Harmonic Distortion Assessment due to Operation of Static Var Compensator at Chorrillos Substation

Evaluación de la Distorsión Armónica debida a la Operación del Compensador Estático de Potencia Reactiva en la Subestación Chorrillos

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Abstract

The Ecuadorian expansion planning program encompasses the new 500 kV transmission system development. A Static Var Compensator (SVC) has been installed at 230 kV level of Chorrillos substation as a fundamental facility of this system. This equipment allows dynamic voltage control at Chorrillos 230 kV busbar using thyristors for current modulation. However, switching operation of these semiconductor devices produces current and voltage waveform distortions.

This research shows the modeling of this SVC, for harmonic assessment in the Ecuadorian transmission system, using the power system simulation software PowerFactory, and determines the effect of the harmonic content on the National Transmission System (SNT) caused by the operation of the equipment under different scenarios.

The results of harmonic level assessment caused by this equipment added to actual harmonic content in the SNT allows to determine if voltage and current harmonic levels are within the limits established in CONELEC 003/08 standard.

Finally, K-Factor and Factor K, needed to quantify harmonic effect due to SVC operation, are analyzed for relevant power transformers.

***Index terms*– Static Var Compensator, Harmonics, FACTS, Power Quality, K-Factor and Factor K in Transformers.**

Resumen

La subestación Chorrillos 500/230 kV, la cual forma parte del plan de expansión del nuevo sistema de 500 kV del Ecuador, incorpora en una de sus bahías un Compensador Estático de Potencia Reactiva (SVC por sus siglas en inglés). Este equipo permite un control de voltaje en la barra de 230 kV de esta subestación a través del uso de tiristores para el control de corriente. Sin embargo, la maniobra de estos dispositivos semiconductores produce distorsiones en la forma de onda de corriente y voltaje.

Por lo antes mencionado, el presente trabajo muestra la modelación del SVC en el programa computacional PowerFactory, y determina, para diferentes escenarios de operación, el efecto del contenido armónico sobre el Sistema Nacional de Transmisión (SNT).

El resultado del efecto armónico provocado por este equipo sumado al contenido armónico preexistente en el SNT permite determinar si los armónicos de voltaje y corriente se encuentran dentro de los límites establecidos en la regulación CONELEC 003/08.

Adicionalmente se analiza el K-Factor y Factor K en los transformadores del SNT, considerando el efecto armónico producido por la operación del SVC.

***Palabras clave*– Compensador Estático de Potencia Reactiva, Armónicos, FACTS, Calidad de Energía, Factor K de transformadores.**

Recibido: 22-06-2017, Aprobado tras revisión: 15-11-2017
Forma sugerida de citación: Jadán, B.; Ordoñez, F.; Vargas, W.; Arcos, H. (2018). "Harmonic Distortion Assessment due to Operation of Static Var Compensator at Chorrillos Transmission Substation". Revista Técnica ***"energía"***. No. 14, Pp. 122-130
ISSN 1390-5074.

1. INTRODUCTION

The Ecuadorian government promotes renewable energy development and displacement of thermal power plants through the incorporation of new hydro power plants, such as Coca Codo Sinclair, Sopladora, Manduriacu, among others. These facilities, labeled as emblematic, will satisfy the increasing electrical demand as well as will allow to exchange energy through international tie lines to Colombia and Perú.

In order to maintain a reliable energy transfer from new power plants to main consumption centers, an extra high voltage transmission system has been built at 500 kV. Due to this new scenario, dynamic reactive power compensation is necessary to fullfil planned and real time operational requirements of the network. For this reason, a Static Var Compensator (SVC), belonging to FACTS family, has been installed to control 230 kV voltage level at Chorrillos substation (Guayas). Expected harmonics generated by operation of thyristor based equipment, which is the case of this SVC, is one of the main concerns of current and voltage distortion in Ecuadorian power system. These waveform variations cause, among other consequences, heating of electrical equipment (capacitors, cables, transformers, motors and generators), in addition to possible misoperation of regulation, control, and protection devices.

Present research is focused on the modeling of an SVC to quantify its harmonic effect on the Ecuadorian transmission system, under different operating scenarios. Final results will be contrasted with the local power quality standard requirements. Thus, section III introduces SVC operation background and modeling for harmonic assessment. Specific SVC modeling at Chorrillos substation is performed in section IV, whereas evaluation of SVC operation is carried out in section V. Finally, section VI covers conclusions and recommendations regarding current and voltage harmonic distortion assessment in the Ecuadorian transmission system.

2. SVC FUNDAMENTALS AND MODELING

An SVC consists mainly of Thyristor Switched Capacitors (TSC) and Thyristor Controlled Reactors (TCR); however, depending on specific performance requirements, it may also contain Mechanically Switched Capacitors bank (MSC) or Reactors bank (MSR). Additionally, it has harmonic filters (FC) and a step up transformer [1].

According to [2], a basic single phase TSC consists of a pair of antiparallel thyristor valves which acts as a bidirectional switch connected in series with a capacitor and a current limiter small reactor (see Fig. 1). In order to reduce switching transients, the thyristor valves are activated when trigger signal is sent, and minimum voltage is detected through the valves. Disconnection operation, on the other hand, is achieved when trigger signal is canceled at current zero through the thyristors. It should be mentioned that, excluding switching transients, current through the TSC is sinusoidal and free from harmonics. In addition, this element does not allow phase control like the TCR.

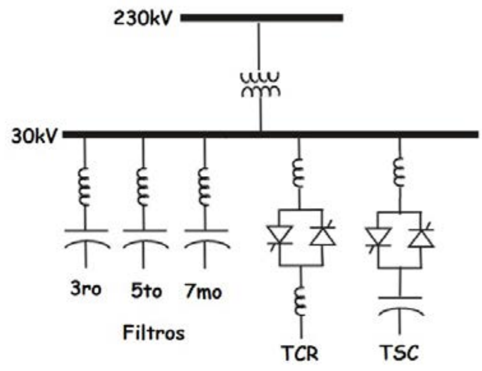
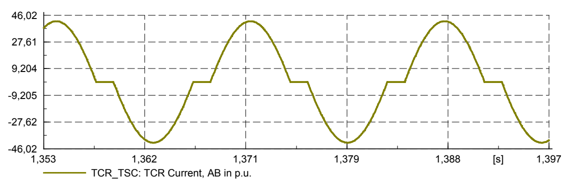


Figure 1: SVC Connection Scheme

A single-phase TCR consists of an air core reactor and a two-way thyristor valve composed of two antiparallel thyristors (see Fig. 1). It uses a firing angle control (α) that regulates the effective value of current that flows through the reactance [3]. The firing angle of the thyristors is measured from the zero crossing of the voltage wave through its terminals. The controllable range of the TCR firing angle goes from 90° to 180°. Thus, α = 90° allows complete thyristor conduction with continuous sinusoidal current flow. On the other hand, for an α = 180°, the current is zero because the firing angle increases, the current decreases and flows as symmetrical discontinuous pulses in the positive and negative half-cycles of the waveform [2]. (See Fig. 2). When α < 90°, DC components are introduced into the current, disturbing the symmetrical operation of the two branches of the antiparallel valves [2].

(a)



(b)

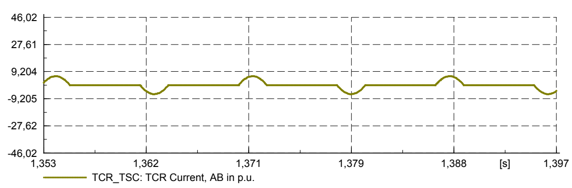


Figure 2: TCR Current. (a) ∝ = 106°, (b) ∝ = 155°

Following [2], total RMS current generated by the TCR is related to firing angle as shown in (1).

$$I_n(\propto) = \frac{V}{\omega L}\frac{4}{\pi}\left(\frac{\sin(\propto)\cos(n\propto) - n\cos(\propto)\sin(n\propto)}{n(n^2-1)}\right) \quad (1)$$

where:

$n = 2k + 1$

$k = 1, 2, 3, \ldots$

Fourier states that a periodic sinusoidal function can be expressed as the sum of sinusoidal functions at frequencies that are multiples of the fundamental frequency. This multiple is known as harmonic. Each harmonic has different effects on electrical networks, so it is necessary to know the magnitude of each harmonic [4]. If both positive and negative half-cycles are identical, Fourier series contains only odd harmonics, which simplifies the evaluation. However, even harmonics usually indicates there is a problem in the network equipment [5]. In addition to harmonics, a distorted waveform may also contain interharmonics, which are those components whose frequencies are not integer multiples of the fundamental frequency. [6]

In this way, it is natural to consider thyristor based equipment as sources of harmonic current. In fact, harmonic current source has become the most commonly used model for representing nonlinear loads. [6]

2.1. SVC Modeling

The complete SVC model is shown in Fig. 3. The Static Var System (SVS) element represents the TCR and TSC. Harmonic filters are modeled through the shunt/filter (RLC) element and the step up transformer is modeled with the transformer element available in the general library.

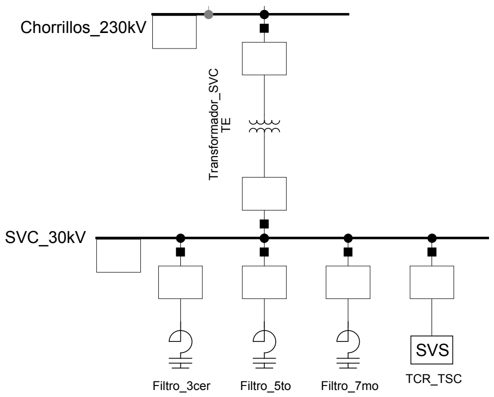


Figure 3: SVC Model Used in PowerFactory

2.2. SVC Operation

The characteristics of the SVC connected in Chorrillos are shown in Table 1, and its connection diagram is shown in Fig.1.

Table 1: SVC Technical Data

Operation Range	Inductive Power [MVAr]	–30
	Capacitive Power [MVAr]	120
Step Up Transformer	Rated Power [MVA]	150
	Rated Frequency [Hz]	60
	Voltage Ratio [kV]	230/30
	Vector Group	YNd1
	Shortcircuit Impedance [%]	12
Dead Band	Vmax [p.u.]	1,05
	Vmin [p.u.]	0,95
TCR	Rated Power [MVAr]	100
TCS	Rated Power [MVAr]	47,7
3rd Harmonic Filter	Rated Power [MVAr]	18,5
5th Harmonic Filter	Rated Power [MVAr]	28,8
7th Harmonic Filter	Rated Power [MVAr]	18,5

SVC's operation is shown in Fig. 4. As long as the SVC output is less than 60 MVAr, the TSC remains off. On the other hand, when reactive power greater than 60 MVAr is required, the TSC turns on immediately and the TCR smoothly regulates the reactive power output. Harmonic filters are always required due to SVC capability and power quality constraints. This operation strategy allows a fast and smooth SVC control, allowing, at the same time, to reduce losses [7].

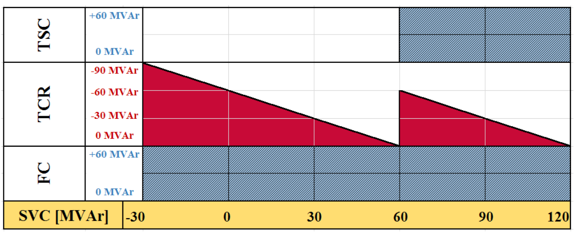


Figure 4: SVC Operation at Chorrillos substation [7]

Considering 500 kV transmission system operation, it is desired to determine the critical point of operation of the SVC. Thus, a N-1 contingency evaluation has been considered for transmission lines close to Chorrillos substation. The main goal of this task was to show how robust, regarding voltage levels, the Ecuadorian power system becomes after operation of the new 500 kV transmission system.

The aforementioned assessment was performed for three different daily demand scenarios of high hydrology (April 2017). In fact, low voltage conditions frequently exist during high hydrology because thermal generation units close Chorrillos substation are out of service. Table 2 summarizes the final contingency evaluation results.

Table 2: N-1 Contingency Evaluation at Chorrillos Substation

HIGH HYDROLOGY						
N-1 Contingency	Chorrillos Substation Voltage					
	3:00 hours		12:00 hours		19:00 hours	
	[kV]	[pu]	[kV]	[pu]	[kV]	[pu]
Operación Normal	232,56	1,011	232,80	1,012	232,63	1,011
Chorrillos - Quevedo [230kV]	231,42	1,006	231,51	1,007	231,59	1,007
Chorrillos - Pascuales [230kV]	232,56	1,011	232,81	1,012	232,62	1,011
Chorrillos - Nueva Prosperina [230kV]	232,58	1,011	232,79	1,012	232,57	1,011
Chorrillos - Esclusas [230kV]	232,31	1,010	232,57	1,011	232,36	1,010
Molino - Pascuales [230kV]	230,33	1,001	230,00	1,000	229,90	0,999
Chorrillos - Tisaleo [500kV]	227,46	0,989	226,29	0,984	226,02	0,983
El Inga - Tisaleo [500kV]	231,90	1,008	231,60	1,007	232,00	1,009

It should be mentioned that the SVC has a dead band voltage of ± 5%, i.e. it will control voltage profile anytime voltage exceeds the upper o lower limit (1.05 pu or 0.95 pu respectively). Thus, and according to results obtained in Table 2, the new system will be robust and voltage at 230 kV Chorrillos busbar will be within the deadband. Operative speaking, this means the SVC will deliver 10 MVAr, which is its default setting for this operation zone.

It is worth to recall harmonic assessment is a steady state issue. That is, normal operation state of the power system is the main time period considered for the present study. Therefore, N-2 contingencies were not included for the assessment due to the fact that dynamic SVC performance is of major relevance during this stage, which is out of the scope of this research, and it seldom occurs.

3. SVC HARMONIC ASSESSMENT

Once the point of operation of SVC has been determined, it is required to obtain the harmonic current content this equipment delivers under this condition. Due to this, an Electromagnetic Transient (EMT) simulation, available in PowerFactory, is performed so that the harmonic current spectrum can be extracted from the current waveforms. For this simulation, a reduced equivalent of Ecuadorian power system is derived in order to avoid initialization issues of generator control systems (Fig. 5), which are no relevant for SVC harmonic evaluation purpose.

The network equivalent is defined by means of positive and zero sequence impedances obtained from shortcircuit calculation at 230 kV level of Chorrillos. Moreover, this network includes a load to simulate the desired reactive power output. In this case, the SVC output should be set to 10 MVAr. Under this condition, the TCR firing angle is equal to 110° and the number of capacitors activated is equal to zero (Fig. 6).

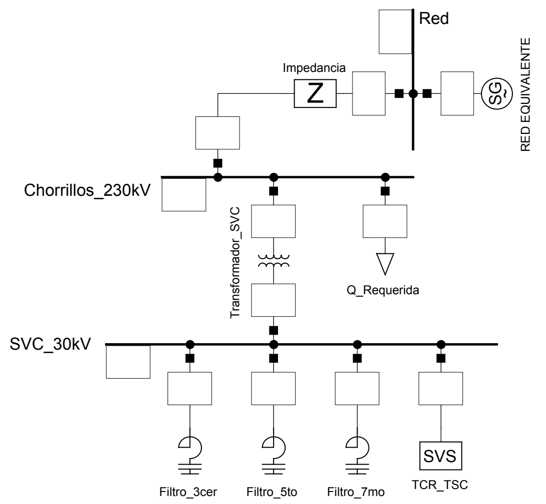


Figure 5: Network Equivalent for EMT Simulation

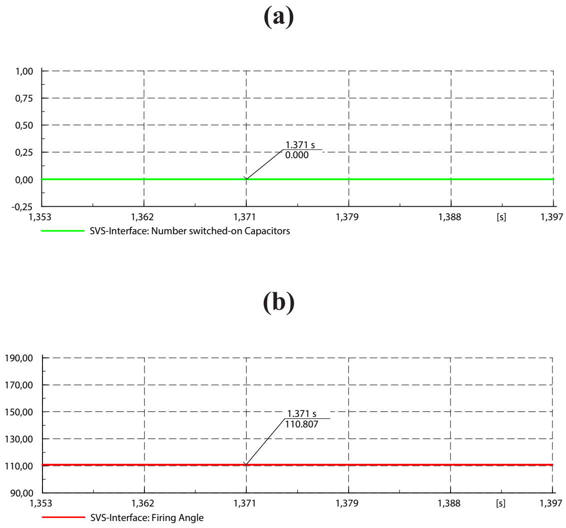


Figure 6: TCR and TSC Control Signals. (a) Active TSC Capacitors, and (b) TCR Firing Angle.

In order to obtain harmonic waveform content, Fast Fourier Transform is performed using PowerFactory element VisFft. The harmonic content is obtained within one cycle up to the 20th harmonic. Higher harmonics are considered neglible in this research.

According to [8], under balanced system conditions, the delta connection of the TCR does not allow triple harmonic currents (3rd, 9th, 15th, ...) to be injected into the network and remain enclosed in delta connection. This effect can be checked by comparing the harmonic content shown in Fig.7 in contrast to Fig. 8.

In order to observe harmonic effects on the SVC step up transformer, the harmonic distortion of current injected at low voltage side of the transformer is obtained (Fig. 9).

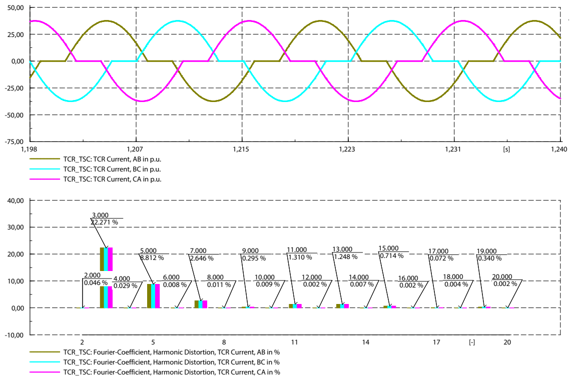


Figure 7: TCR Current within Delta Connection

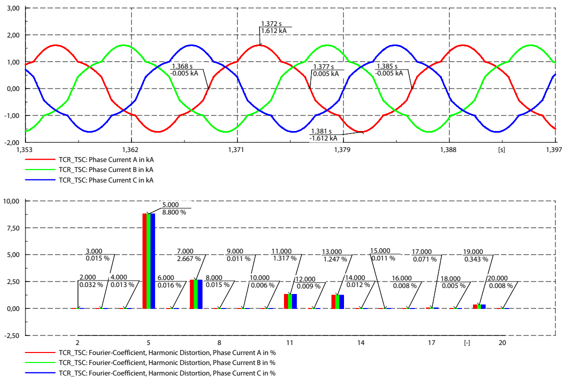


Figure 8: TCR Output Current

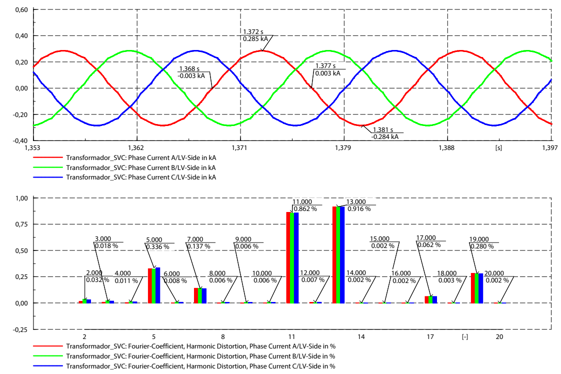


Figure 9: SVC Current at Low Voltage Side of Step Up Transformer

In Fig. 9, it is also observed that harmonics 3rd, 5th and 7th have decreased drastically due to the performance of filters connected at 30 kV of the SVC.

Harmonic sources can be modeled through a current source connected at the measuring point of the system [9]. Thus, the harmonic effect of the SVC is modeled by means of an equivalent current source connected at 30 kV busbar. It is worth mentioning other elements are disconnected so that current injection is considered only once for harmonic load flow (Fig. 10). Furthermore, data gathered from measurement campaigns is incorporated at different points of the system, similar to the SVC modeling previously described.

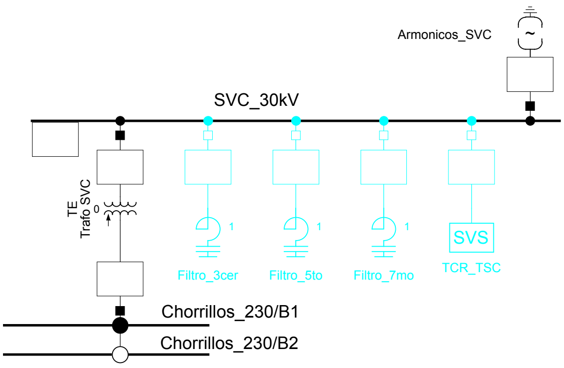


Figure 10: SVC Modeling for Harmonic Load Flow

In order to evaluate the power system model for harmonic distortion, where current sources are included, a harmonic load flow is performed using Power Quality module of PowerFactory. The harmonic load flow calculates voltage and current harmonic distributions based on defined harmonic sources and grid characteristics. The frequency dependent representation of network elements such as lines, cables, three-winding transformers, machines, loads, static filters, among others is also supported within PowerFactory [9].

4. RESULTS

Final results after harmonic load flow are contrasted to determine if voltage and current distortion fulfill Ecuadorian power quality standard [10]. Hence, 230 kV voltage THD, at some transmission substations, are calculated under three different scenarios described next:

- Base Case: Current power system operation and topology.
- Scenario 1: Base case and 500 kV transmission system operation considered.
- Scenario 2: Scenario 1 and SVC operation considered.

The voltage THD results are summarized from Table 3 to Table 5 as follows:

Table 3: Minimum Demand (3:00 hours)

Substation	Voltage [kV]	THDv [%]		
		Base Case	Scenario 1	Scenario 2
Santo Domingo	230	0,526	0,647	0,648
Baba	230	0,752	0,713	0,715
Quevedo	230	0,995	0,785	0,787
Chorrillos	230	0,532	0,656	0,657
Pascuales	230	0,535	0,664	0,665
Esclusas	230	0,671	0,821	0,823
Trinitaria	230	0,631	0,779	0,780
Nueva Prosperina	230	0,559	0,697	0,698
Dos Cerritos	230	0,548	0,685	0,686
Milagro	230	0,786	0,975	0,977
Zhoray	230	0,594	0,666	0,666
Molino	230	0,565	0,617	0,617
Sopladora	230	0,824	0,975	0,976
San Bartolo	230	0,808	0,956	0,957
Riobamba	230	0,723	0,272	0,272
Totoras	230	0,630	0,193	0,193

Table 4: Average Demand (12:00 hours)

Substation	Voltage [kV]	THDv [%]		
		Base Case	Scenario 1	Scenario 2
Santo Domingo	230	0,391	0,444	0,445
Baba	230	0,386	0,456	0,457
Quevedo	230	0,391	0,457	0,458
Chorrillos	230	0,456	0,406	0,407
Pascuales	230	0,465	0,424	0,426
Esclusas	230	0,583	0,617	0,619
Trinitaria	230	0,534	0,563	0,565
Nueva Prosperina	230	0,482	0,467	0,468
Dos Cerritos	230	0,528	0,510	0,512
Milagro	230	0,951	0,990	0,991
Zhoray	230	0,622	0,481	0,480
Molino	230	0,573	0,412	0,412
Sopladora	230	1,048	1,653	1,655
San Bartolo	230	1,029	1,624	1,626
Riobamba	230	0,679	0,413	0,414
Totoras	230	0,556	0,438	0,439

Table 5: Maximum Demand (19:00 hours)

Substation	Voltage [kV]	THDv [%]		
		Base Case	Scenario 1	Scenario 2
Santo Domingo	230	0,350	0,423	0,424
Baba	230	0,360	0,415	0,416
Quevedo	230	0,356	0,403	0,404
Chorrillos	230	0,480	0,422	0,423
Pascuales	230	0,489	0,443	0,444
Esclusas	230	0,562	0,644	0,646
Trinitaria	230	0,520	0,587	0,589
Nueva Prosperina	230	0,477	0,475	0,476
Dos Cerritos	230	0,540	0,510	0,512
Milagro	230	0,862	0,878	0,878
Zhoray	230	0,504	0,394	0,394
Molino	230	0,458	0,336	0,336
Sopladora	230	0,852	1,494	1,496
San Bartolo	230	0,835	1,466	1,468
Riobamba	230	0,438	0,458	0,459
Totoras	230	0,362	0,515	0,516

Reference [10] establishes 1.5 % as THDv limit for 161 kV and higher; therefore, at minimum demand (Table 3), total harmonic voltage distortion is within limit specified by the standard. However, for the other two demands (Table 4 and Table 5), THDv violates and is very close to this limit, respectively.

On the other hand, individual harmonic voltage limit for 161 kV and above is declared to 1%. Thus, for minimum demand, there is not harmonic distortion problems as shown in Fig.11 and Fig.12. Conversely, Fig. 13 and Fig. 14 show limit violations, especially for 7th harmonic, at 230 kV level of Sopladora substation. This problem occurs for maximum and average demand.

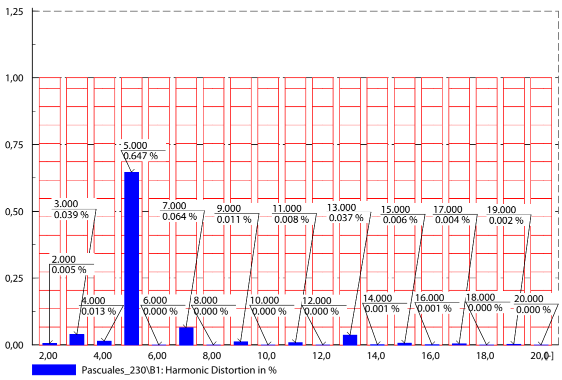


Figure 11: Harmonic Voltage Distortion at 230 kV Pascuales Substation – Minimum Demand, Scenario 2

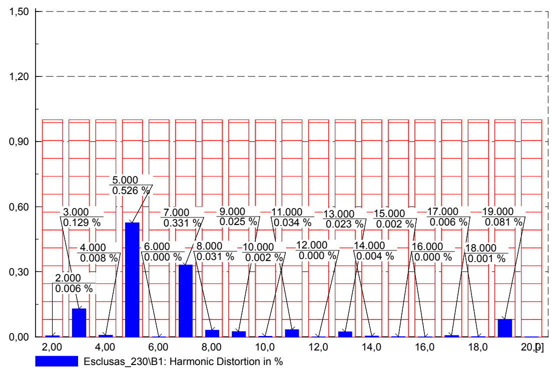


Figure 12: Harmonic Voltage Distortion at 230 kV Esclusas Substation – Maximum Demand, Scenario 2

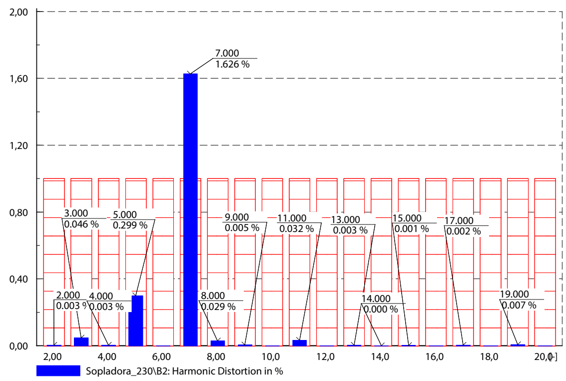


Figure 13: Harmonic Voltage Distortion at 230 kV Sopladora Substation – Average Demand, Scenario 2

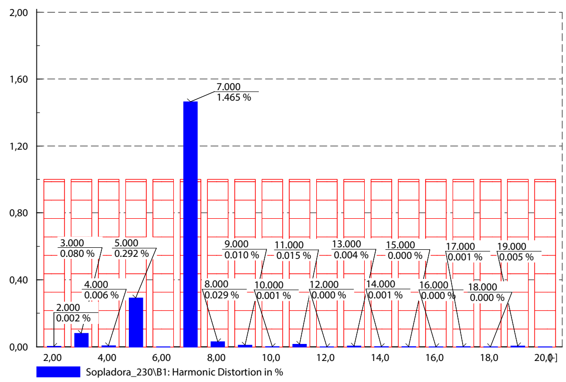


Figure 14: Harmonic Voltage Distortion at 230 kV Sopladora Substation – Maximum Demand, Scenario 2

Regarding to current harmonic content, and based on short-circuit ratio (SCR) at 230 kV Chorrillos substation, SVC fulfills current regulation, as shown in Fig. 15. For the case of average and maximum demand, the limits established for elements close to Sopladora and San Bartolo were also analyzed (Fig. 16). It is clear that no harmonic violation problems are presented.

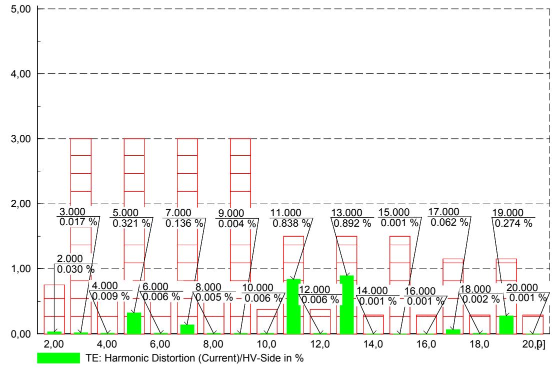


Figure 15: Harmonic Current Distortion at 230 kV SVC – Average Demand, Scenario 2

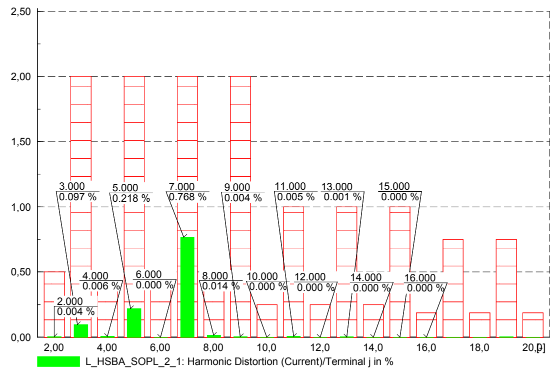


Figure 16: Harmonic Current Distortion at Sopladora – San Bartolo Transmission Line – Maximum Demand, Scenario 2

5. HARMONICS IN TRANSFORMERS

Transformers experience increased losses in the presence of power system harmonic currents. In the worst-case, excessive losses can lead to transformer overheating and subsequent failure.

Losses in transformers are due to stray magnetic losses in the core, and resistive losses due to eddy currents flowing through windings. Among these losses, eddy current losses are of most concern when harmonics are present because they increase approximately with the square of the frequency [11].

The transformer withstanding to handle harmonic loads can be monitored using two indices:

K-Factor

Factor K

K-Factor (According to UL 1562)

Mainly used in the United States to calculate the factor increase in eddy current loss and specify a transformer designed to cope [11]. Following the calculation of the K-Factor, an appropriate harmonic-rated transformer can then be selected which has a higher K-rating. The standard range are 4, 9, 13, 20, 30, 40, 50. K-factor is given by (2).

$$K = \sum_{h=1}^{h_{max}} I_h^2 . h^2 \qquad (2)$$

Where:

I_h is the RMS current at h in per unit of total current.

h is the harmonic order.

Factor K (According to BS 7821)

Mainly used in Europe to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed fundamental design loss [11]. See Equation (3).

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^2 \sum_{n=2}^{n_{max}} \left(n^q \left(\frac{I_n}{I_1}\right)^2\right)\right]^{0.5} \qquad (3)$$

where:

- e is ratio of eddy current loss (60 Hz) to resistive loss.
- n is the harmonic order.
- q is dependent on winding type & frequency, typically 1,5 to 1,7.
- I_n is the magnitude of the h harmonic.
- I is the rms value of the sinusoidal current including all harmonics, and is given by (4).

$$I = \left[\sum_{n=1}^{n_{max}} (I_n)^2\right]^{0.5} \qquad (4)$$

In the present research, a DPL script in PowerFactory has been developed for calculate these parameters and the results are shown in the Table 6.

Table 6: Factor K and K-Factor Results

Transformer	3:00 Hours		12:00 Hours		19:00 Hours	
	Fac K	K-Fac	Fac K	K-Fac	Fac K	K-Fac
	(%)	-	(%)	-	(%)	-
MILA_ATK	99,999	1,000	99,996	1,002	99,997	1,001
DCER_ATK	99,979	1,009	99,968	1,013	99,991	1,004
CHRR_ATJ	99,988	1,006	99,947	1,025	99,966	1,015
TE_SVC	99,956	1,026	99,956	1,026	99,956	1,026
SALI_ATR	99,998	1,001	99,999	1,000	99,999	1,000
CARA_ATQ	99,961	1,016	99,931	1,029	99,923	1,032
ESCL_ATT	99,311	1,318	99,629	1,164	99,659	1,147
MILA_ATU	99,964	1,020	99,978	1,010	99,986	1,006
NPRO_TRK	99,999	1,000	99,826	1,099	99,991	1,005
POLI_ATQ	99,998	1,001	99,999	1,000	99,999	1,000
POSO_ATQ	99,999	1,001	98,730	1,534	99,198	1,332
PASC_ATQ	99,980	1,008	99,977	1,010	99,981	1,008
TRIN_ATT	99,993	1,003	99,994	1,003	99,993	1,003
LOJA_ATQ	99,988	1,005	97,601	2,089	99,972	1,012
SINI_TRK	99,672	1,143	99,990	1,004	99,998	1,001

6. CONCLUSIONS

The robustness of the new 500 kV transmission system, under N-1 contingencies close to Chorrillos substation, allows the SVC to operate within the deadband and deliver 10 MVAr. In this operating condition, the SVC harmonic influence on the Ecuadorian transmission system is minimum. However, the incorporation of the 500 kV system influences the harmonic voltage distortion level and make that 7th harmonic at Sopladora and San Bartolo substations are out of limits established in CONELEC 003/08 standard.

The main SVC element responsible of current distortion waveform is the TCR. The harmonic content of this equipment is related to firing angle of thyristors, which is a variable for reactive power control and system voltage.

During dynamic operation, under contingencies, the SVC operates outside the dead band, but because it is a transient event, it does not produce a significant effect on system harmonic content. For this reason, the quasi-stationary state of the SVC is considered to be the most likely scenario, where harmonic effect is almost permanent.

The analysis of the Factor K of the transformers on the SNT allows to determine that there are no problems of overheating due to the harmonic loads connected under different demand scenarios. On the other hand, the K-Factor study establishes an important specification for the acquisition of new transformers that will be connected in zones of high harmonic contamination.

It is recommended to model and incorporate the harmonic effect of arc furnaces present in the southwestern zone, and, based on these results, to determine if harmonic mitigation methods are needed in the area.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Ecuadorian Electric Corporation, CELEP EP Transelectric.

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