A Feasibility Study for Conversion of 345/138 kV Auto-Transformers into Fault Current Limiting Transformers

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Abstract - It is proposed to convert an existing 345/138 kV auto-transformer into a Fault Current Limiting Transformer (FCLT) by the addition of a series impedance (capacitive or inductive) and a small phase shifting transformer. To perform transient and steady state dimensioning studies, PSCAD/EMTDC and phasorial models of the FCLT were developed and tested. Since the auto-transformer was not specifically designed for this application, operating limitations were identified.

Keywords: Short circuit levels, fault current limiting transformer (FCLT), Interphase power controller (IPC), modeling, PSCAD.

I. INTRODUCTION

The growth of the Brazilian electrical system has resulted in an increase in short circuit currents to levels no longer compatible with installed circuit breakers in some areas. This is particularly true at sub-transmission levels such as 138 kV, widely used nationally. To address this problem, the Brazilian ISO (ONS – Operador Nacional do Sistema Elétrico) jointly with other entities in the electrical sector, have initiated investigations into various possible solutions. These investigations include studies of all types of short circuit limiting devices and where they may be applicable [1].

One such study, described herein, examined the Jacarepaguá substation (Fig. 1), a 345/138kV substation in the suburban part of greater Rio de Janeiro. Short circuit levels on the 138kV side of this substation have already reached the breaker capacity of 37 kA and some corrective measures need to be taken.

This work was supported by FINEP and ONS.

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Presented at the International Conference on Power Systems Transients (IPST´05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST-251

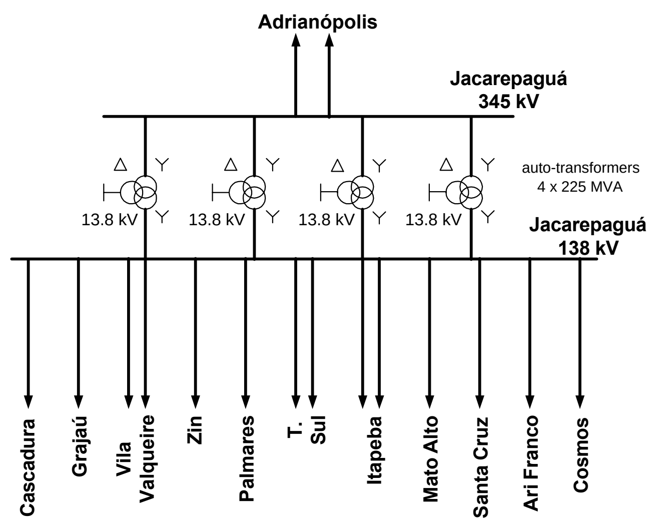

Fig.1. Simplified single line of the Jacarepaguá Substation

The Jacarepaguá substation features 4 nearly identical 345/138kV, 225 MVA auto-transformers with small (13.8 kV, 75 MVA) delta connected tertiary windings. The tertiary windings feed the station auxiliary power and can also be connected to 30 MVAr shunt reactors for voltage control. In one bank, however, the tertiary winding is unused.

Fault Current Limiting Transformers (FCLTs) have been proposed [2] as a special case of the Interphase Power Controller (IPC) technology [3]. A FCLT requires a phase shifted voltage to be imposed on a series impedance. During faults the series impedance limits fault currents while in normal steady state operation, the device acts as a power controller.

Phase shifting transformers have long been used as power flow devices [4]. In a typical application [5] a phase shifted voltage is applied across a parallel impedance, where the parallel impedance may be a parallel transmission line or perhaps even a more significant part of the electrical network. The FCLT also requires a phase shifted voltage which is applied across a parallel impedance. However, in the case of the FCLT, the parallel impedance is almost a short circuit made by one or more local transformers connected in parallel. As will be seen in the following sections, this near short circuit results in the phase shifted voltage falling across a local series impedance, which is a part of the FCLT's electrical circuit. The controllability of the phase shifted voltage (by its tap changer) plus the type (L or C) and size of the series impedance, give the FCLT its attractive characteristics.

The possibility of building a minimum cost FCLT, using an existing auto-transformer's unused tertiary winding, is examined in this paper. The development of suitable models of the device and the application of these models to evaluate the performance of the various alternatives were examined. The series impedance can be either inductive or capacitive and both alternatives were studied in detail. Resonances caused by the choice of a capacitive series impedance are also considered. Since the auto-transformer was not specifically designed for this application, loading was checked carefully.

II FCLT USING A SERIES CAPACITOR

A. Basic Description

By connecting one side of a 2 winding transformer across the B phase auto-transformer's 13.8 kV delta connected tertiary winding and the other side in series with the A phase auto-transformer's 138 kV terminal, as shown in Fig. 2, a phase shifted voltage e_{ser1A} is obtained.

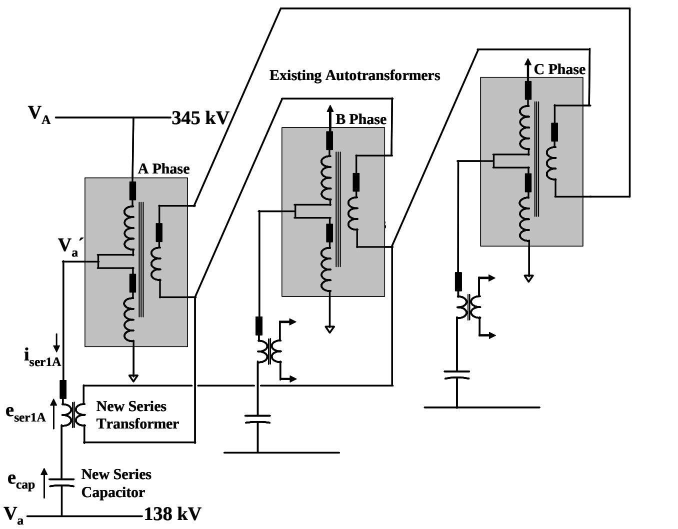

Fig. 2. Implementation of a FCLT installing a series transformer and series capacitor in the 138 kV connection of the auto-transformer.

Fig. 3 shows the phasor relationship:

$$V_a' = e_{ser1A} + e_{cap} + V_a$$

In this relationship, the voltage drop across the series transformer leakage reactance ($i_{ser1A} \cdot x_{ser}$) is small and is neglected for the moment. In Fig. 3, using the same variable names as in Fig. 2:

V_A is the 345kV A phase bus voltage,
V_a is the 138kV A phase bus voltage,
V_a' is the 138kV A phase bus voltage at the auto transformer 138kV terminal,
e_{ser1A} is the series transformer voltage and is in phase with $-V_B$,
e_{cap} is the capacitor voltage,
i_{ser1A} is the capacitor (and 138kV load) current, leading the capacitor voltage by 90° electrical and δ is the angular displacement between the 345kV and 138kV buses.

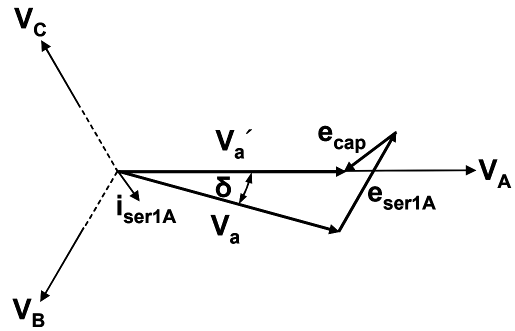

Fig. 3. Simplified phasor diagram of the FCLT using a series capacitor

In Fig. 3 the angular displacement δ is greatly exaggerated to permit easier visualization of the voltage phasors. In the case being examined in this study, the FCLT is paralleled by one or more auto-transformers that constrain δ to be within the range of a few degrees. It can also be noted that the angular position of e_{ser1A} (and consequently e_{cap}) is determined by the B phase 345 kV voltage. The magnitudes of e_{cap} and i_{ser1A} are determined by e_{ser1A} , which is set by the series transformer tap changer.

Unlike the parallel auto transformers where the power flow is a sensitive function of δ, in the FCLT the power flow is controlled by adjusting the magnitude of e_{ser1A}, a function of the series transformer's tap position. Similar to the more complete IPCs described in [3] the FCLT offers an approximately constant power characteristic for small variations in δ and other main circuit quantities. Since i_{ser1A} (the 138kV load current) must always lag V_a (the 138kV bus voltage) it is not possible to completely control the reactive power flowing into the FCLT. Limited control is possible however by adjusting the auto-transformer's 138kV terminal voltage, V_a'.

During ac faults, the current flow through the FCLT is limited by the high series impedance. Fig. 4 illustrates the case of one FCLT in parallel with 3 auto-transformers.

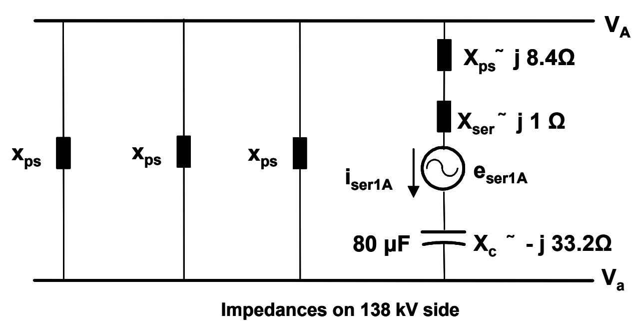

Fig. 4. One FCLT (using a capacitor) in parallel with three auto-transformers.

Using the impedance values in Fig. 4, compared to a conventional auto-transformer with a leakage reactance of x_{ps}, the FCLT has about 3 times the impedance and, during ac faults, will contribute about 1/3 of the fault current.

B. Description of models in Mathcad and PSCAD/EMTDC

In order to dimension the additional components needed in the FCLT, and to calculate the steady state P and Q characteristics, both steady state and transient models of the FCLT and the parallel auto-transformers were developed. Fig. 5 illustrates the circuit represented in the Mathcad model. Using Kirchoff's voltage and current laws, 5 circuit equations in 5 unknowns were solved. In this model the voltages (magnitude and phase) at the remote busses (V_{345} and V_{138}) are fixed by the user and all other variables can then be determined. The program results were validated by comparing the results with the PSCAD model described in the following sections.

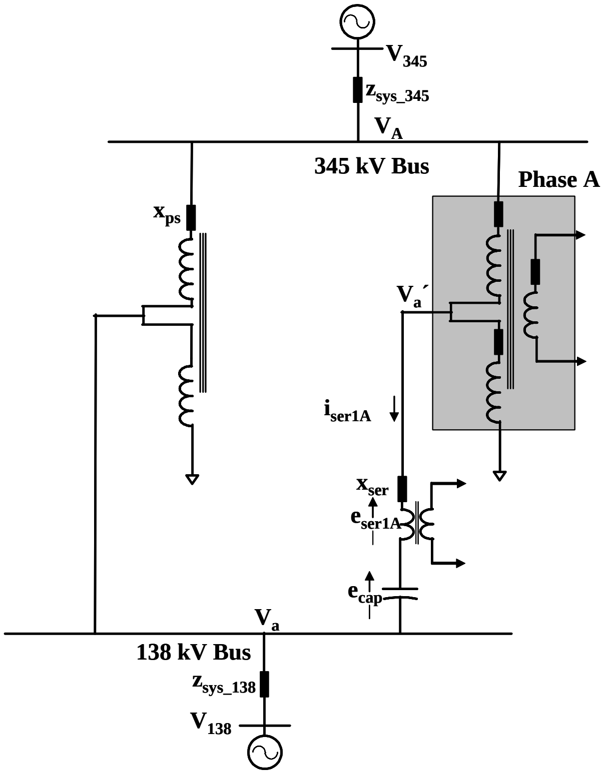

Fig. 5. Single line diagram of FCLTs and parallel auto-transformers as represented in Mathcad

In order to study the transient behavior of the FCLT during faults, a PSCAD/EMTDC model was developed. This model permitted a detailed 3-phase representation of the power system. Validation of the more complete PSCAD model in steady state was achieved by comparing main circuit quantities (short circuit current levels at various busses, voltages, real and reactive powers in the FCLT and ac lines) with a similar case run using the power flow program ANAREDE. Steady state results were also compared with the Mathcad models. Satisfactory agreement was obtained in all comparisons.

Fig. 6 shows the PSCAD layout for the Jacarepaguá substation, while Fig. 7 illustrates a typical auto-transformer modified to act as a FCLT. The AC network equivalents are based on the single line diagram shown in Fig. 1.

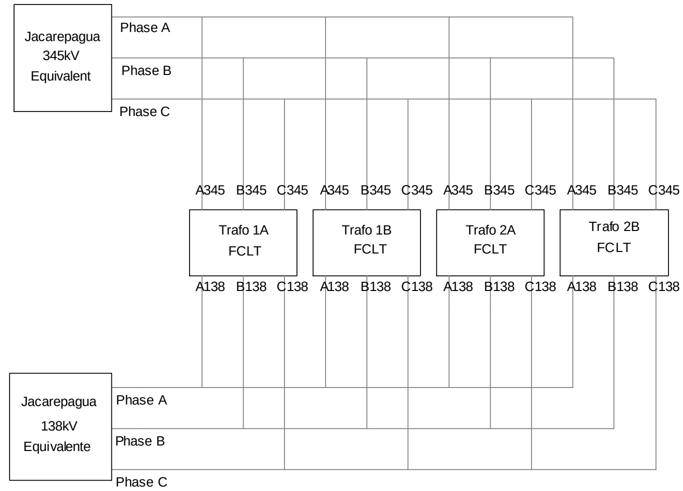

Fig. 6. PSCAD representation of the Jacarepaguá Substation

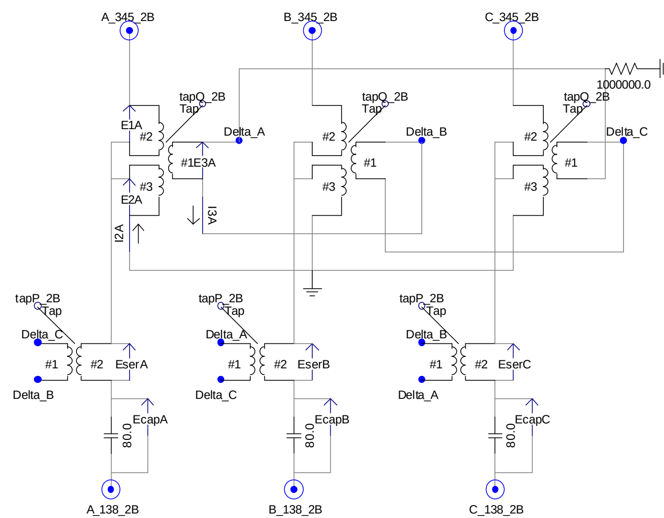

Fig. 7. PSCAD representation of a FCLT

C. Study Results

The dimensioning process involves determining the values of C_{ser}, (the series capacitor) n_{ser21} (the turns ratio of the series transformer) and, to a lesser extent x_{ser}, (the leakage reactance of the series transformer) subject to the constraints that the power transfer should be maximized without overloading the auto transformer. The 138 kV and 345 kV ac voltages on both sides of the Jacarepaguá substation were fixed at 1.0 pu with an angular difference of $\delta = 5.68°$, a value that provides rated power transfer through the parallel auto-transformers. By trial and error $C_{ser} = 80$ µF and $n_{ser21} = 0.5593$ were found to result in nominal loading on the auto-transformer's 138 kV winding and these values were selected as a starting point for further investigation. It was noted that the real power passing through the FCLT was only about 74% of the ideal, unity power factor rating of 225 MW. By using the auto-transformer's 138 kV tapchanger, reactive power flows were minimized and the real power flow reached 83%.

To a reasonable extent, the series transformer´s tap changer n_{ser21} controls the real power flow while the FCLT's auto-transformer´s 138 kV tap changer controls reactive power flow. Figures 8 and 9 illustrate this.

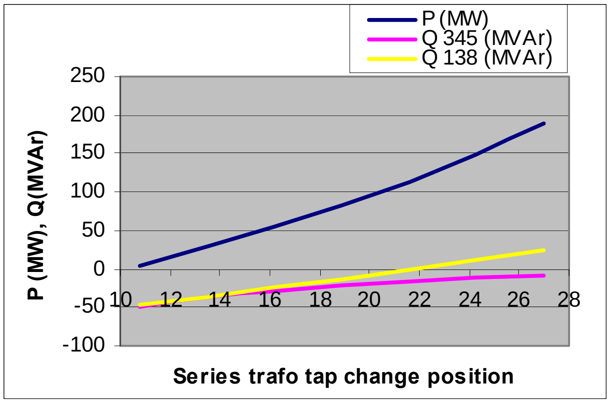

Fig.8. P and Q as a function of the series transformer´s tap position

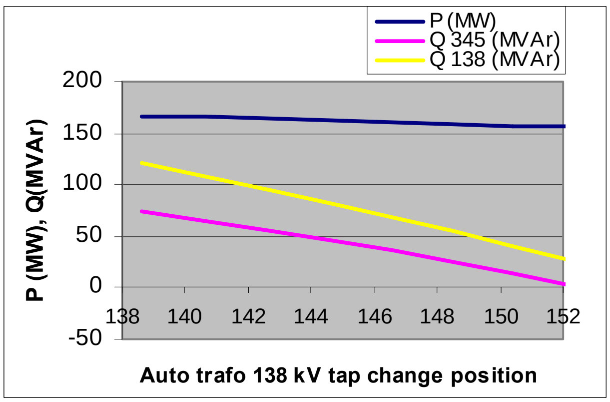

Fig.9. P and Q as a function of the auto-transformer´s 138 kV tap position

The equipment ratings were determined to be:

Capacitor:

- nominal voltage = 27.0 kV
- nominal current =0.815 kA
- MVA per phase = 22.0 MVA
- capacitor value = 80 μF

Series transformer:

- nominal primary voltage = 30.8 kV with taps to allow variation from 10 to 30.8 kV
- nominal primary current = 0.815 kA
- MVA per phase = 25.1 MVA
- nominal secondary voltage =15.4 kV
- leakage reactance = 0.04 pu on transformer's base

Using the PSCAD/EMTDC model, transient performance was examined by the application of ac faults at various locations. Fig. 10 shows results for an illustrative 2 cycle solid 3-phase fault on the 138 kV bus. In this case, Bank 2B is operated as a FCLT while the remaining 3 banks (1A, 1B and 2A) are operated as conventional auto-transformers. During and after the fault, oscillatory currents and voltages are observed. Fourier analyses of the waveforms indicated 88 Hz and 108 Hz resonances. Circuit analyses using Mathcad showed that the former is a positive sequence resonance and the latter is a zero sequence resonance. Adjusting the capacitor size, the series transformer leakage reactance and the number of parallel auto-transformer banks resulted in shifts in the resonance frequencies. However, the resonances continued to occur at rather lower frequencies (60 to 100 Hz).

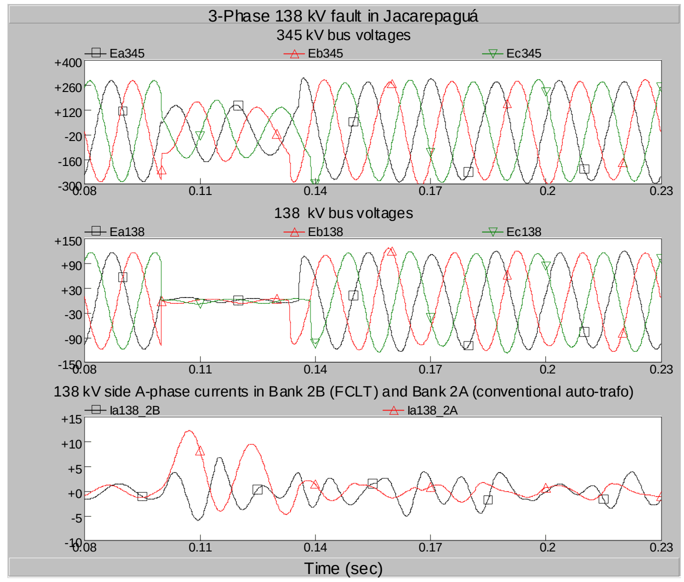

Fig.10. 3-phase 138 kV side ac fault

Series capacitors may reduce the damping of some torsional modes in nearby thermal plants, giving rise to a risk of sub-synchronous oscillations [6]. This possibility was not investigated herein, as the replacement of the series capacitor by a series inductor (described in the following sections) eliminated the need for such an investigation.

III FCLT USING A SERIES INDUCTOR

The oscillatory behavior observed using the capacitive FCLT can be eliminated completely by replacing the capacitor with an inductor and reversing the connections between the series transformer and the auto-transformer delta winding, as shown in Fig. 11.

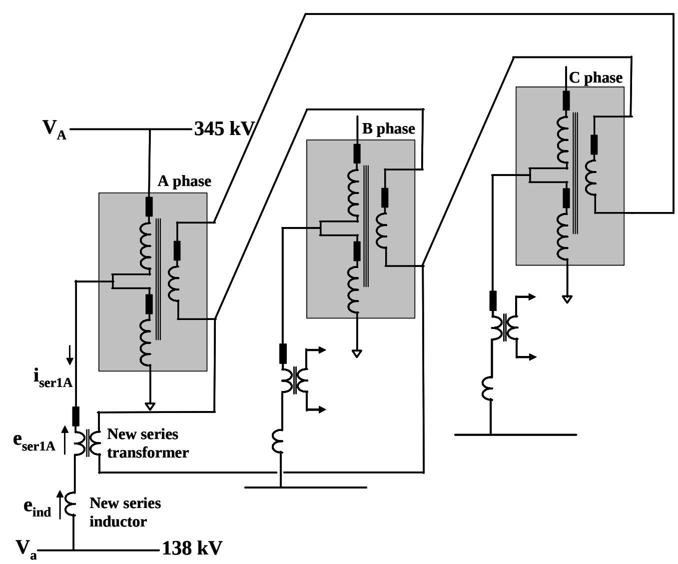

Fig. 11. FCLT using a series inductor

Similar to the steps outlined previously for the capacitive FCLT, both steady state and transient models were developed and used to dimension the FCLT series transformer and inductor as well as to study transient behavior during ac faults. Only the results are described here.

Maximum power through the FCLT occurs close to the values of L_{ser} = 40 mH and n_{ser21} = 0.7300 with the auto-transformer's 345 kV winding being the limiting factor. By adjusting the auto-transformer's 138 kV tap, a maximum real power transfer of 85.7 % of the unity power factor rating of 225 MW can be achieved. Figures 12 and 13 illustrate the effect of the tapchangers on the control of real and reactive power.

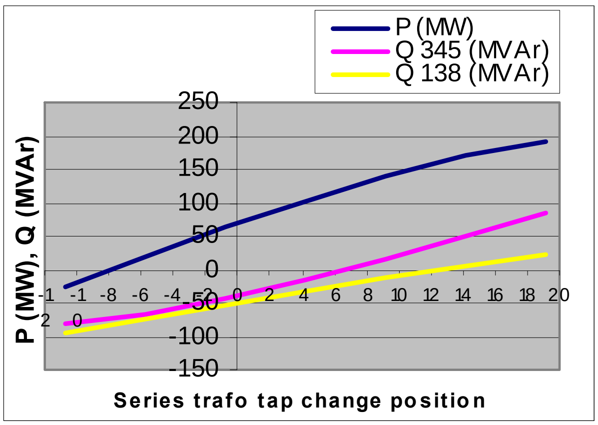

Fig.12. P and Q as a function of the series transformer´s tap position

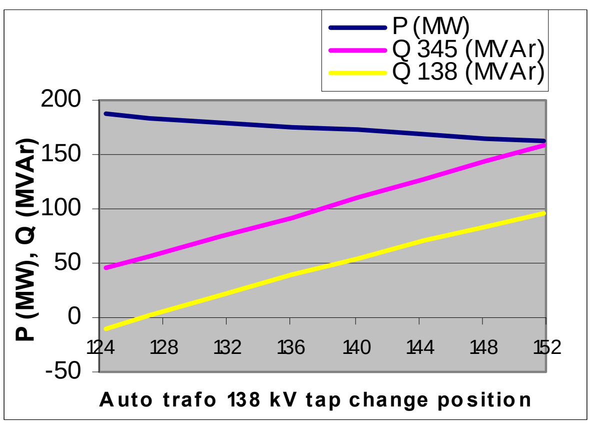

Fig.13. P and Q as a function of the auto-transformer´s 138 kV tap position

Summarizing the series inductor and series transformer ratings:

Inductor:

- nominal voltage = 12.2 kV
- nominal current =0.812 kA
- MVA per phase = 9.91 MVA
- inductor value = 40 mH

Series transformer:

- nominal primary voltage = 19.2 kV with taps to allow variation from -10 kV to +19.2 kV
- nominal primary current = 0.812 kA
- MVA per phase = 11.8 MVA
- nominal secondary voltage =13.8 kV
- leakage reactance = 0.14 pu on transformer's base

Analogous to the capacitive case, the transient performance was examined by the application of ac faults at various locations.

Fig. 14 shows typical results for an illustrative 2 cycle solid 3-phase fault on the 138 kV bus. As before Bank 2B is operated as a FCLT while the remaining 3 banks (1A, 1B and 2A) are operated as conventional auto-transformers. The oscillation observed in the capacitive case has been eliminated and the fault current contribution of the FCLT is only 27% of the value measured in the conventional auto-transformers.

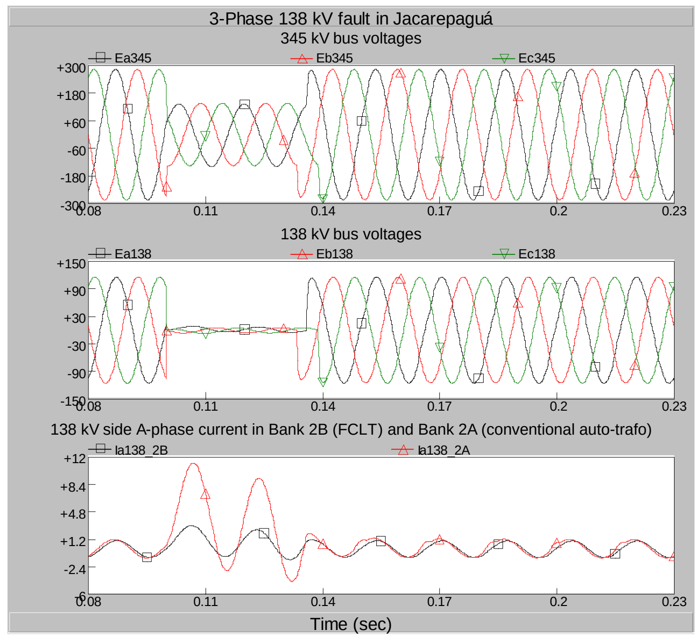

Fig.14. 3-phase 138 kV side ac fault

While the effectiveness of the FCLT as a device that limits current flow during faults is clearly demonstrated in the above figures, it is important to measure the currents flowing into the fault rather than just the individual contributions of each transformer bank. Table 1 shows the current in a 3-phase fault applied to the Jacarepaguá 138 kV bus. The number of FCLTs is varied from 0 to 3.

Transformer Banks				138 kV Fault Current (kA rms)
1A	1B	2A	2B	
auto trafo	auto trafo	auto trafo	auto trafo	40.2
auto trafo	auto trafo	auto trafo	FCLT	39.0
auto trafo	auto trafo	FCLT	FCLT	37.5
auto trafo	FCLT	FCLT	FCLT	35.7

Table1 - Total 138 kV fault current as a function of the numbers of FCLTs

According to the results presented in Table 1, it can be concluded that even though the FCLT contributes only about 27 % as much current as a conventional auto-transformer, the total fault current does not change significantly. This happens because the 345 kV network contributions are not dominant and limiting them does not greatly reduce the total fault current. More than 50% of the fault current comes directly from the 138 kV system.

IV CONCLUSIONS

The auto-transformers used in the Jacarepaguá substation can be converted into fault current limiting transformers by the addition of a small series reactance and series transformer placed in the 138 kV connection. The ratings of these new components are about 0.15 pu of the nominal 225 MVA rating of the auto-transformer.

The use of a series reactor avoids the oscillatory performance observed in the series capacitor case. Fault currents in the FCLT are reduced to less than 1/3 of the values measured in the conventional parallel auto-transformers. By appropriate use of the auto-transformer’s 138 kV tap changer (for Q control) and the series transformer’s tap changer (for P control) an active power through put of about 0.86 pu can be achieved without overloading the auto-transformer.

It was observed that for faults in the 138kV network, the fault current contribution originating from the 345 kV network, passing through the substation, is not predominant. Limiting this contribution by the use of FCLTs does not have a great impact on the 138 kV fault levels. Other locations for this type of FCLT would be more appropriate.

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VI Biographies

Don Menzies was born in Shoal Lake, Manitoba, Canada on March 28, 1947. He graduated with a B.Sc. (EE) from the University of Manitoba and an M.Sc. from Imperial College of Science, Technology and Medicine. Employment experience included Manitoba Hydro, EGAT, ABB, and FURNAS, principally involved in HVDC related activities. He is a member of CIGRÉ and IEEE.

Andréia M. Monteiro was born in Rio de Janeiro State, Brazil, on December 27, 1970. She received a B.Sc. Degree from Fluminense Federal University in Rio de Janeiro State, in 2000. At this time she is a M.Sc. student at the COPPE/Federal University of Rio de Janeiro and she works at ONS (Brazilian ISO) in power systems analysis. Her main fields of interests are power systems studies, equipment and electromagnetic transient studies.

Sandoval Carneiro Jr. was born in Brazil in 1945. He received the degree of Electrical Engineer from the Faculty of Electrical Engineering (FEI), of the Catholic University of São Paulo, Brazil, in 1968; the M.Sc. degree from the Graduate School of Engineering (COPPE) / Federal University of Rio de Janeiro (UFRJ) in 1971 and the Ph.D. degree in Electrical Engineering from University of Nottingham, England, in 1976. From 1971 to the present date he has been a Lecturer at the Federal University of Rio de Janeiro and in 1993 was promoted to Full Professor. From 1978 to 1979 he was Deputy-Director and from 1982 to 1985 Director of COPPE / UFRJ. From 1987 to 1988 and in 1994 he was Visiting Professor at the Department of Electrical Engineering of the University of British Columbia, Vancouver, Canada. From October 1991 to June 1992 he was General Director of CAPES-Ministry of Education Agency for Academic Improvement. From January, 2002 he has been the Chairman of the IEEE PES Distribution System Analysis Subcommittee. His research interests comprise Simulation of Electromagnetic Transients in Power Systems and Distribution System Analysis.

Alquindar S. Pedroso was born in Rio Grande do Sul, Brazil, on May 30, 1934. He graduated with a B.Sc in Electrical Engineering from the Federal University of Rio Grande do Sul - Brazil, and an M Sc in Electrical Engineering from Purdue University-USA. Since 1960 he has been involved in teaching and research in power system stability. Consulting experiences include the Itaipu Project, load-frequency studies for the Brazilian National Grid-SIN, and more recently pre operational studies of the SE-NE interconnection in Brazil. He is a member of Cigré and a Life Member of IEEE.