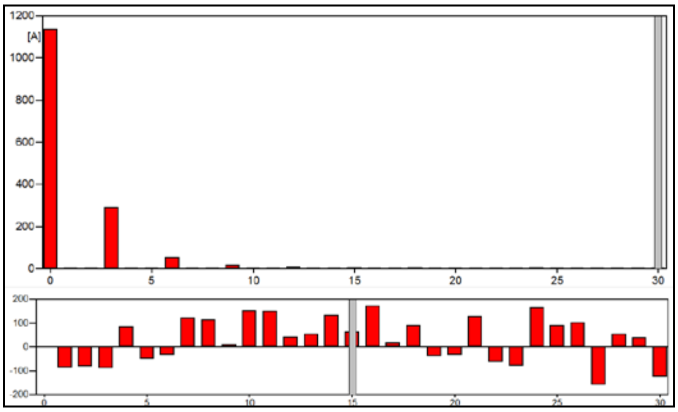

Fig 11. – Frequency Harmonic Spectrum of rectifier output current

In the output rectifier current frequency harmonics spectrum is notable a high level of third-order harmonics, with a peak value of 288.7 and a significant harmonics level of sixth order, corresponding to 49.64.

4.3 DC Motor Current Harmonic Analysis

This analysis evaluates the existing current harmonic contents in the electric traction motor of trains. It is important that DC motor current has reduced harmonic content, since a high level of harmonics can cause damage to the train engine, such as vibrations, excessive heating, in addition to increasing electrical losses. The Fig. 12 represents the traction motor current power supply waveform.

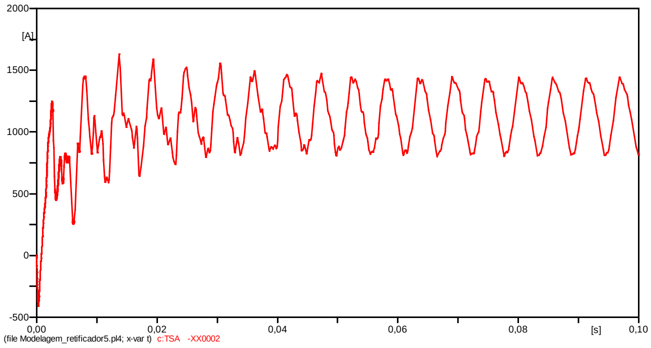

Fig 12. – Waveform of DC motor current

Analyzing the Fig. 12, it is concluded that the current oscillations remain, mainly due to the presence of the third-order harmonic, in according the frequency spectrum as shown in Fig. 13 corresponding to this analysis.

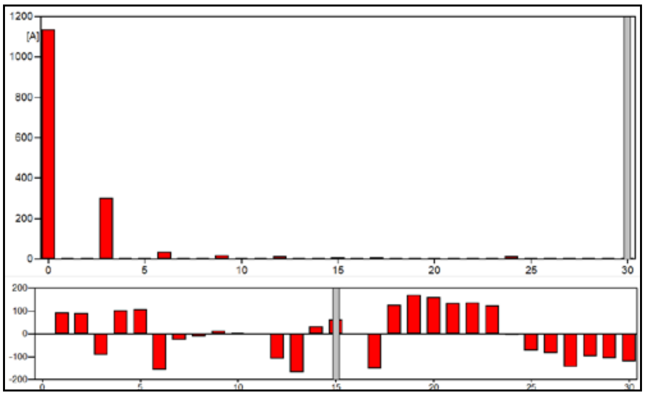

Fig 13. – Frequency Harmonic Spectrum of DC motor current

Note that the filter is working properly in the frequencies of 720 Hz, 1,080 Hz and 1,440 Hz, corresponding to the harmonics of order 12, 18 and 24 respectively. But on the frequency 360 Hz, there is a harmonic insertion of the sixth order in current motor, with a peak value of 32.42. This fact is due to the values of inductor and capacitor of this branch of the filter that are not perfectly adjusted in resonant frequency. The replacement of 2.92 mH inductor by a 3 mH inductor would make the filter act more efficiently.

These simulation analysis is the most important part of this study, because the research group can verify the real conditions of the circuit and propose a better solution.

4.4 Rectifier Transformer Primary Current Harmonic Analysis

This analysis checks if there are high rectifier transformer primary current harmonic distortion. Is of great importance that the current harmonic content is low on the primary of the transformers, as the harmonic currents cause overheating, vibrations and excessive increase copper and magnetization losses. The Fig. 14 illustrates the primary transformer current waveform.

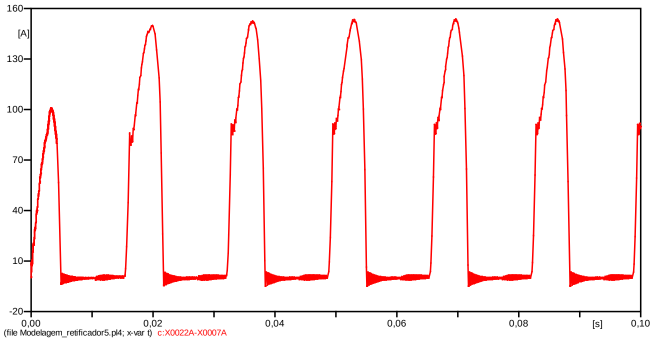

Fig 14. – Waveform of primary transformer rectifier current

It is possible to note that the primary transformer current waveform is so distorted confirming a high harmonic content.

Through the frequency spectrum it is possible to identify the order of current harmonics, as shown in Fig. 15.

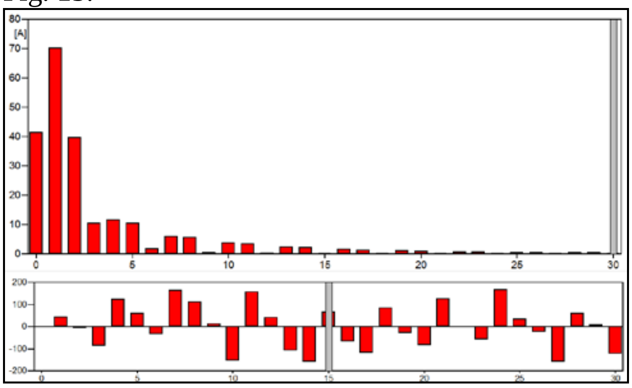

Fig 15. – Frequency Harmonic Spectrum of primary transformer rectifier current

The ATP program computes the harmonic distortion rate to evaluate the existing harmonic content. In this case, the formula that is the reference is the same showed in the Equation (2).

$$THD_i(\%) = \frac{\sqrt{\sum_{h=2}^{h=h_{max}} I_h^2}}{I_1}.100\ \% = 64\% \quad (2)$$

As it has a $THD_i(\%)$ greater than 50%, it proves to be a significant harmonic pollution, which may result in malfunction of electrical equipments in substation.

There are several others different points for explore during the research, but this paper presented only some part of the checked points.

5 Proposed Solution

In these analyses is possible to identify that the voltage level at the motor and transformer rectifier primary terminals are suitable for power quality. On the other hand, the current level is "polluted" requiring corrective actions.

5.1 DC Motor Current

As noted in the DC motor current simulation, there is the harmonics of order 3 and 6. In relation to the third order harmonics its insertion into the circuit can be prevented in two ways:

a.1) Proper winding connection between the secondary transformer voltages this alternative would be possible with the rectifier transformer replacement by another transformer with secondary Delta-Wye, since the Delta transformer connection acts as filter for 3 multiple-order harmonics, thus avoiding the insertion of these harmonics in the circuit. This solution would require a very high investment and the maintenance team must evaluate the solution economic investment. Given the same principle it is possible to use a three-phase full-wave rectifier or a transformer with three windings (Wye-Delta-Wye) building a 12 pulses rectifier.

a.2) To insert a new tuned filter branch adjusted for third order harmonic. This solution is more simply to implement and it has a low investment.

To insert a tuned filter branch adjusted in 180 Hz is necessary to determine the values of inductor and capacitor for resonance frequency, i.e., $X_l = X_c$. To meet this condition is necessary to get a value combination of these components that make the mentioned equality true. To meet this equality two possible values for the inductor and the capacitor would be: L = 7.84 mH and C = 100 µF.

These values could be obtained by combining four 1.96 mH series inductors and four 25 µF capacitors in parallel. This filter configuration is a more robust because the voltage level is 3,000 VCC.

Special attention should be given in the specification and build solution, because 25 µF-3 kV capacitance are so difficult to get. The commercially available capacitors have the range from 0.75 to 0.125 µF. So, would be requiring several units in parallel, which would make the bank too expensive and would take too much space. In addition, there is the problem of the filter quality factor. A branch tuned in 180 Hz will present an extremely relevant leakage current at 60 Hz. It is necessary to choose a proper rectifier transformers connection to remove these harmonics.

With respect to order six harmonics, it is verify that the filter is not set in an efficient configuration, since there is these harmonics in the circuit. Calculating the values of inductor and capacitor at resonance frequency to filter out the 360 Hz frequency harmonics, the results are: L = 3mH and C = 64 µF.
It is possible to observe that the capacitor value is exactly the same used at the original filter, but the filter inductor is 2.92 mH. The inductor has a value very close to the calculated but the small difference in the inductance is responsible for the appearance of the sixth-order harmonic in the motor current.
Through the calculated values the maintenance team can do a new simulation with the insertion third-order filter harmonics branch and replacement of 2.92 mH inductor by a 3 mH inductor. The Fig. 16 represents the motor current waveform for this new setting.

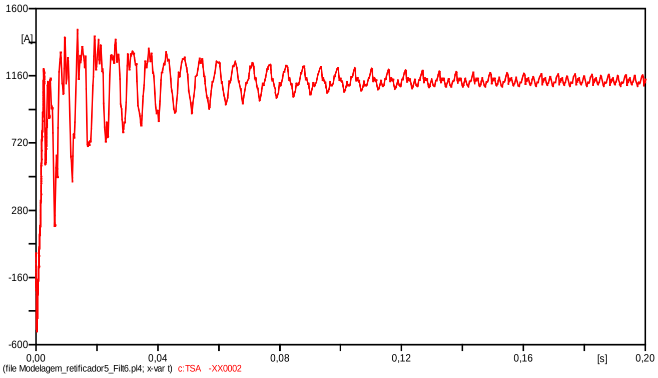

Fig 16. – Waveform of DC motor current after filter adjust

There is a clear level current oscillation improvement and a decreasing in the current harmonics amplitude. The Fig. 17 illustrates the current frequency spectrum.

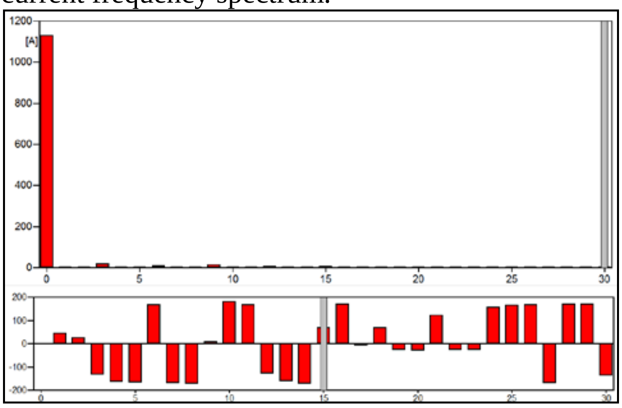

Fig 17. – Frequency Harmonic Spectrum of DC motor current after filter adjust

In this spectrum analysis, it is concluded that the branch insertion to attenuate the 3rd order harmonic and the change in the inductor value in the 6th order harmonic branch caused a decreasing in the traction motor current power supply harmonics content.

5.2 Rectifier Transformer Primary Current

As noted in the simulation for the rectifier transformer primary current, there is a high harmonics level of various orders current. The transformer connection type used in this rectifier substation is quite old and it isn´t very efficient. The standards IEC 60146-1-2 and IEC 61378-1 recommend certain settings indicating the rectifier type to be used in accordance with the transformer configuration that feeds it. These recommendations are made in order to eliminate low-order harmonics through the transformer connections or thyristors trigger angle for controlled converters. This adjustment in the filter design minimizes costs because the passive components for attenuation of low-order harmonics have high cost in high-voltage levels.

5.3 Comparative Analysis between Rectifier Output Voltage and DC motor terminals voltage for the new proposed model

In Fig. 18 the green waveform represents the voltage at the rectifier output and the red waveform represents the DC motor terminals voltage. It should be noted that there was a significant voltage amplitude harmonic decreasing due the proposed solutions cited by researches in this paper.

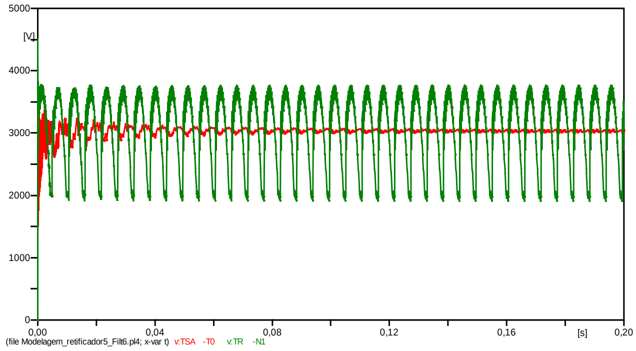

Fig 18. – Comparative output rectifier and motor voltage analysis

5.4 Comparative Analysis between Output Rectifier Current and DC motor current for the new proposed model

In Fig. 19, the waveform represented in green indicates the output rectifier current and the red waveform indicates the input current in DC motor circuit.

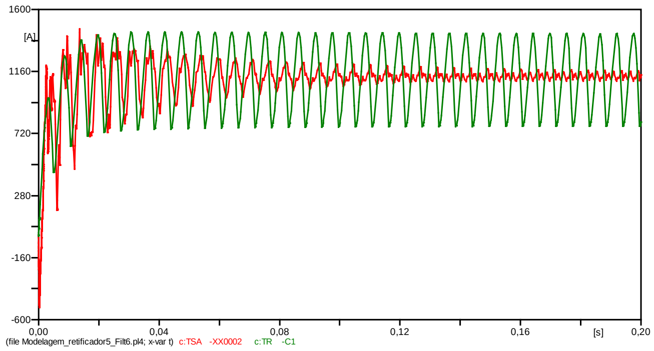

Fig 19. – Comparative output rectifier and motor current analysis

5 Conclusions

Incorporate real case including harmonic analysis in a rectifier substation of railway systems and engineering software is the methodology used in this paper . The real case is studied with an objective to get a complete overview about harmonics and others bad quality energy problems and to present the use o ATP software to help the analyses and to get better solutions by simulations. For the analysis were considered two relevant points that are the circuit load, i.e. the train traction motor and the rectifier transformer primary.

In relation to the DC motor is essential that the current harmonic content will be reduced because the harmonic presence in its supplied circuits can cause vibrations and overheating in the engine. In relation to voltage harmonics, these are not as worrisome as the current harmonics, but it is important that the power supply circuits do not have large oscillations.

In the rectifier transformer primary circuit is important that the current harmonic distortion index is within the recommended power quality standards, because high levels can cause high losses in copper and in the transformer core, in addition it can cause high level of noise, overheating and may affect the equipments isolation. Therefore, this analysis had its due importance in this work.

In the simulations carried out for the various analyses found that the harmonics voltage content is low at all points of the substation circuit and at the terminals of the electric traction motor. So, in spite of the rectifier generate voltage harmonics, the filter is tuned properly to mitigate undesirable harmonics.

The analysis for current harmonics of train power supply circuit was found some relevant considerations. The first is in relation to the current that feeds train DC motors, where the analysis identifies high third-order harmonics and the sixth order harmonic presence. For solving this problem was inserted a tuned filter to a 180 Hz frequency with the goal of eliminating the current harmonics of 3rd order in the power supply circuit. In addition, the study suggest to change the inductance value of the filter tuned to the frequency 360 Hz in order to make more accurate filtering and mitigate best sixth-order harmonics. The result was satisfactory with a current waveform with less harmonic amplitude and frequency spectrum with minimum values harmonics. Through these filter changes, in addition to improving the quality of electrical current, it is possible to increases even more the quality of the trains supplies voltage.

The analysis on the transformer's primary current met a high harmonic content, with a THD of 64%, this value is higher than recommended. For a corrective act would be necessary to change the configuration of the transformer connection with rectifier, once the standard IEC 61378-recommends settings that low order filter harmonics and these are the most critical to the substation transformer analyzed.

References:

[1] EEUG - European EMTP-ATP User Groups Website, www.eeug.de.

[2] P.M.Miguel, Introdução à Simulação de Relés de Proteção usando a Linguagem "Models" do ATP, 1st edition, Ed. Ciência Moderna, 2011.

[3] E. Mollerstedt, B. Bernhardsson, Out of control because of harmonics – an analysis of the harmonic response of an inverter locomotive, *IEEE Control Systems* , Vol.20, 2000.

[4] S.El-Rabaie, V.F.Fusco, C. Stewart, Harmonic Balance Evaluation of Nonlinear Microwave Circuits – A Tutorial Approach, *IEEE Transactions on Education*, Vol.31, 1988, 181.

[5] L.A. Snider, E. Lo, T.M. Lai, Harmonic Simulation of DC Traction System with multi-train operation, *Proceedings of the 5th International Conference on Advances in Power System Control, Operation and Management*, 2000.

[6] G. Skarpetoeski, W. Zajac, W. Czuchra, Analytical Calculation of Supply Current Harmonics generated by Train Unit, *Proceedings of the 12th International Power Electronics and Motion Control Conference*, 2006.

[7] M.Brenna, F. Foiadelli, D. Zaninelli, M.Roscia, Harmonic Emission of Double Stage Converter for Auxiliary Services in Electric Trains, *Proceedings of the 9th International Conference Electrical Power Quality and Utilization*, 2007.

[8] M. Popescu, A. Bitoleanu, M. Dobriceanu, Harmonic Current Reduction in Railway Systems, Journal *WSEAS Transactions on Systems*, Vol. 7,2008.
[9] F. Shania, M.B.B. Sharifian, Harmonic Analysis and Modeling of Transformerless Electric Railway Traction Drives, *Proceedings of the 13th International Conference on Electrical Drives and Power Electronics*, 2005.
[10] H. Lee; C. Lee; G. Jang, S.Kwon, Harmonic analysis of the Korean high-speed railway using the eight-port representation model, *IEEE Transactions on Power Delivery*, Vol.21, 2006.
[11] P.E. Sutherland, M. Waclawiak, F.McGranaghan, Analysis of Harmonics, Flickers and Unbalance of Time-Varying Single-Phase Traction Loads on a Three-Phase System, *Proceedings of the International Conference on Power Systems Transients*, 2005.
[12] Y.T.Hsiao, K.C. Lin, Measurement and characterization of harmonics on the Taipei MRT DC system, *IEEE Transactions on Industry Applications*, Vol.40, 2004.
[13] M.Z.Fortes, G.P. Brandão, B.H. Dias, C.J.M. Albuquerque, Software support for the evaluation of energy losses from leaks, *IEEE Potentials*, Vol.33, 2014.
[14] H.O. Henriques, C.E.V. Pontes, S.F. Costa, M.Z.Fortes, M.C.Costa, J.C.O.Aires, Thermodynamic models and three-dimensional analysis for determination of load limits Transformers, *IEEE Latin America*, Vol.11, 2013.
[15] M.Z. Fortes, V.H. Ferreira, A.P.F. Coelho, The Induction motor parameter estimation using genetic algorithm, *IEEE Latin America*, Vol.11, 2013.
[16] Railway Technical Website, www.railway-technical.com.
[17] ATPDRAW- User´s Manual – version 5.6 Website,:www.atpdraw.net/getipdf.php?myfile =ATPDMan56p.pdf.