Performance of Static Var Compensators in Degradated Transmission System Conditions: Dynamic Studies Versus Electromagnetic Transient Studies

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Abstract -. **The operation of Static Var Compensators – (SVC) in weak systems demands a careful analysis of their control stability with appropriated models and simulation tools. This paper analyzes the stability of a SVC connected to a regional system, part of the interconnected North - Northeast Brazilian system, where even operating with reasonable stability margins in normal conditions, it has been verified the real possibility of dangerous unstable conditions during temporary system switching procedures, when the Effective Short Circuit Ratio (ESCR) becomes excessively low.**

The use of modern adaptive control strategies, able to detecting and avoiding on real time such conditions, is suggested for these situations, due the difficulties of the system operational planner to predict all possible abnormal and emergency operational conditions. Also, the employment of control gains to assure the stability for all expected conditions seems to be not suitable since it will restrict severely the SVC performance for normal conditions.

Keywords: Static Compensator, Radial Transmission System, Oscillations, Control System, Stability, Transient.

I. INTRODUCTION

The use of static var compensators (SVC) represents an effective way to improve power quality levels, as they provide a fast voltage control during system transients through continuos injection of reactive power [1]. To improve voltage control, two SVC were installed at Fortaleza and Milagres substations at years 80. Both substations are situated in CHESF North transmission system, which has radial characteristics (Fig. 1), and is composed by 800km of 230kV transmission lines, connecting the generation center of Paulo Afonso to Fortaleza city, that has about two millions of inhabitants. During the outage of Fortaleza 230kV busbar, it was verified the possibility of supplying part of 69kV Fortaleza load through CHESF West transmission system, composed by Sobral II, Piripiri and Teresina substations and Boa Esperança hydro plant, as marked in Fig. 1. This configuration is characterized by low short-circuit power levels at 230kV Fortaleza busbar, where is connected the SVC and a lightly loaded transmission system, increasing the difficulty of performing voltage control. In a situation like that, it is very important to have Fortaleza SVC operating in automatic mode, considering the powerful voltage control features offered by this equipment. To verify if it is possibly to have Fortaleza SVC operating in automatic mode on the degradated transmission system configuration here referred, there were performed the dynamic and electromagnetic transient studies described in this paper.

Fortaleza SVC has two capacitor banks and two thyristor controlled reactors, that together with a step-down transformer, compose a twelve pulse system, dimensioned so that it can supply to the transmission system busbar a range value of reactive power comprehended, respectively, from 200Mvar capacitive to 140Mvar inductive.

Fig. 2 presents a simplified one-line diagram of Fortaleza SVC and Fig. 1 shows its position in the electrical network.

II. GENERAL COMMENTS

A SVC model for ATP (Alternative Transient Program), with detailed modeling of its control system by means of TACS (Transient Analysis of Control Systems) subroutine was developed for Fortaleza and Milagres SVC. The results obtained were compared with simulations performed in TNA (Transient Network Analyzer), where a replica of actual SVC control system was used [1]. This confirmed the viability of using digital simulations to perform transient studies involving SVC, as is the case of CHESF North subsystem, with lower costs and higher flexibility than those associated with a TNA study. On the other hand, the peculiar behavior of Fortaleza busbar voltage, that takes few seconds to recover after fault clearing, suggests an important presence of dynamically active loads on that substation, which must be appropriately modeled. Induction motor model, through type 3 "Universal Machine" model of ATP, was used for this purpose during transient studies [3].

First, there were performed studies using stability programs, where the electric network is represented as a phasor approach and the SVC is modeled by an equivalent variable admittance. The results did not present any instability problem, even in such degradated network conditions.

To check these results, it was decided to perform ATP simulations using detailed models of all elements involved.

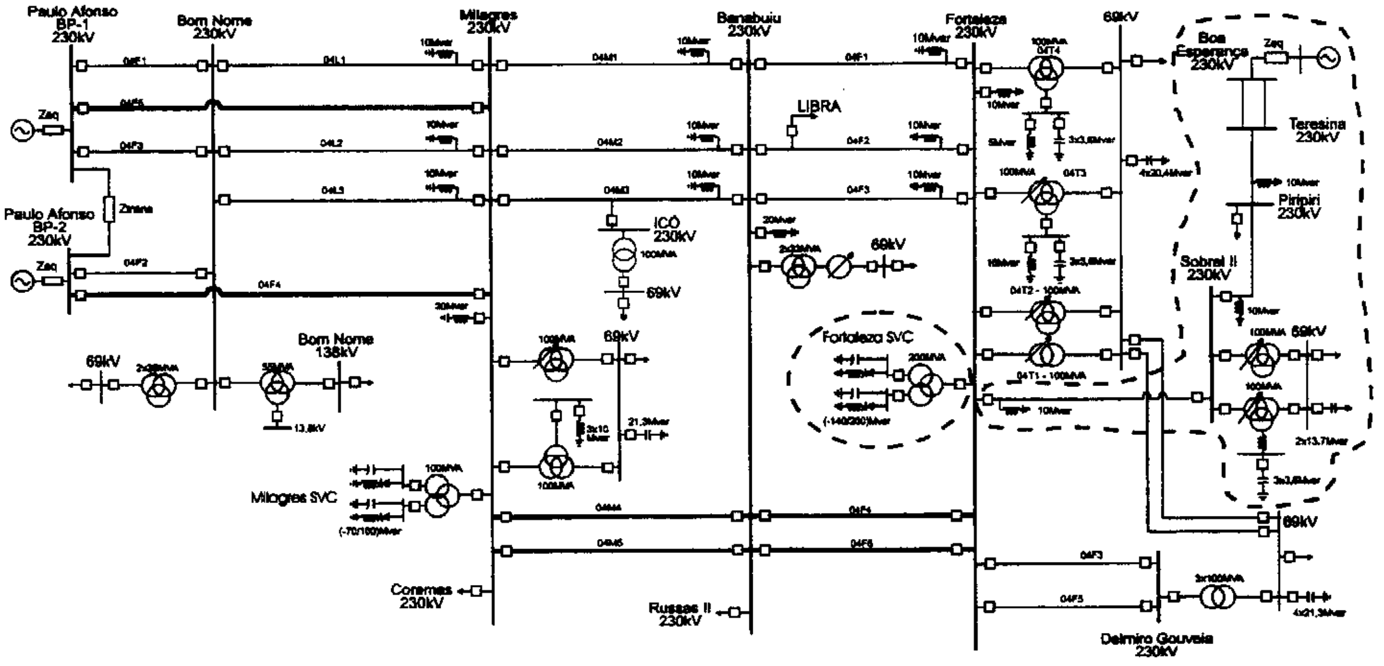

Fig. 1. One - line diagram of CHESF North and West transmission system

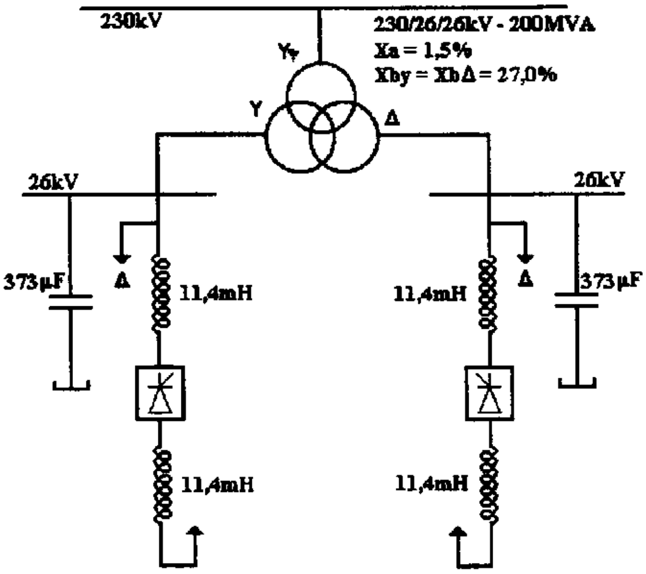

Fig. 2. Fortaleza Static Var Compensator

III. COMPONENTS MODELING IN ATP STUDIES

The loads were modeled by constant impedances, except Fortaleza load, represented partially by an induction motor. Percentages from 25% to 60% of Fortaleza load were represented by an equivalent induction motor, through type 3 "Universal Machine" model, available at ATP, in order to study the influence of the presence of motor loads at Fortaleza substation on system stability. Electromagnetic transient studies using this model to represent part of Fortaleza 69kV load and a comparison with site tests are described in [3].

Fortaleza SVC control system is mainly a PI (proportional and integral) controller, with a dynamic current limiter to protect the thyristor valves against overload. The main control functions of Fortaleza SVC represented in the ATP model are described in [1].

IV. TECHNICAL ANALYSIS

A. Influence of ESCR on System Stability

It was studied Fortaleza SVC small disturbances response, through the application of 5% steps on its error voltage, considering light and medium load conditions, with about 35MW supplied by Fortaleza 69kV busbar, a three-phase short-circuit power at Boa Esperança 230kV of 2450MVA and Fortaleza SVC operating close to 7MVAr capacitive.

This produces a three-phase short-circuit power of 148.2MVA at Fortaleza 230kV busbar and an Effective Short-Circuit Ratio (ESCR) of 0.74 (148.2 divided by 200). ESCR is calculated as the ratio between the three-phase short-circuit power at SVC high voltage busbar and its rated reactive power. As stated in [6], the ESCR plays an important role in the SVC dynamic performance and in its interactions with the electric network, specially when too low values are considered, as in the studied case.

Starting from a proportional gain (Kp) of 0.40V/V for the SVC PI controller, defined by the studies reported on [3], there were obtained the results resumed on Table I.

Table I

Kp (V/V)	System Performance
0.40	Strongly Unstable
0.30	Strongly Unstable
0.20	Unstable
0.10	Stability Limit
0.05	Stable

These results show that it is not possible to operate Fortaleza SVC in automatic mode in these network conditions, since the gain value necessary to assure stable operation is so small that will produce a very poor performance during normal conditions. Besides, it is not available at Fortaleza SVC up to now an adaptative control scheme, able to automatically modify the control system parameters, according to changes on transmission system configuration. The referred instability is probably due to interactions between SVC control system and the electric network and this effect is very common on systems with low ESCR values [5]. In order to find the minimum transmission system configuration possible to operate Fortaleza SVC in automatic mode in the studied conditions, 69kV load of this substation was increased from 35 to 100MW. The results obtained are resumed on Table II.

Table II

Kp (V/V)	System Performance	Percentual Overshoot (%)
0.40	Stability limit	138.65
0.30	Stability limit	52.00
0.20	Stable	31.20

As can be seen in Table II, increasing the load supplied by Fortaleza substation allows to operate the SVC with higher Kp values, assuring a stable performance. However, studies reported in [3] show that operation during normal transmission system conditions with gain values of 0.20V/V would produce a very poor SVC performance. It was decided, so, to operate Fortaleza SVC in this transmission system configuration only in manual mode, to avoid instability problems.

To quantify the effects of increasing the short-circuit levels at Boa Esperança 230kV and, consequently, the ESCR values on the equivalent system stability (power system and SVC), there were repeated the step simulations on Fortaleza SVC control error, considering short-circuit levels of 1.5, 2 and 3 times the short-circuit power of 2450 MVA used in the first group of simulations and taken as a reference value during this study. The results obtained are presented on Table III.

By these results, it can be seen that for a short-circuit power of one and half times the reference value, it is possible to operate Fortaleza SVC in automatic mode with a proportional gain of 0.30V/V, a stable performance and a percentual overshoot of 30%. This value is considered acceptable by the literature [4].

When the short-circuit levels at Boa Esperança 230kV are increased to two and three times the reference value, the simulations show that the system is also stable and the steady state after the step application is reached in time intervals smaller than in the case where it is used a short-circuit power level of one and half times the reference one.

Table III

Scc (pu) *	Kp (V/V)	System Performance	Percentual Overshoot (%)
1.5	0.40	Unstable	-
	0.30	Stable	30.0
	0.25	Stable	30.0
2.0	0.40	Stability Limit	30.0
	0.30	Stable	
	0.25	Stable	30.0
3.0	0.40	Stability Limit	30.0
	0.30	Stable	30.0
	0.20	Stable	30.0

(*) In per unit of the reference short-circuit power in Boa Esperança 230kV busbar

Figs. 3 to 8 show the input (error voltage) and output (control voltage) signals of Fortaleza SVC PI controller, named, respectively, ENTPI (-x-) and SAIPI (-o-) obtained from ATP simulations.

Figs. 3 and 4 show the results of ATP simulations, considering loads represented by constant impedances and a short-circuit power at Boa Esperança 230kV equal to one and half times the reference value. As can be seen, for this configuration, the use of Kp=0.40V/V produces unstable performance. However, if Kp is reduced to 0.30V/V, the system has a stable behavior. Therefore, when is considered the short-circuit level reference value, the system has a stable performance, in the same network configuration, for a maximum proportional gain value of 0.20V/V.

It can be concluded that ESCR values have strong influence on system stability in the presence of static compensators, specially in a weak transmission system, as is the studied case. It can be concluded also that the unstable behavior of the equivalent system (electric power system and SVC) is due to interactions between network and SVC, aggravated by the low ESCR values of the studied configuration [5], [6]. ESCR values have strong influence on the system stability in the presence of static compensators, specially in a weak transmission system, as is the studied case.

B. Influence of Dynamically Active Loads on System Stability

To study the influence of the presence of dynamically active loads, which is very pronounced in Fortaleza substation, on system stability, there were performed simulations of step on control error of Fortaleza SVC with percentages of motor loads of, respectively, 25, 40 and 60% of the total load supplied by Fortaleza 69kV busbar. The simulations results indicate a slight tendency of instability in the equivalent system (SVC and transmission system) with the introduction of an induction motor representing part of the load, when compared with the cases where only constant impedance loads were considered.

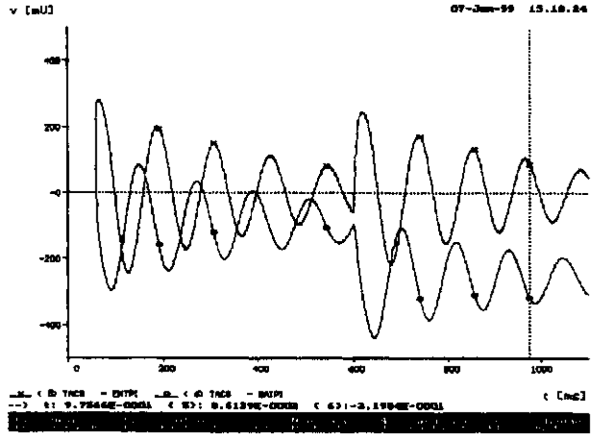

Fig. 3. Fortaleza SVC control and error voltage for a 5% step, SVC close to 7MVAr capacitive, constant impedance loads, Kp=0.40V/V, Scc=1.5Sccref (ESCR=1.11)

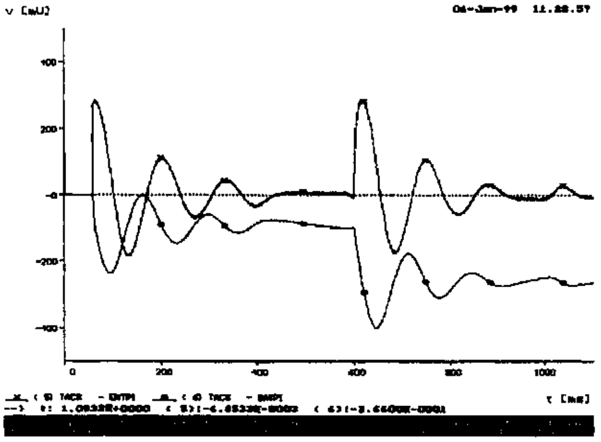

Fig. 4. Fortaleza SVC control and error voltage for a 5% step, SVC close to 7MVAr capacitive, constant impedance loads, Kp=0.30V/V, Scc=1.5Sccref (ESCR=1.11)

When is increased the percentage of motor loads at Fortaleza 69kV from 25 to 40%, the system becomes more unstable and for instance, for Kp=0.30V/V, it has unstable behavior. On the other hand, for a motor load percentage of 25% and Kp=0.30V/V, the system operates on its stability limit. These effect can be observed in Figs. 5 and 6. For a motor load percentage of 60%, the system performance is very close to the case with 40% of motor loads.

This behavior can be explained by the following arguments:

- The mechanical system inertia of the equivalent induction motor, represented in the ATP model by a shunt capacitance, has a large value due to the load amount involved.
- A radial transmission system with low short-circuit power levels is characterized by large series inductance values for the transmission lines.
- These inductances, combined with the large shunt capacitances of the slightly loaded transmission lines and the capacitance used to model the equivalent motor inertia, produce oscillation frequencies that can be situated close to the low transmission system resonant frequencies, leading the overall system to an unstable performance.

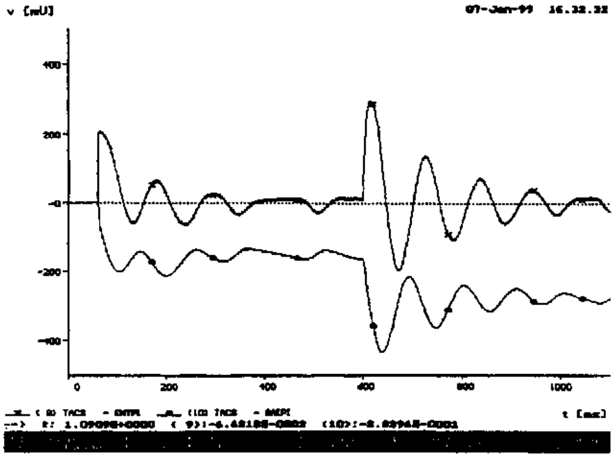

Fig. 5. Fortaleza SVC control and error voltage for a 5% step, SVC close to 0MVAr, 25% of motor loads at 69kV busbar and Kp=0.30V/V, Scc=1.5Sccref (ESCR=1.11)

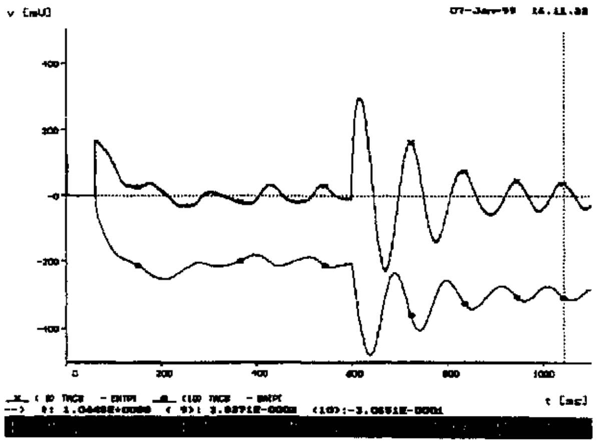

Fig. 6. Fortaleza SVC control and error voltage for a 5% step, SVC close to 0MVAr, 40% of motor loads at 69kV busbar and Kp=0.30V/V, Scc=1.5Sccref (ESCR=1.11)

C. Influence of SVC Operation Point on System Stability

To complete the analysis of the influence of the more relevant factors on the system stability, it was studied the dependence of the SVC operation point on the system performance. For this, there were repeated the simulations of step on SVC error voltage, considering this equipment operating, respectively, with 100MVAr capacitive and 100MVAr inductive. The loads were represented by constant impedances and it was used a short-circuit power level equal to 1.5 times the reference value. By the simulations results showed in Figs. 7 and 8, it can be said that:

- Considering Fortaleza SVC supplying to the network 100MVAr capacitive, the system has a stable performance for a proportional gain value of 0.40V/V, with a percentual overshoot of 30% and oscillations completely damped in three cycles after the step applying. This behavior is quite similar to the obtained during normal network conditions. In this case, the operation of the SVC on strongly capacitive points contributes to increase the equivalent system stability (Fig. 7).

- Considering Fortaleza SVC supplying to the network 100MVAr inductive, the system is unstable, with a percentual overshoot of 33% and lightly damped oscillations for Kp=0.40V/V. For Kp=0.35V/V, the system operates on its stability limit with a percentual overshoot of 30%. Otherwise, for Kp=0.30V/V, the system has a stable performance, with a percentual overshoot of 30% and oscillations are completely damped in three cycles after the step applying. In this case, the system has a behavior quite similar to the one of 100MVAr capacitive and Kp=0.40V/V (Fig. 8).

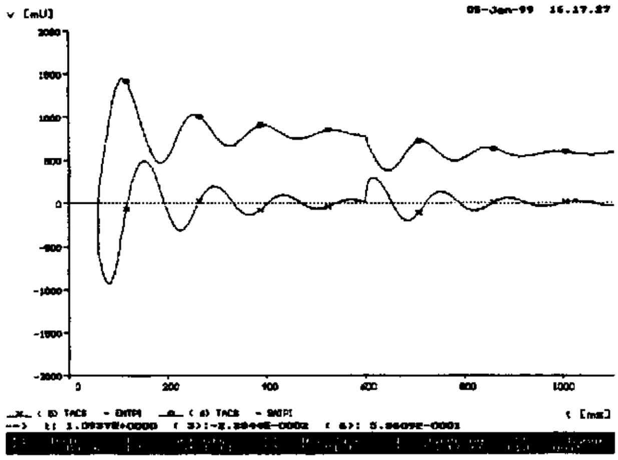

Fig. 7. Fortaleza SVC control voltage and error for a 5% step, SVC supplying 100MVAr capacitive to the network and Kp=0.40V/V, Scc=1.5Sccref, (ESCR=1.11)

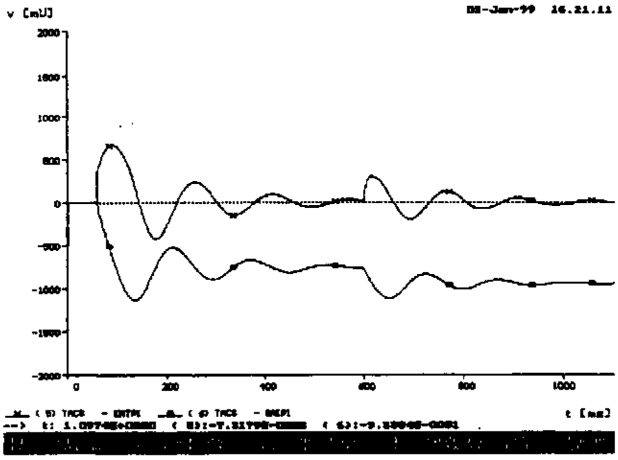

Fig. 8. Fortaleza SVC control voltage and error for a 5% step, SVC supplying 100MVAr inductive to the network and Kp=0.30V/V, Scc=1.5Sccref, (ESCR=1.11)

By these results, it can be seen that the stability of the studied system depends significantly of Fortaleza SVC operation point and that the most favorable condition, in order to have a stable performance, is the operation in strongly capacitive points. On the other hand, the most critical condition for the system stability obtained during this study is with the SVC operating in slightly capacitive points.

V. CONCLUSIONS

I. A weak transmission system, characterized by low short-circuit levels, is very susceptible to dynamic interactions with SVC control systems. These interactions could lead the equivalent system to an unstable performance for some SVC gain values. Therefore, these weak systems have slower values for the first resonant network frequency and variations in a wider range for the mode associated to voltage control. These effects can produce stronger interactions between the modes associated to SVC voltage control and the network resonant frequencies, that is considered the main cause of the unstable performance presented in the studied case [5].

II. In those cases, the analysis using dynamic tools (stability programs) could lead to results that do not reproduce the actual system behavior, as the electric network is normally represented, in these programs, by a phasor approach and only the dynamic behavior of equipments like SVC and synchronous machines is considered in a simplified way [5], [6]. On the other hand, the time domain analysis using electromagnetic transient programs takes into account in a very complete way the electric network dynamic behavior, and consequently, the interactions between this network and the other system components.

III. The results presented show the importance of using in SVC adaptative control schemes, where it is possible to automatically modify the control system parameters based on the identification of changes on network configuration. Using this feature, it would be possible, in the studied case, to operate Fortaleza SVC in automatic mode in all system configurations, including the degradated network conditions here described, with acceptable SVC performances.

IV. The new SVC designs incorporate the feature of automatically modifying the control system parameters, considering changes on the electric network or the detection of some unstable operation (hunting detection). In this case, the hunting detector identifies the existence of unstable performance and slightly reduces the SVC control system gain, to eliminate this undesirable behavior [2].

V. By the presented results, it can be concluded that when studying critical operating network conditions, it is necessary to perform electromagnetic transient studies (time domain studies), with detailed modeling of the involved elements, like SVC, dynamic active loads and the electric network, to complement the dynamic studies and adequately reproduce the interactions among these elements.

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