Discrete Model of a TCSC for Automation and Planning Studies of the Electrical Transmission System in Colombia

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Abstract: - This paper presents the development of a discrete Thyristor Controlled Series Capacitor, TCSC, model using the software DIgSILENT PF. The discrete model is based on switchable inductances. The model was inserted in a practical large network of the Electrical Transmission System in Colombia (ETSC) for automation and planning purposes, as much in steady as transient analysis. The results of the studies with the discrete model were very satisfying and allowed to propose further automated solutions to the needs of expanding the ETSC. .

Key-Words: - Automation of high voltage networks, control systems, power electronics, Thyristor controlled series capacitor.

1 Introduction

The development of models for Thyristor Controlled Series Capacitors, TCSC, as for many other FACTS, has been a concern during the last decades for automation of large electrical networks. Models have been implemented using different scopes based either on phasor techniques or transient approaches with excellent results [1,2,3]. The models are developed following a continuous response as the commutation angle of thyristors is activated. In some of the approaches, it has been necessary to simulate the TCSC arranged in a series of multimodules to, e.g., expose fine tuning [3]. Maybe the reasons are a better cost-benefit situation. The multimodule idea led our research to think that it could be possible to develop a reliable discrete model of a TCSC based on the series inductors switched by breakers on a steady state scope, see Fig. 1.

In Fig. 1, Xcsv represents the lumped series capacitor of a TCSC, TCRi are the series inductors whereas CBi are the breakers.

In this paper, it will be explained the functioning, setting and performance of the TCSC discrete model and its general implementation in DiSILENT PF [4]. The model is required to be used in power flow and transient stability simulations.

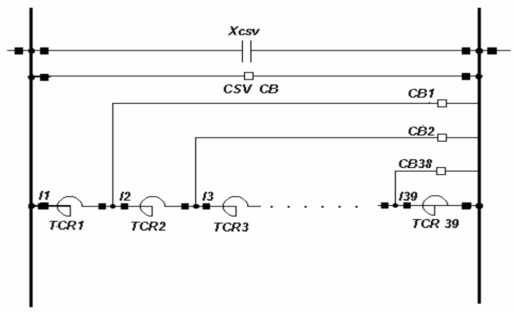

Figure 1. TCSC discrete model

The final target with such a discrete model was its use in planning studies of large transmission networks. The model was successfully applied in Colombian transmission studies and compared against conventional proposals [5], showing in addition, the increased advantages of the TCSC for reinforcing the Electrical Transmission System of Colombia (ETSC) in the levels of 230 and 500 kV.

2 Model implementation with Digsilent PF Software

DIgSILENT PF has a Digital Simulation Llanguage (DSL), which allows implementing and creating a wide variety of blocks and special functions (e.g., controllers, regulators). For this work, the TCSC model was implemented using DSL.

This section is intended to explain the elements that compose the TCSC model for the Power Control Model of a TCSC [1]. It is important to remind, that the model will be applied in electric planning studies of power flow and transient stability.

2.1 Requirement for load-flow studies

In load-flow studies, only the static impedance of a TCSC is considered, in our case the device is modeled as a variable reactance in the system and set to reach a value defined by its control system (within a range) to satisfy some specific conditions.

2.2 Internal and External control for a TCSC model

The TCSC control system is divided in two parts; Internal and External Control. The External Control is in charge of keeping the system variables (rms values) in the predetermined values. This is achieved controlling the effective reactance of the TCSC. On the other hand, the internal control has the function to keep adequately all the elements that compose the power circuit to produce the compensation required, depending of the order sent from the external control.

2.3 Model for steady state stability analysis

A stability Program has the property of analyzing dynamic conditions of a power system during a time interval. This is why the variation of the net reactance of TCSC must be done in a dynamic way, so the device can be incorporated in this type of simulation. To achieve this, the model must be in conditions of modifying the net impedance in the line where the TCSC would be located.

The External Control associated to this type of command could change according to the application.

The Power Flow Control is the main component and its function is to maintain the power in a predefined value by a reference signal (Pref) comparing it continuously against the power of the line (Pmed), see Fig. 2. The error signal is then introduced into a controller that provides an impedance value that must be compensated, in such a way that the device can bring the transmitted power to the value Pref.

It is important to take into account that the control circuit will modify the net impedance of the line. That is to say, how the section of the model that connects the line and the control circuit is going to be represented. It is also remarkable, that in the complete work, it was always searched for the variation of the impedance through an inductive reactance in parallel with a series capacitor, since it is a simple way to initiate the modeling process.

2.4 Controller implemented for stability studies

For the features of DSL models in DIgSILENT, the TCSC model developed is able to satisfactorily operate under transient stability conditions, the compliance is shown further in this paper.

3 General description of the controller

In a typical controller for a TCSC, the reactance value that must be compensated is transformed in triggering pulses to the thyristor valves that are connected in series with the inductive reactance. The present model is achieved without the use of thyristors, developing algebraic relations for a net impedance of TCSC as a function of a fixed capacitor in parallel with switched inductances.

In Fig. 1, a variable reactance is achieved by the operation of breakers CB1, CB2, CB3. It can be seen that closing CB1, the reactance is given by the value XTCR1, but if CB2 is closed and CB1 is opened, then the inductive reactance would be given by XTCR1 and XTCR2. Therefore, it can be observed that a series variable reactance is achieved by breakers array.

In the block diagram of Figure 2, the active power that flows through the line is the input signal. This signal is taken since it is the desired controlled variable. This signal goes to the normalizer block, which has the function of per-unitizing the power taken by the measurement circuit. This step is done having as base (S base) the power transmitted at the first instant of the simulation (T= 0 s).

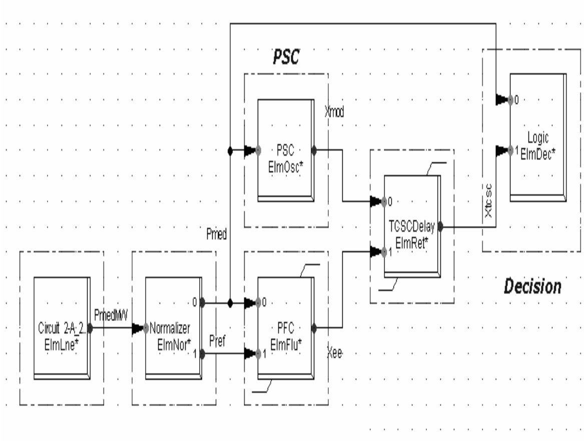

Figure2. TCSC model in DIgSILENT environment block diagram

The block also has a first order function that has the objective of simulating the delay of measurement devices in data collection. Also, this block is where the reference power (Pref) is introduced, which is part of the signals at the normalizer output.

The signs Pref p.u. and Pmed p.u. are processed to a main control (Power Flow Control). This controller has the function of adjusting the order reactance of the TCSC in a way that the measured power approximates to the sign previously established by the reference.

After the Power sign is processed by the line, it is compared against the rule, generating an error sign that goes into the controller, so it can generate an action on the variable reactance based on such signal, in order to keep the active power transmission constant.

For this case, the power flow control is composed of a PI controller, since it makes the steady state error tend to cero. The control that has been used is discrete, therefore it is necessary to add a block that has the function of submitting a zero value; while the control is inside a tolerance band, the tolerance is given by the maximum power change the device can achieve due to the reactors commutation. The function (block) previously mentioned, is known as Dead Band Block and is implemented so the control does not loose the reference because of the continuous time integration of a constant error.

The reactance signal goes in a delay and limiter block. All this delays must be compensated by the power circuit, coming from the PI control. In this block, the operative limits are applicated close to the reactance that the device would be able to supply.

The other variables that compose the block diagram of Fig. 2 are the following:

Xee (Reactance order to be compensated for keeping the power flow constant).

Xmod (Reactance to mitigate power oscillations; in this case will be disabled, i.e., a Power Swing Controller PSC is off).

Parameter TTCSC (Time constant associated to the delay to conduct the operation in the TCSC).

Output signals: (XTCSC: total value of the reactance that should be compensated for achieving the control requirements).

Limits: The operation range of the TCSC is determined by a maximum and a minimum limit, those are XTCSC _max and XTCSC _min respectively.

When the control knows already which reactance must be compensated, this signal enters the decision block, whose function is to know what breakers must be switched in order to obtain the reactance value required by the control circuit. This part is composed of three internal blocks that have been designed with the purpose of isolating the inductive and capacitive regions of a TCSC. By doing this, it can be achieved that if the system requires a power flow increase through the line where the FACTS device is located, then the decision blocks created by the capacitive region will work. On the opposite, if the system needs to decrease the transmission bulk power, then the block designed for the inductive region will operate. This is shown by means of Table I and II.

The connection between the last block of the control process and the power system is done through events in DIgSILENT PF. That would be equivalent to simply switch the breakers to achieve a predefined rule. This is a reason why this block does not have an output signal. There is a block connected to this whole diagram with the purpose of decreasing power oscillations (Power Swing Controller, PSC block), but it is important to take into account that, although this block is implemented, it is not studied in this paper.

All the blocks previously mentioned are connected with an object known in DIgSILENT PF as Composite Frame, which has the capacity of interconnecting all the signals belonging to the modeled system.

To guarantee a good performance of the whole model, it is necessary for the model to be in the power system. To accomplish this, the object Composite Model of DIgSILENT PF must be used, the latter has the function of interpreting all the information.

4 Studied case

The design and simulation of a TCSC for planning purposes in the Colombian Transmission System, ETSC is achieved. On the first stage, a proper tuning of the model is obtained with a reduced portion in the Colombian networks composed of four generators, fifteen buses and lumped loads, see Fig. 3. The transmission line named Circo - Paraiso at 220kV and 50 km is considered as the case of important concern of branch participation, to i.e., analyze the effects of including a TCSC .

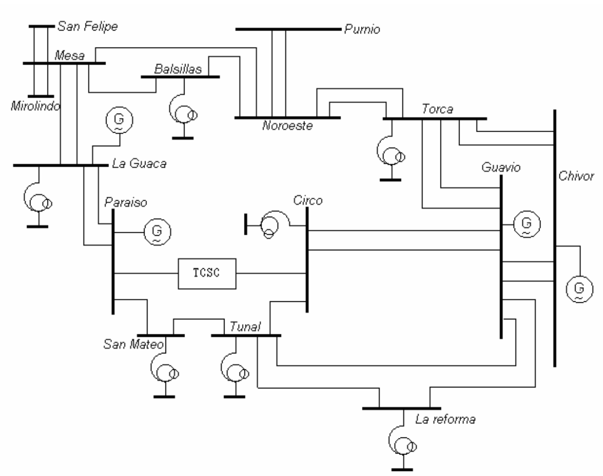

Figure3. Simplified transmission network for tuning of the TCSC discrete model

For this line we have a reactance of Xline= 24.0391Ω. The compensation proposed is: 20% variable and 40% fixed, and with the following targets of regimen compensation:

XTCR = 0 to 4,807802 for inductive zone
XTCR = 4,807802 till 9,615604 for capacitive zone.

Using ten reactance steps for each region, and the developed function relating net equivalents between capacitor and switched inductors, analytical expressions for each zone can be generated via polynomial tendency. In our case, each step will have a 0,4807 value (XTCR) in reactance and the reactor value to be simulated accumulates in the same quantity. See XTCR projected values in Tables 1.0 y 1.1.

Table 1. Inductive model region

INDUCTIVE

Transmission Line				TCR	X_TCR
P_line		Q	Load		Ω
MW	p.u	Mvar	%		
43,60	1,000	45,03	17,98	capacitor	open
38,92	0,893	38,62	15,86	Bypass	0,00000
38,46	0,882	38,02	15,65	0,1Xcsv	0,481
37,90	0,869	37,29	15,40	0,2Xcsv	0,962
37,20	0,853	36,39	15,10	0,3Xcsv	1,442
36,31	0,833	35,25	14,71	0,4Xcsv	1,923
35,12	0,806	33,78	14,20	0,5Xcsv	2,404
33,48	0,768	31,78	13,50	0,6Xcsv	2,885
31,06	0,712	28,92	12,48	0,7Xcsv	3,365
27,13	0,622	24,49	10,87	0,8Xcsv	3,846
19,63	0,450	16,75	7,92	0,9Xcsv	4,327
0,00	0,000	0,00	1,13	Xcsv	4,808

Table 2. Capacitive model region

CAPACITIVE

Transmission Line				TCR	X_TCR
P_line		Q	Load		)
MW	p.u	Mvar	%		
43.60	1.000	45.03	17.98	Capacitor	Open
38.92	0.893	38.62	15.86	Bypass	0.00000
89.26	2.047	207.85	59.14	1,2Xcsv	5.769
70.70	1.622	97.47	33.18	1,3Xcsv	6.250
61.62	1.413	75.94	27.31	1,4Xcsv	6.731
57.03	1.308	66.91	24.71	1,5Xcsv	7.212
54.29	1.245	61.96	23.24	1,6Xcsv	7.692
52.48	1.204	58.83	22.30	1,7Xcsv	8.173
51.19	1.174	21.65	21.65	1,8Xcsv	8.654
50.23	1.152	55.10	21.16	1,9Xcsv	9.135
49.48	1.135	53.90	20.79	2Xcsv	9.616
47.36	1.086	50.59	19.76	2,5Xcsv	12.020
46.36	1.063	49.08	19.28	3Xcsv	14.423
45.40	1.041	47.66	18.82	4Xcsv	19.231
44.94	1.031	46.97	18.60	5Xcsv	24.039
44.18	1.013	45.88	18.25	10Xcsv	48.078

Now, through successive load flow simulations, the power P_line in the latter tables can be calculated when the XTCR estimates are increased from XTCR, 2XTCR, 3XTCR to 10XTCR for inductive region; and from1,2XCSV to 2XCSV for the capacitive region. This is accomplished in the TCR Grid (Thyristor Controlled Reactor in Fig. 1) closing the breaker I1 while breaker CB1 is closed, for each reactor a value is selected accordingly. In the same way the power is calculated completing the column in tables 1 and 2 (Pline in MW and p.u.).

It is important to remind again, that the base power is assumed by the model as the power in MW that the line transmits with only the variable capacitor introduced and probably a fixed capacitor in series with the transmission line. In the present simulation, the base power is 43,60 MW. This power must be obtained leaving the reactors breaker open (named I1) in the TCR Grid of Fig. 1.

To obtain the power that the line transmits if the TCSC were out of service in Bypass, it is proceeded to close the total breaker CSV CB in the TCR Grid of Fig.1. For this case, it was obtained a power flow of 38,92 MW (0,89266 p.u = 38,92/43,60). Done this measurement, the breaker CSV CB is opened again.

The Figures 4 and 5 will allow to generate a polynomial equation for the Pline =f (XTCR). To achieve this, a mathematical tool is employed, using 6th grade polynomial fitting. In Figures 4 and 5 the equations generated in each region and the high grade of correlation R2 obtained with the 6th grade polynomial are shown.

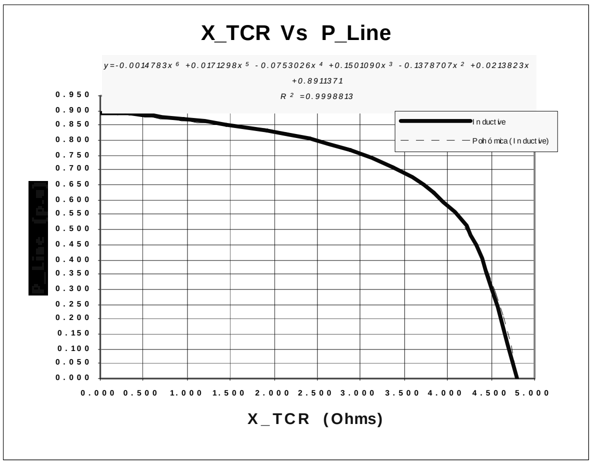

Figure 4. Fitted characteristic for inductive region of the TCSC

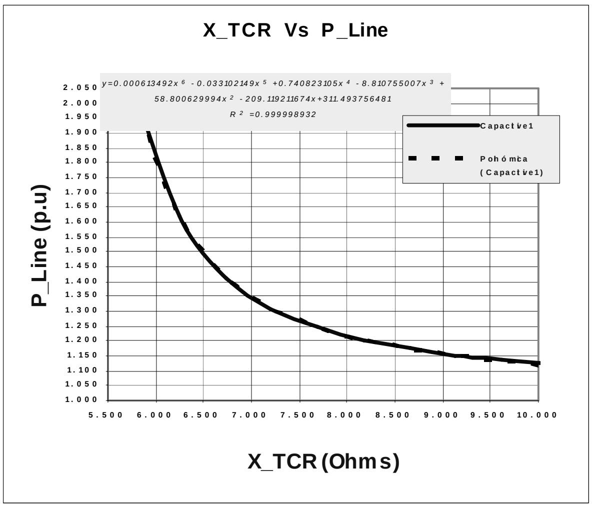

Figure 5 Fitted characteristic for capacitive region of the TCSC

Based on the polynomial approach and several tuning simulations, the discrete model is built up of 19 reactors (XTCR) fitted for the inductive region and 20 reactors fitted for the capacitive region. The idea is to divide power range for each zone between the number of reactors available (19 and 20) in order to obtain a constant power differential that will be substracted from the Pline column (Tables 3 and 4).

Table 3. Inductive fitted region

INDUCTIVE

	P_line	Limits		X_TCR series	X_TCR
	p.u	Upper	Lower	□/λ	□/λ
Bypass	0.893	1.000	0.869	0.00000	0.00000
TCR1	0.846	0.869	0.822	1.68436	1.68436
TCR2	0.799	0.822	0.775	2.49980	0.81544
TCR3	0.752	0.775	0.728	3.00805	0.50825
TCR4	0.705	0.728	0.681	3.40889	0.40084
TCR5	0.658	0.681	0.634	3.70322	0.29433
TCR6	0.611	0.634	0.587	3.91134	0.20812
TCR7	0.564	0.587	0.540	4.06487	0.15353
TCR8	0.517	0.540	0.493	4.18462	0.11975
TCR9	0.470	0.493	0.446	4.28226	0.09764
TCR10	0.423	0.446	0.399	4.36460	0.08234
TCR11	0.376	0.399	0.352	4.43581	0.07121
TCR12	0.329	0.352	0.305	4.49859	0.06278
TCR13	0.282	0.305	0.258	4.55474	0.05615
TCR14	0.235	0.258	0.211	4.60559	0.05085
TCR15	0.188	0.211	0.164	4.65208	0.04649
TCR16	0.141	0.164	0.117	4.69494	0.04286
TCR17	0.094	0.117	0.070	4.73472	0.03978
TCR18	0.047	0.070	0.023	4.77184	0.03712
TCR19	0.000	0.023	0.000	4.80780	0.03596

Table 4. Capacitive fitted region

CAPACITIVE

	P_line	Limits		X_TCR series	X_TCR
	p.u	Upper	Lower	□/λ	□/λ
TCR20	2.047	2.047	2.002	5.76937	0.96157
TCR21	1.956	2.002	1.933	5.84739	0.07802
TCR22	1.910	1.933	1.888	5.89003	0.04264
TCR23	1.865	1.888	1.842	5.93552	0.04549
TCR24	1.819	1.842	1.796	5.98430	0.04878
TCR25	1.774	1.796	1.751	6.03691	0.05261
TCR26	1.728	1.751	1.705	6.09401	0.05710
TCR27	1.682	1.705	1.659	6.15646	0.06245
TCR28	1.637	1.659	1.614	6.22538	0.06892
TCR29	1.591	1.614	1.568	6.30228	0.07690
TCR30	1.545	1.568	1.523	6.38927	0.08699
TCR31	1.500	1.523	1.477	6.48928	0.10001
TCR32	1.454	1.477	1.431	6.60670	0.11742
TCR33	1.409	1.431	1.386	6.74822	0.14152
TCR34	1.363	1.386	1.340	6.92456	0.17634
TCR35	1.317	1.340	1.295	7.15319	0.22863
TCR36	1.272	1.295	1.249	7.46223	0.30904
TCR37	1.226	1.249	1.203	7.89461	0.43238
TCR38	1.180	1.203	1.158	8.53341	0.63880
TCR39	1.135	1.158	1.135	9.61361	1.08020

In this way, 39 power values are generated and this is now shown in the P_line column of Tables

3 and 4. With each of these powers, the respective reactance value is obtained (column X_ TCR series in the tables) that would force the line to demand such power. For example, for the inductive zone, the expression 0.89266/19= 0.04698 allows to obtain the power differential in p.u. wich will be substracted successively, and for each power value exists a reactance obtained solving the 6th grade polynomials (the X_TCR series column values are determined in both tables). In Tables 3 and 4, a second column named X_TCR presents the equivalent differential steps that must be introduced for the reactances.

With the objective of achieving a discrete control due to the TCSC implementation with variable differential reactors, the desired power through the line in p.u. will be within upper and lower limits as shown in the respective columns. To such limit will correspond a unique discrete value identified in the P_line column. For example, if the desired power is 60 MW, being 43,60MW the base power, the value will be 1,37614 p.u. corresponding to P_line=1,36296 p.u. The model will select to switch the TCR Grid breakers needed to include 34 reactors in series accumulating a value of 6,92456 (X_TCR series column)obtaining the desired power.

In order to accomplish the objective, the limits in Tables 3 and 4 must be introduced in the logic decision for each reactor (variables TCR0 to TCR39).

To execute the study case the user should modify the reference power (Pref MW), run power flow study to get initial conditions and then start a time domain simulation. To show convergence and behavior of the shown in Fig. 3 for a TCSC between Paraiso – Circo 230 kV line, Fig. 6 is for the capacitive response of TCSC when the desired power to be transmitted is increased from the base power value. The delay of the response was exaggerated on purpose, tuning accordingly the time and proportional constants of the PI control, so as to show discrete response steps and stabilization – convergence of the studied case.

The next step was to incorporate the TCSC in the Electrical Transmission System of Colombia, ETSC, at 230 – 500 kV. The used network also included some 110 – 44 kV sub-networks. The total amount of buses in which the developed TCSC discrete model was inserted exceeded 1500.

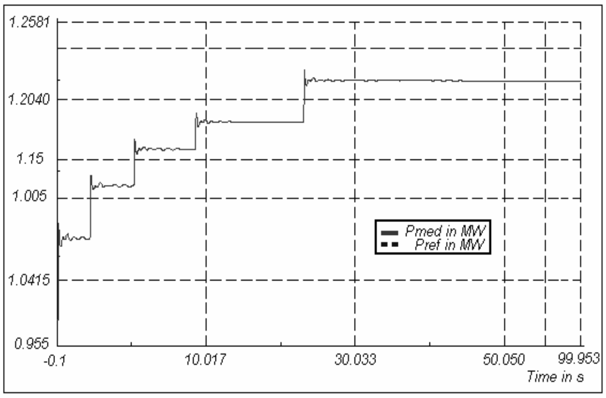

Figure 6. Response of the digital model f the TCSC in capacitive zone for the power flor control mode.

According with the expectations for the transmission networks reinforcements of the Colombia National Entity UPME, the main application for which the TCSC was simulated in the ETSC was for the Power Flow Control function. In this function, the line having the TCSC, forces the power flow to keep a reference. This allows other lines to have an adequate load transfer, avoiding overload conditions limiting the transfer capacity in certain regions of the ETSC, a main bottle-neck in some cases.

According to the expected needs established by UPME in [5], a large 500 kV new network has to be built around 2007. The intention is to eliminate or decrease the restrictions of the region called Oriental in Fig 7. A main restriction is that under certain load conditions and topologies, the transmission lines Purnio – Noroeste (Fig.7) are overloaded, decreasing the possibilities of a power transit towards Oriental region, and so more power has to be generated inside this region allowing some generator utilities increase their energy costs. According to Table 5, with the 500 kV system alternative: El Sol – Primavera – Ocaña – Copey – Ternera, the lines Purnio – Noroeste are discharged in 133.84 MW. Instead of the last alternative, and after installing the TCSC in several places, it was found very advantageous to propose a new line Primavera – Noroeste with an Hybrid TCSC (composed of fixed and variable reactance) regulating the power through the line at 600 MW, see Fig. 8. According to Table 5, with this alternative the lines Purnio – Noroeste are discharged in 149.36 MW; more than the value reached with the 500 kV alternative. In the Base Case, without any new alternative, the lines Purnio Noroeste are at 84.4% of their load capacity.

Table 5. Electrical results according to conventional and FACTS alternatives

Case/Alternative	Total charge in Purnio-Noroeste lines [MW]	Load Capacity [%]
Base	298.68	84.4
500 kV	231.76	65.5
Hybrid TCSC	224	63.3

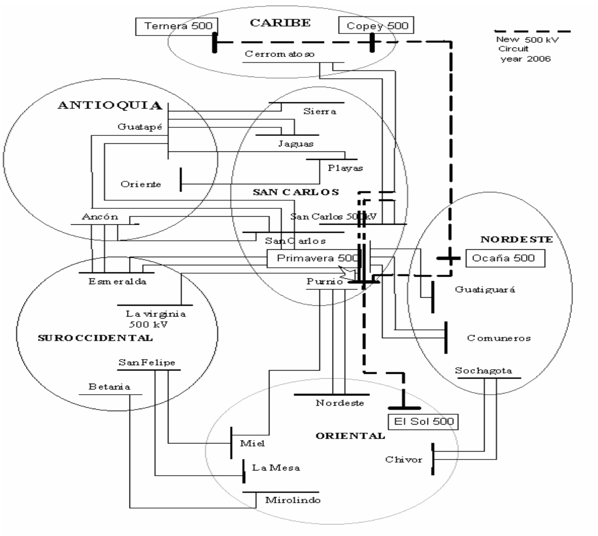

Fig. 7. Equivalent of the ETSC showing interconnection between Regions and proposed 500 kV expansion.

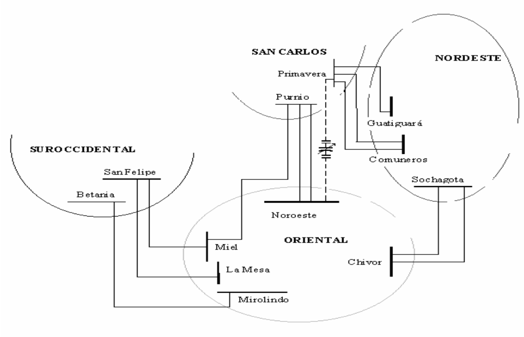

Fig. 8. Proposed TCSC alternative

With the TCSC solution, the power transit can be fixed at 600 MW through the mentioned line. In case of a strong system dynamic contingency, i.e. the opening of one of the lines Purnio - Noroeste, it must be expected little consequences through the controlled line. The Fig. 9. shows the Power reference of 600 MW as a percentage value per unit as the horizontal line. It can be seen that the contingency indicated occurring at 5 s and removed at 30 s, does not de-stabilize the reference wanted around 600 MW. This also contributes in showing good performance of the TCSC discrete model developed and its application to dynamic and transient studies.

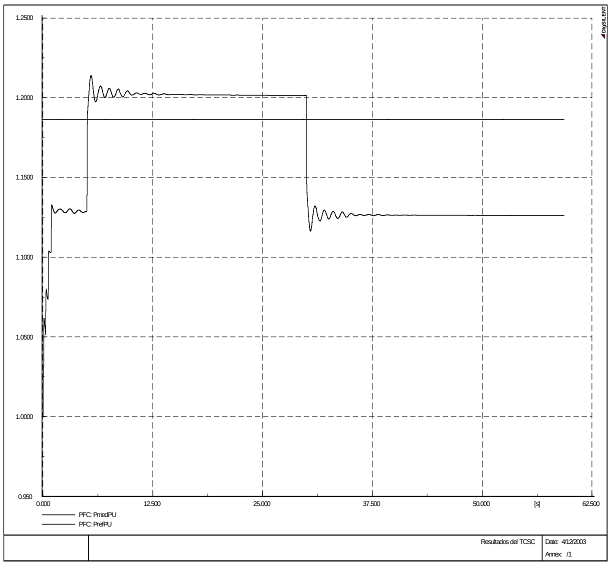

Fig. 9. Dynamical behavior of the TCSC when one of the lines Purnio – Noroeste is abruptly opened.

It is necessary to leave clear that the final decision to define the installation of the TCSC instead of conventional infra-structures, depends on the economical studios, in which it is also taken into account some other factors like the main intention of certain Project [6]. The aim of this work, is just to give ideas to the expansion studies entities, of how could impact the ETSC an automation solution like TCSC.

5 Conclusion

The TCSC discrete model developed is a proper alternative tool for the electrical planning study in large electrical networks. For special reasons of available software or type of licenses, sometimes there could be constraints or lack of compatibility to model specific power electronic devices. The discrete commutation of inductances can fulfill the needs to reach the goal of implementing

FACTS solutions as for steady-state as for dynamic and transient studies.

As a second main objective of this work, the discrete model was employed as the tool to study the impact of recent automation solutions for the Colombian Electric Transmission System (230 and 500 kV). The study was achieved so using discrete control and analysis of the responses of the system with and without automated solutions. The results with the TCSC are very good and from the technical point of view, they provide interesting advantages and challenges for the future of the Colombian Transmission Network.

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