Transient Behavior Of Harmonics Filter Operation In A Railway Network

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Abstract - **Measurements of harmonics and waveforms were made in an electric system that feeds a railway network. The analyzed network is composed by cables in 20 kV and 6-pulse rectifiers, which are connected to a system in 132 kV.**

The results of these measurements were used to adjust a digital model of this network. The purpose of this model, built with the ATP, was to determine the transient behavior that occurs during the harmonics filter operation. This filter was designed taking into account the harmonics found in the railway network.

Keywords: Harmonics, Transients Analysis, Modellling, ATP.

I. INTRODUCTION

In a railway network high levels of harmonics were detected in the voltage and in the current, which were very superior to the levels allowed by the National Regulatory Agency (ENRE) in Argentina.

6-pulse non-controlled rectifiers, which feed the train system, are the generators of these harmonics. The harmonics are amplified by a resonant circuit formed by the source inductance and the distribution cables capacitance of the 20 kV railroad electrical system. (Fig. 1)

Measurements of harmonics and waveform of voltage and current were made in the feeding bus to obtain useful information of these disturbances and to know with more detail the system behavior.

Different alternatives for the mitigation of the harmonics injected in the feeding network were evaluated. One of them was the installation of a filter system located in the feeding bus.

This system consists of resonant branches in derivation for the 5^{th}, 7^{th} and 12^{th} harmonics, this last branch intends to mitigate the 11^{th} and 13^{th} harmonics.

The design also contains a reactor to compensate the reactive power of the filter system and the 20 kV cables.

The purpose of this paper is to show the results of the study made to determine the transient behavior that occurs during the filter system operation.

II. DESCRIPTION OF THE NETWORK

The electrical system railway is composed by 20 kV cables with a total length of approximately 150 km. This grid has the layout of a double ring and is fed from a single 20 kV feeding bus (Fig. 1). The system is ungrounded. The ages of the cables are varied, and some of them are more than 80 years old.

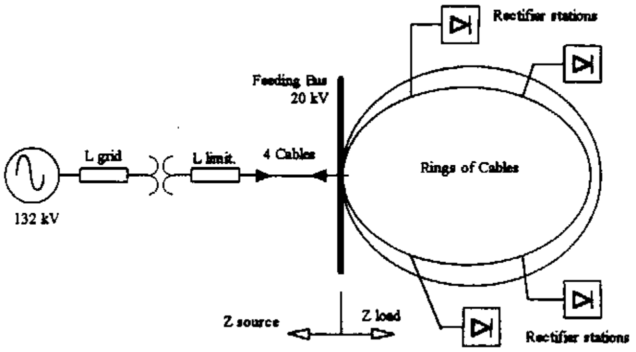

Fig. 1. Single-wire of the network to simulate.

The load is formed mainly by non-controlled 6-pulse rectifiers (bridge of diodes) located in ten stations, the installed power is 46 MW.

The Distribution Company supplies energy through a 60 MVA transformer of 132/20/13,2 kV.

The connection between the feeding network and the cable rings is through a limit reactor of 1.5 mH and four cables of approximately 2.5 km.

III. FIELDS MEASUREMENTS

Measurements of harmonics were made in the feeding bus.

It was observed that the harmonics (mainly 5^{th}) sent from the load to the external network exceed the allowed levels.

Waveform of voltage and current were measured. The current was measured in cables of connection to the feeding bus, and the voltages were measured between phases and ground in the same point.

Harmonic contents of the following orders were measured (referred to the value of fundamental): I5=60%, I7=7%, U5=27%., U7=6%.

The registered values of harmonics widely exceed the allowed levels by the National Regulatory Agency (ENRE), which are: I5=12%, I7=8,5%, U5=27%., U7=5%.

The active power consumption varies during the day, reaching a minimum near to zero (0.4 MW) and a maximum of 12.8 MW. The reactive power is practically constant during the day and has a capacitive value (-3,6 MVAr).

In Fig. 2 the results of the measurements are summarized. The following variables, registered during a day, are shown: distortion of voltage and current, RMS values of currents and powers. These values correspond to 10 minutes averages.

IV. THE EQUIVALENT CIRCUIT.

A. Equivalent circuit of the source

The relation between voltage and current was obtained for each harmonic from the measurement registers. These relations results practically straight lines that intersect the origin for each harmonics and their slopes are the impedance magnitudes. The values of the corresponding impedances are expressed in the following table.

Impedance	[Ohm]
Z1(50 Hz)	3.3
Z3 (150 Hz)	12.7
Z5 (250 Hz)	16.9
Z7 (350 Hz)	26.2
Z11 (550 Hz)	54.6

An equivalent source L-circuit was synthesized using these values. The value of the inductance is

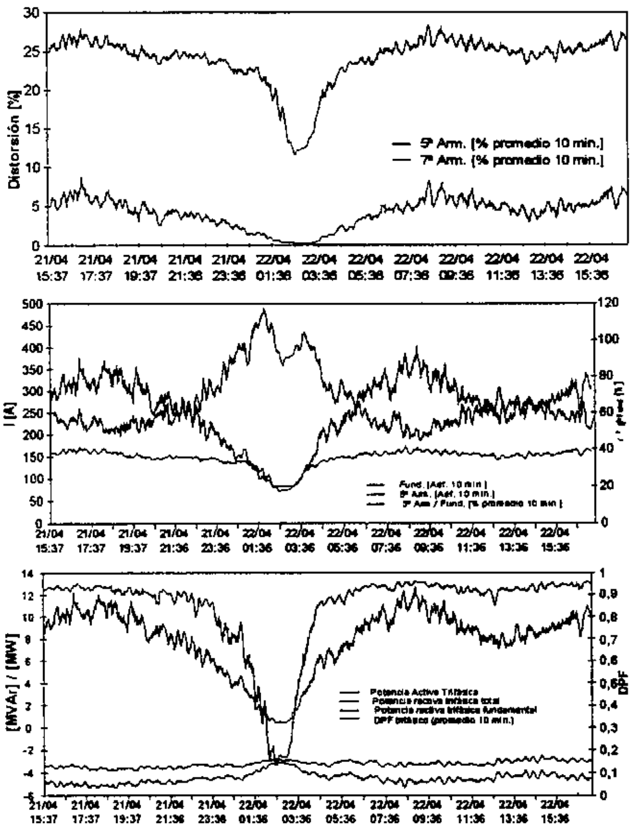

Fig 2. Registered variables. Time Representation. Average of 10 minutes.

a). Distortion of the voltage 5^{th} and 7^{th}

b). RMS value of fundamental current, current of 5^{th}, and distortion of 5^{th}.

c). Active power, total reactive power, reactive power of the fundamental, power factor.

L_{source}=9,93 mH, and the value of capacitance is C_{source}=3,12 nF. The impedance value at 50 Hz agrees with the short circuit power level in the feeding bus and the capacitance value is similar to the capacitance of the four cables of 2.5 km connected in parallel. So, these values agree with the physical description of the grid. The resonance of the circuit occurs at 900 Hz.

The adopted resistance was of 1 Ω, due to the relation between the reactance and the resistance at 50 Hz of the 132 kV network of three. The resistance variation with the frequency was not considered. Using the 'Frequency Scan' option of the ATP this equivalent Z_{source} was verified (see Fig 3).

The measured values of voltage and current for the third harmonic are small and consequently, the quotient of these magnitudes displays greater dispersion than the rest of harmonics. Therefore, the value of measured impedance respect to the synthesized one has greater error in this harmonic.

B. Equivalent circuit of the load

An equivalent circuit of the load (rectifier and cables network) that suitably represents the measurement results is obtained, for a typical case. This equivalent allows the filter system design and the transient behavior verification.

The short circuit power levels, at different points of the cable network, are very similar and around 120 MVA. Using data available of reactances and resistances of cables and typical values of capacitances, harmonics power flows calculations were performed with an appropriate program.

Current sources of 5th and 7^{th} harmonics were injected in different points of the network. It was verified that the amount of harmonic currents flowing to the external network is independent of the location of these points.

The frequency response of the system was calculated connecting a generator of 1A in the feeding bus. The maximum voltage was observed near to fo=275 Hz., which is the admittance pole.

The value of equivalent load capacitance Cc, is obtained with the measurement of the load reactive power

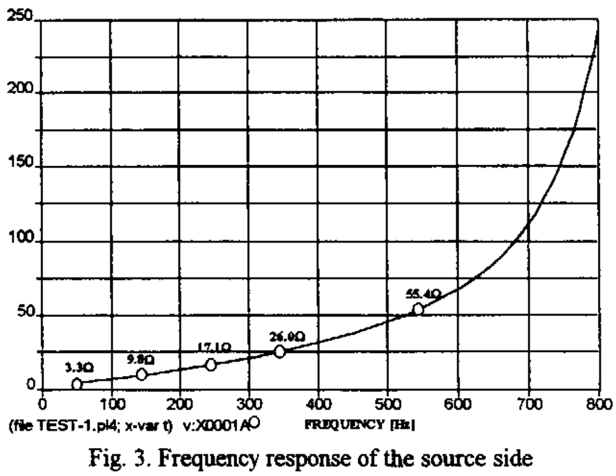

Fig. 3. Frequency response of the source side impedance (Zsource).

(Q_l) at rated frequency. It is practically the ring of cable capacitance. As $Q_l \approx 3{,}6$MVAr, then is Cc around 30 µF.

This capacitance (Cc) added to the 4 feeders cables capacitance (Csource), and the equivalent inductance, (Lsource) give to the resonance frequency fo estimated previously.

$$(2\cdot\pi\cdot fo)^2=((Cc+Csource).L_{source})^{-1}$$

Taking this into account, the load can be represented by an equivalent circuit formed by a capacitor (Cc: capacitance of the cable network) and an inductance (Lc) that feeds only one 6-pulse rectifier. This equivalent circuit is shown in Fig. 4.

The values of the equivalent inductance (Lc) and the DC resistance (Rcc) were estimated from the theoretical formulations of the 6 pulses rectifiers and from the transfer function between the current injected by the rectifier (I_{load}) and the current measured ($I_{measured}$) in connection cables: $T(s) = I_{measured}/I_{load}$. The theoretical formulations assume perfectly smooth DC current and a zero resistance in the AC side, and consider an inductance value in the AC side.

In Appendix I the used equations are expressed. Using these equations, the value of Lc was calculated and the Cc value was adjusted (this value should be similar to 30µF).

After this preliminary calculation, the equivalent circuit for the chosen typical case was modeled with the ATP and the results of the simulation were compared with the measurement. Then the load circuit parameters (mainly Lc of the AC side and Rcc, Lcc of the DC side) were fit to obtain simulation results similar to the measurements.

In Fig. 5 the comparison between measurement registers and simulation results of the chosen case are shown.

The active power of this case is 7.6 MW. In the following table the simulated and measured RMS current values are presented, for the fundamental and for 5th and 7th harmonics. These values were obtained with Cc=31.7µF, Lc=20mH, Rcc=74Ω, Lcc=500 mHy.

Frequency	Measurement	Simulation
50 Hz	337 A	343 A
250 Hz	218 A	208 A
350 Hz	20 A	17.5 A

V. FILTER PARAMETERS.

The filter system proposed for the mitigation of the harmonics levels is connected in the feeding bus of the cable network. This system consists of three branches: 5th and 7th harmonic branches of high merit factor (Q) and the third branch for the 12th harmonic with suitable Q to mitigate both 11th and 13th harmonics.

The reactive power (at 50 Hz) of cables and filters is compensated with a reactor in delta connection.

This installation allows fulfilling harmonic levels required by the National Regulatory Agency.

The parameters of the branches per phase are:

Harmonic branch of 5th: capacitors C =16 µF; filter reactors L =25.3 mH; Q>100 at 250 Hz. Resistance is not needed.

Harmonic branch of 7th: capacitors C =8 µF; filter reactors L =25.3 mH; Q>100 at 350 Hz. Resistance is not needed.

Harmonic branch of 12th: capacitors C =8 µF; filter reactors L =8.8 mH; Q>100 at 600 Hz; Resistance R =200 Ω.

VI. TRANSIENT SIMULATIONS

The filter systems will be operated with one circuit breaker. Then, are of interest the simulations with digital models of the open and closing operation of this circuit breaker in order to determine the transient behavior of the systems.

There are not expectable severe transients due to the closing of the circuit breaker. Here, the phenomena such as those that happen in the connection of capacitors bank are highly mitigated because of the presence of the inductive reactance of each filter. In fact, the simulations made with the model confirm this asseveration.

Nevertheless, due to the particular characteristics of

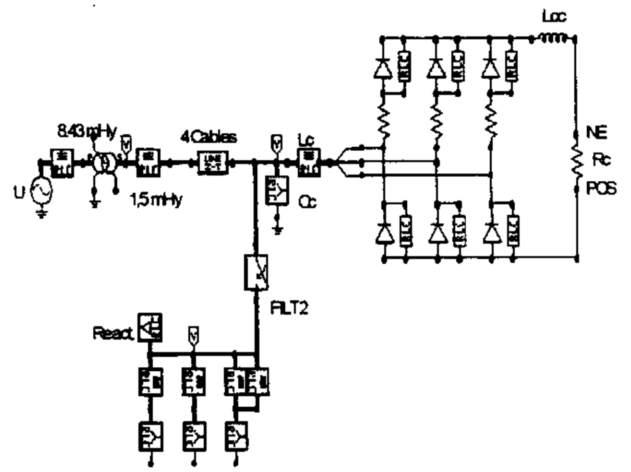

Fig. 4.Equivalent Circuit.

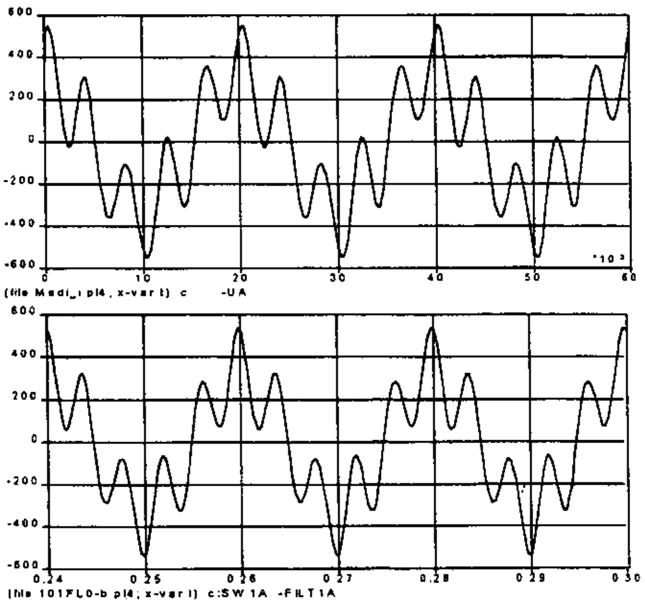

Fig. 5. Waveform of current measured and simulated.

this system at both sides of the circuit breaker, It can be expected some relevant stresses in the breaker opening operation. Principally, the transient recovery voltage (TRV) between contacts of the circuit breaker can exceed the rated standard values specified by the International Standard IEC 56 [2].

In this point, it is necessary to make a brief description of this International Standard, that define the standard values of the rated TRV that the circuit breaker must be able to support.

A. Standard values of rated TRV

The waveform of TRV varies according to the arrangement of actual circuits.

According to IEC 56 International Standard [2], for systems with a voltage less than 100kV, this waveform is adequately represented by an envelope consisting of two line segments, defined by means of two parameters.

Fig. 6 show this representation, and the two parameters are the reference voltage (u_C=TRV peak value, in kV), and the time to reach u_C in microseconds (t3 in the Fig. 6).

In general, this form of representation of the TRV has the objective to control two phenomena:

- The *thermal reignition* in the first μs after the current interruption (between 0 and t_3 in Fig.6)
- The *dielectric reignition,* at a later moment ($t>t_3$).

In the first case is important the slope of the TRV, whereas in the second case its peak value matters.

If one of them happen, it can cause a current interruption fail.

In this manner, the standard specifies limits for the TRV. It is necessary, for the successful opening of the circuit breaker, that in all instants after the interruption of the current the TRV stays bellow this envelope.

According to the rated voltage of the circuit breaker, the standard specified the limits values of u_c and t_3 under different situations, each of them represented by the *Basic Short-circuit Test Duties*.

Nevertheless, because t_3 is of the order of the microseconds, and the transients in analysis are of low frequencies, is then u_C the parameter of interest.

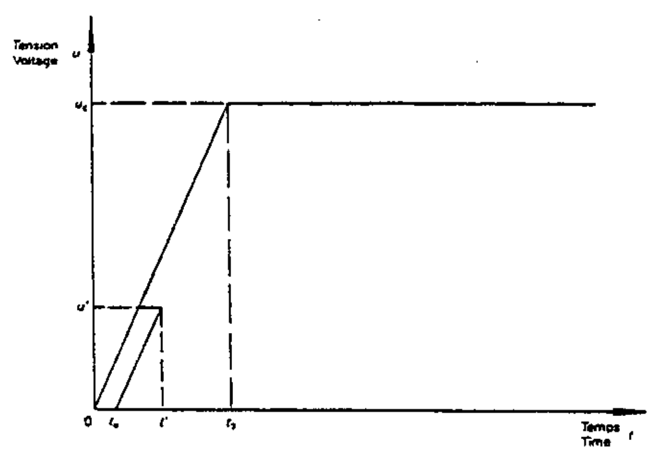

Fig. 6. Two parameters method for TRV.

For a circuit breaker of 24 kV of rated voltage, the standard specifies basically two values of u_C, depending on the relation between the current to be interrupted and the rated short-circuit breaking current. For currents below 60% of the rated short-circuit breaking current is **u_C=44kV**, and for highest currents is **u_C=41kV**.

The IEC standard also contemplates the case when a circuit breaker has an assigned rated out-of-phase breaking current. In this special case, the admissible TRV peak value u_C is 61kV.

Also, where circuit breakers are for use in installation having more severe conditions, the values shall be subject to agreement between manufacturer and user.

B. Simulations of the opening operations of the circuit breaker

The simulations of the switch opening were made in normal conditions and with single-phase fault in a point of the system, in order to verify that the TRV stays within the limits admitted by the standard.

1. Normal opening of the circuit breaker.

The operation criterion is that the filters are always in service, but in certain cases it will be necessary to disconnect them, for example, for maintenance tasks.

Fig.7 shows the TRV waveform in each phase of the circuit breaker, obtained from simulations of this case with the digital model.

The current interrupted is the rated current of the filter system, which is much less than the 60% of the rated short-circuit breaking current, and then it must be considered 44 kV as limit value of u_C.

It is observed in Fig. 7 that this value is not exceeded in any phase, and then this maneuver is not dangerous for the circuit breaker.

2. Open the circuit breaker with a single-phase fault in the system.

As the system is ungrounded, it can continue in service even with a single-phase short circuit in some point of the network, and then the overcurrent relays do not operate as

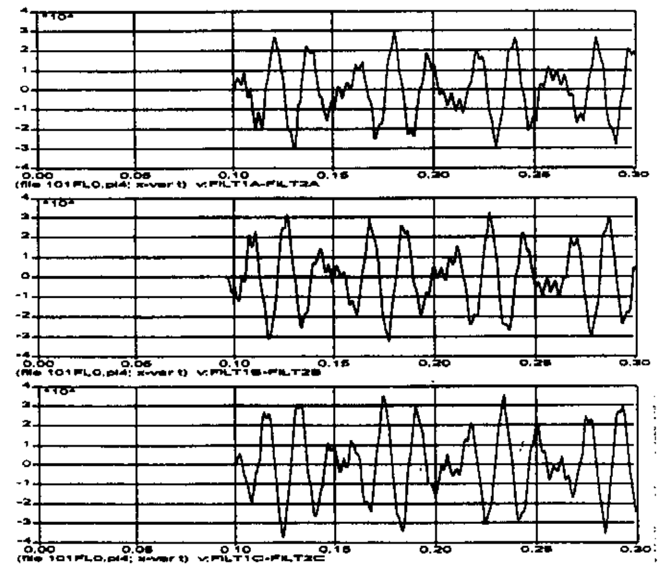

Fig. 7. Waveforms of the TRV in phases A, B and C, for normal opening of the CB.

a result of the fault. In these studies, it is considered that some worker makes this maneuver manually, at a time sufficiently after the occurrence of the fault.

It is to emphasize that, in our case, the probability of single-phase faults is greater than the normally expectable for systems of this voltage level, mainly due to the antiquity of cables installed in the network.

Despite the system is ungrounded, the single-phase short circuit current is not null, being its value practically determined by the capacitance of the extensive cable network.

With respect to the point where the single-phase fault occurs, the possibilities are:

Case 1: the fault is located in some point within the cable network (source side of the circuit breaker), or

Case 2: the fault is located in the filter system.

Fig.8a shows the simulation waveform of the TRV in the phase C for the Case 1, when the fault is applied in the phase A.

This waveform, is the composition of the waveform of the voltages to earth at both sides of the circuit breaker, which are shown in Fig. 8b and 8c.

The TRV peak value is near to 60 kV, which exceeds the limit of 44kV. Even, it approaches the limit value of a circuit breaker that has an assigned rated out-of-phase breaking current, for which the admissible TRV peak value u_C is 61 kV.

It is observed that:

a) The system is ungrounded, and with a capacitive zero sequence impedance, and therefore the voltage in the healthy phases reaches high values.
b) The frequency of free oscillation of the filter system is near the rated frequency, with low damping. There is a progressive displacement between the voltage waveform at both sides of the circuit breaker. The high values of the TRV occur at the moments where these voltages are out-of-phase.

For Case 2 the situation gets worse. The TRV peak value is greater than 61 kV, as it is observed in Fig. 9a.

In this case in addition, when opening the three phases, the system in the source side of the circuit breaker has trapped charge, as it is observed in Fig. 9b. This is because the openings of the last two phases of the circuit breaker are not simultaneous.

The obtained values are slightly variable with diverse factors like the phases opening sequence of the circuit breaker (which is unpredictable), the value of the fault impedance, and the system voltage at the moment of the operation. In general, in all cases the peak values of the TRV are equal or superior to 60 kV.

Then, the opening maneuver of the circuit breaker when a single-phase fault occurs in some points of the system can be dangerous for it, even if it has an assigned rated out-of-phase breaking current.

VII. A PROPOSAL OF SOLUTION.

Without any change in the system, the solution to this problem is, for example, the installation of a circuit breaker of higher nominal voltage, or an agreement between manufacturer and user with respect to the values of the TRV to be supported by the circuit breaker.

As mentioned previously, it is observed that the free oscillation of the filters has an important effect on the value of the TRV because its frequency is near the rated one and there is a progressive displacement between the voltage waveform at both sides of the circuit breaker. Also the ungrounded condition of the system and the trapped charge in the cable system are important factors.

Then another possible solution is the implementation of an artificial neutral system (a reactor with zig-zag connection). The value of the reactor zero sequence impedance (Z_0) can be chosen, so that the voltage frequency oscillations in the source side of the circuit breaker, is approximately equal to the main frequency oscillation of the voltage to ground of the filters, which is near to 71 Hz. This artificial neutral is needed because the 20 kV side of the transformer is in delta connection.

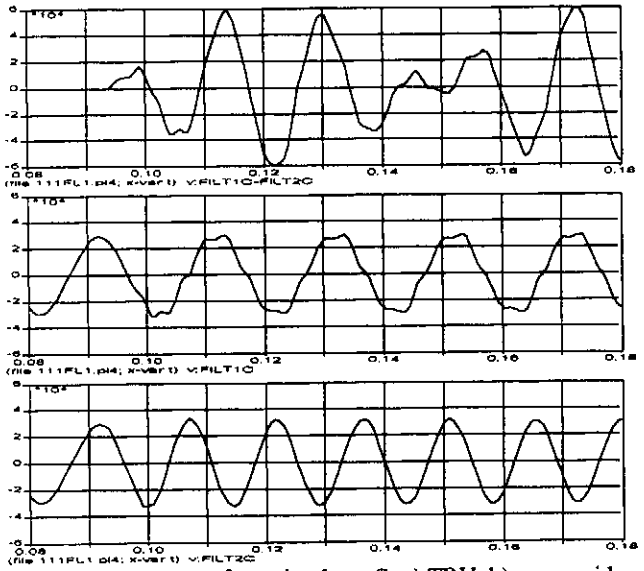

Fig. 8. Case 1: waveforms in phase C, a) TRV, b) source side voltage, c) filter side voltage.

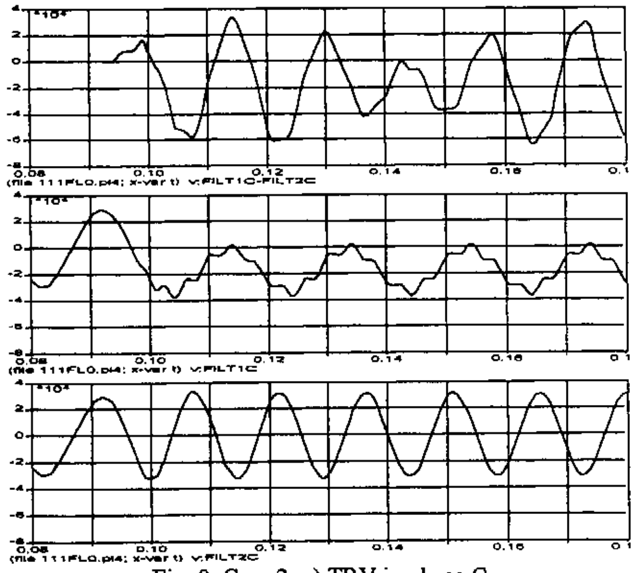

Fig. 9. Case 2: a) TRV in phase C, b) source side voltage, c) filter side voltage

The inclusion of this element has other benefits for the system, because it contributes to reduce the voltage of the healthy phases when a single-phase fault occurs, and also provides a path to ground for the trapping charge of the cables previously mentioned.

Because the total capacitance (C) of the system is approximately 34.8 μF, a simple calculation shows that the value of the Z_0 must be around 45.3 Ω.

It is truth that the value of Z_0 will depend on the amount of 20 kV cables in service. Nevertheless, the field measurement shows that the configuration of the network does not change throughout the day. Therefore it can be assumed that C is constant, and then Z_0 too.

Fig. 10 shows the results of the simulations of the Case 2 with this artificial neutral. Fig. 10a shows the waveform of the TRV in the worst phase, and Figs. 10b and 10c show the waveform of the voltage at source and filter sides of the circuit breaker, respectively.

It can be observed that the peak value of the TRV is less than 40 kV, and then within the limits admitted by the IEC Standard, so this method is an alternative solution to the problem.

VIII. CONCLUSIONS

With the aid of the field measurements, it was possible to construct an acceptable digital model of the system.

The simulations made with this model show situations where the electrical stresses on the circuit breaker exceed the limits admitted by the IEC Standard, with respect to the standard rated value of the TRV.

Then, it is necessary an agreement between manufacturer and user with respect to the circuit breaker characteristics and the model allow obtaining useful information about this subject. At least a circuit breaker with an assigned rated out-of-phase breaking current will be necessary.

Alternatively, the installation of an artificial neutral in the system is effective to limit the value of the TRV within the limits admitted by the IEC Standard which also improves the behavior of the system when single-phase faults occur.

IX. REFERENCIAS

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Appendix I.

Equations and hypothesis to obtain the load equivalent circuit.

In this appendix, the simplified equations of the 6 pulses rectifiers Ref[1] are considered. The theoretical formulations assume perfectly smooth DC current and a

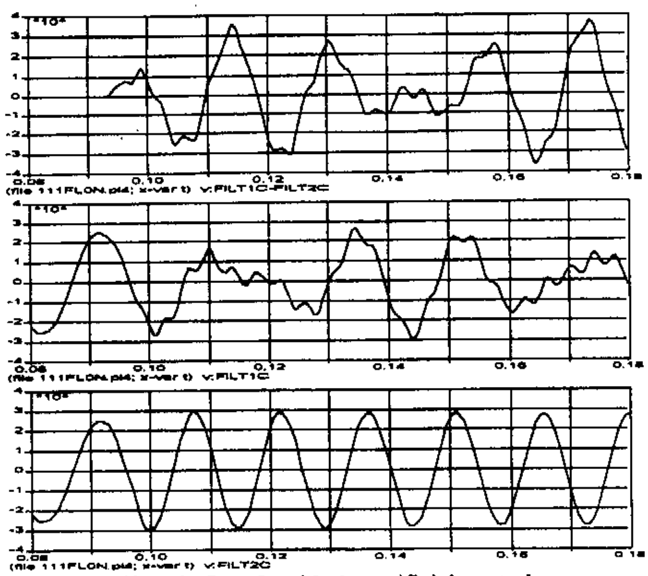

Fig. 10. Case 2, with the artificial neutral.

zero resistance in the AC side, and consider an inductance value in the AC side. These are described as follows:

$$1-\cos(\mu)=x_k \qquad (1)$$
$$x_k = Xk/(Ufase/I)$$

μ : Commutation angle
Xk: short circuit reactance (ω·Lk)
xk: short circuit reactance in per unit.
Uph: phase voltage

$$I= \sqrt{(2/3)}\cdot Icc \qquad (2)$$

I: line current, RMS value
Icc: direct current (DC)

$$P= Icc\cdot Ucc = Icc^2\cdot Rcc \qquad (3)$$

P: active power.
Rcc: load resistance of DC side.

$$Ucc= Uco-(3/\pi)\cdot Icc\cdot Xk \qquad (4)$$

$$Uco= 1.35\cdot Ulef \qquad (5)$$

Ucc: DC voltage
Uco: DC voltage at no load
Ulef: AC line voltage, RMS value

The relation between the harmonic and the fundamental is a function of the commutation angle and may be expressed as:

$$I_i/I_1 = I_{i\,\mu} = 1/i\cdot[\sin(\mu\cdot i/2)]/(\mu\cdot i/2) \qquad (6)$$

i :harmonic number, i = n·6-1, n·6+1, with n =1,2,3..

$$Xk =[xk(1-xk/2)1.35\ Ulef^2]/[\sqrt{2}P] \qquad (7)$$

$$Icc =P/[(1-xk/2)1.35\ Ulef] \qquad (8)$$

The harmonic sources are assumed to generate harmonic currents whose values are determined by the short circuit power (angle of commutation μ with (6)).

The harmonic currents of the rectifier are amplified by the transference of the circuit determined by the source inductance L_{source} and the total capacitance $C=C_{source}+Cc$

$$I_{measured}/I_{load} = T(s) = 1/[1+s^2 \cdot L_{source} \cdot C] \quad (9)$$

$s=2\pi f j$; f: frequency ; $j=\sqrt{-1}$

$$(2 \cdot \pi \cdot fo)^2 = 1/(L_{source} \cdot C) \quad (10)$$

fo: resonance frequency.

$$T(f) = 1/[1-f^2/fo^2] \quad (11)$$

Using the measured data of active power (P) and harmonic distortion (5ta and 7ma), the value of the inductance (Lc) was estimated and the capacitance (Cc) was adjusted to obtain the harmonic currents that were measured. The measured distortion of 5^{th} and 7^{th} harmonics are: i5m = I5/I1, i7m = I7/I1

$$T(250Hz)/T(50Hz) = i_{5m} / I_{5c\,\mu}(\mu) \quad (12)$$

Where i_{5m} and i_{7m}, are the measured distortion of 5^{th} and 7^{th} harmonics, respectively.

$$T(250\,Hz)/T(50Hz) = T_5 \text{ then}$$

$$fo = (T_5 \cdot 250^2 - 50^2)/(T_5 - 1) \quad (13)$$

$$T(350Hz)/T(50Hz) = [1-(50/fo)^2]/[1-(350/fo)^2 \cdot] \quad (14)$$

$$T(350Hz)/T(50Hz) = i_{7m} / I_{7c\,\mu}(\mu) \quad (15)$$

Equations (12), (13), (14) and (15) were calculated with different values of the commutation angle. The solution was obtained when (14) and (15) were equal, then the angle μ, the short circuit reactance ($Xk=\omega Lk$), and fo are known.

$$Lk = L_{source} + Lc \quad (16)$$

$$Lc = Lk - L_{source}. \quad (17)$$

The capacitance value must be similar to the total capacitance calculated previously as $C=Cc+C_{source}$.

$$C = 1/(2 \cdot \pi \cdot fo)^2 / L_{source} \quad (18)$$