Brazilian Successful Experience in the Usage of Current Limiting Reactors for Short-Circuit Limitation

J. Amon F., P. C. Fernandez, E. H. Rose, A. D´Ajuz, A. Castanheira

Abstract-- With the deregulation of the Brazilian electric sector, the connection of independent power producers to the basic network causing the increase of short-circuit levels not included in previous long-term planning forecasts requires more and more knowledge of techniques for short-circuit limitation at High-Voltage (HV) levels of the existing network. The objective of this article is to present the Brazilian successful experience in the usage of air-core current-limiting reactor (CLR) for short-circuit limitation at the primary transmission network, regarding aspects like the transmission system performance under steady-state and transient conditions, the definition of the physical dimensions for the equipment, the specifications of the electrical characteristics and the special cares with respect to the possible damages caused by the magnetic flux generated by the CLR to human life, directly or through contact with metallic structures in the vicinities, the economic profits of this limitation in short-circuit level compared to the costs of the substitution of overloaded equipment and facilities and erection in site.

Keywords: Deregulation, Short-circuit limitation, Current-limiting reactor, Overload, Equipment

I. INTRODUCTION

The connection of independent power producers to the basic network causing the increase of short-circuit levels not included in previous long-term planning forecasts will require more and more knowledge of techniques for short-circuit limitation both at high-voltage and at medium-voltage/low-voltage levels of the existing network.

The most common solutions to high fault current levels are [1]: up rating of switchgear and other equipment; splitting the grid and introducing higher voltage connections (AC or DC); introducing higher impedance transformers and series reactors; and using complex strategies like sequential network tripping.

Nevertheless these alternatives may create other problems such as loss of power system security and reliability, high costs, and increase of power losses.

Up to now, for HV applications at the Brazilian interconnected network the adopted solution has been the usage of air-core current-limiting reactor (CLR), both in series with the incoming feeder circuit and in bus tie/coupling [2].

The guidance factors for CLR dimensioning, which could even make the CLR application unfeasible were the voltage drop, the joule losses and the high magnetic fluxes (higher distances/clearances required). On the other hand, despite these disadvantages their effects could be economically compensated when avoiding equipment substitution.

It can also be demonstrated that the presence of a lumped inductance in an electric circuit could lead to an increase in the severity of the transient recovery voltage (TRV) across the circuit breaker (CB) contacts, associated with the interruption of the circuit current [3].

When an air core dry type series reactor (CLR) is inserted into the circuit, for instance, to limit the short circuit current, the rate of rise of the transient recovery voltage tends to drastically increase because of its very large surge impedance (at least few thousands of Ohms).

Fortunately, however, installing a suitable capacitor across the reactor may easily solve this problem. In some cases it might be necessary to also install capacitors from each side of the reactor to ground. In any case, usually an in depth computers analysis must be performed to make sure the circuit breaker characteristics are not exceeded.

II. POSITION AT THE SUBSTATION BUSBAR

Besides the aspects above mentioned, the position of the CLR at the substation busbar to meet better the needs for the specific case should be analised [4].

The possible positions of the CLR at the substation busbar are shown in Figures 1, 2 and 3, ahead:

A. Bus Coupling

Instead of designing the two systems for the total short-circuit current, CLR is installed in the coupling. In case of a fault, it reduces the peak short-circuit current at the very first current rise.

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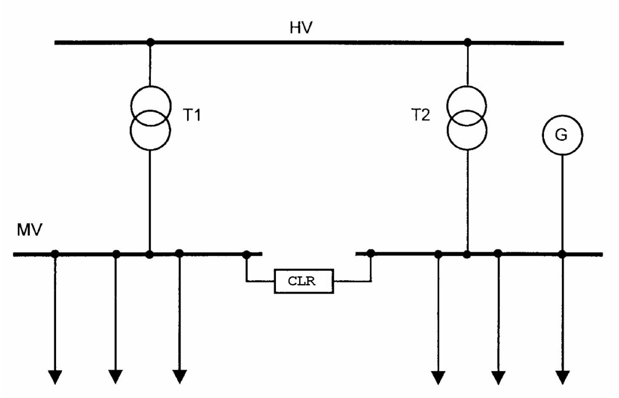

Fig. 1. Bus coupling

Advantages:

- Allow better sharing of transformers loading
- Reduction of the required short circuit capability of the system.
- Reduction of the network impedance.
- The short-circuit current of the feeding sources (transformers and generator) will be reduced

Disadvantage:

- Each incoming feeder contribution is not individually limited.

B. In series with incoming feeders

Instead of designing the system for the total short-circuit current, a CLR is installed in the incoming feeder(s). Also in this case if fault occurs, each CLR will reduce the peak short-circuit current at the very first current rise.

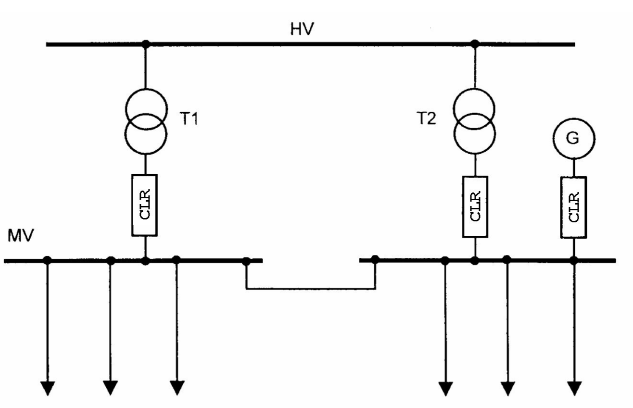

Fig. 2. In series with incoming feeders

Advantages:

- Besides the same as above, the short-circuit current of the feeding sources (transformers and generator) is individually limited

Disadvantages:

- High losses and bad regulation.

C. In series with the outgoing feeders

Instead of designing the sub-systems for the total short-circuit current, a CLR is installed in each outgoing feeder. Also in this application in case of a fault, each CLR reduces the peak short-circuit current at the very first current rise.

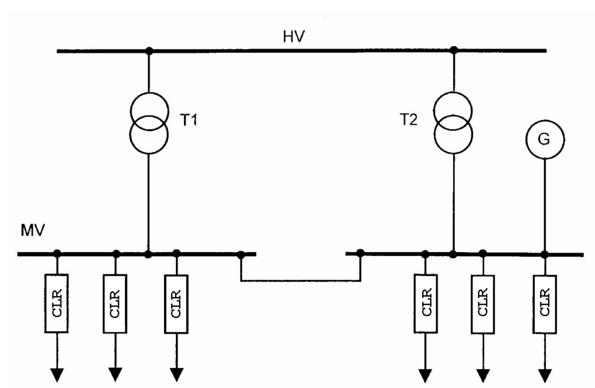

Fig. 3. In series with outgoing feeders

Advantages:

- Besides the same as above, low losses and better regulation

III. FURNAS´ EXPERIENCE

Furnas Centrais Elétricas S. A. is a power utility for generation and transmission, responsible for the supply of bulk energy to the Brazilian south-eastern region.

The voltage levels at FURNAS transmission system are 765 kV, 500 kV, 345 kV, 230 kV and 138 kV (AC) and ±600 kV (DC), all of them classified as high-voltage **(HV)**, resulting in approximately 17500 km of high-voltage transmission lines.

A. Long-term experience:

A common practice in many brazilian power utilities, including FURNAS, is the usage of air-core current-limiting series reactor (CLR) at tertiary windings of autotransformers that supply the auxiliary services at the transmission substations

In these cases, limitation of short circuit level has been needed for the auxiliary services system at several substations since, due to system requirements of small values of H-L impedance for autotransformers, short-circuit levels at their tertiary windings (auxiliary services / rated voltage = 15 kV) resulted higher than the switchgear capacity.

Since practically no effect is caused on the performance of the high-voltage transmission system, this procedure has been a common practice for several years, even by Brazilian transmission utilities other than FURNAS.

Table I shows basic characteristics of 15 kV CLR's installed at FURNAS substations.

TABLE I
CHARACTERISTICS OF 15 KV CLR'S INSTALLED AT FURNAS´ SUBSTATIONS

FURNAS´ Substations	Inductance (μH)	Rated Current (A)	Volt Drop (%)	Maximum Losses ≤ 0.5% (kW)	Rated Short-Circuit Current (kA)	Short-Circuit Limitation	
						From (kA)	To (kA)
ADRIANÓPOLIS	273	2000	2.4	2	40	44	29
FURNAS	4213	272	5	0.6	5.4	15	4
GRAJAÚ	1061	1083	5	2.3	25	124	17
JACAREPAGUÁ	598	1924	5	4.2	39	40	20

B. Recent experience:

For application at the high-voltage transmission system, power system studies started to be developed about 10 years beforehand, in order to avoid equipment substitution by limiting short-circuit levels at the substation.

Two Brazilian power utilities have adopted the usage of CLR's at the primary transmission grid, in series with transmission lines, at voltage levels of 145 kV (CEMIG - middle eighties) and 362 kV (FURNAS - Dec. 1998), in order to bring fault current levels down to the existing equipment ratings. FURNAS case would be the first CLR application in Brazil at 362 kV.

For such applications important aspects must be analysed as the transmission system performance under steady-state and transient conditions, the definition of the physical dimensions for the equipment, the specifications of the electrical characteristics and the special cares with respect to the possible damages caused by the magnetic flux generated by the CLR to human life, directly or through contact with metallic structures in the vicinities. Equal importance should also be given to the economic profits of this limitation in short-circuit level compared to the costs of the substitution of overloaded equipment and facilities.

Table II shows basic characteristics of FURNAS 362kV CLR:

TABLE II
CHARACTERISTICS OF FURNAS 362kV CLR

- rated voltage (kV):	345
- rated frequency (Hz):	60
- per phase inductance (μH):	24000
- rated current (A):	2100
- maximum voltage drop (kV, RMS):	18,9
- rated power (MVAr):	40
- rated short-circuit current (kA, RMS):	25
- impulse insulation level (kV, peak)	1300
- switching insulation level (kV, peak)	850
- quality factor:	300
- type of installation:	external

Figure 4 shows FURNAS 362kV CLR at site.

Figure 4 - FURNAS 362kV CLR at site during erection.

IV. ELETRONORTE ´s EXPERIENCE

Eletronorte is a utility which acts mainly in the north of Brazil where is located the Amazon Forest. The characteristic of the electrical system is to have high hydroelectric potential but far from the load.

Eletronorte's area of coverage represents 58 percent of the entire national territory, including the Brazilian states of Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima and Tocantins.

The previous experience of Eletronorte using CLR was to reduce the short-circuit level at 13.8 kV especially when it's used the tertiary of a high power autotransformer. There is approximately 18 CLR used in 9 substation. In July of 2004 started to operate the application of CLR at the high-voltage substation in Tucurui power plant

Tucuruí Power Plant is one of the world's largest hydro power plants. It's present extension adds 11 generators to the existing 12 units raising the output from 4245 MW to 8370 MW. It's the biggest Brazilian generating station, once that Itaipú is only partially owned by Brazil. This power plant, that has two powerhouses, has two switching substations insulated in air.

In order to increase the system flexibility it was decided to operate both air insulated switchyards in parallel. In this way, the short circuit level reaches a value higher than the withstanding limit of the old equipment installed in the first switching station – 40 kA. Therefore, it was necessary to provide means of reducing the global short circuit level to a suitable limit, usually 90% of the maximum equipment withstanding. The most attractive possibility is the use of a series reactor, connecting both switchyards in the level of 550 kV.

The reactance of the short circuit current limiting device – it was decided to use air insulated reactors, one per phase – was decided based on the results of Load Flow – under normal and emergency conditions – Standard Short Circuit studies, and ATP Short Circuit studies.

This set of reactors, as shown in Figure 5, is connected by two standard one and a half circuit breaker bay, one in the old substation – a standard one – that it is interesting to be maintained without modifications, as for instance the attachment of opening resistors. The results of the studies were responsible for the complete basic specification of the series reactors and of the associated equipment that present as the objective to reduce the TRV level of the circuit breakers during bus bar faults.

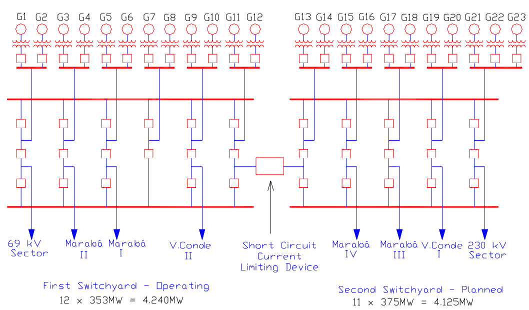

Fig 5–Short Circuit Limiting Device Connection

There are some limits for the reactors size, physical – due to installation restrictions, electrical – due to short circuit level and transmission lines overloads. Besides this, the efficiency of using reactors to control the short circuit level is limited to a small range. Beyond a certain reactance value, there is no net benefit and more, in this particular case, beyond 27 Ω there is a series of problems related to overloads in some of the outgoing transmission lines. This, for sure, can be addressed to the particular Tucuruí System; however, this can be also a general trend.

The effectiveness of the short circuit limiting device, considering the 2010 operating condition, is shown in Figure 6. In this case, it is possible to observe that there is an efficiency limit for the reactance value. Reactance values higher than 30 Ω will not reduce the short circuit level significantly.

However, operational conditions under standard and emergency load flow, for the system and for the equipment, were analyzed. From these conditions are defined the lowest and highest reactance limits. The lowest one is attached to the rated short circuit current of Tucuruí – I circuit breakers and the highest to a switchyard or a transmission line overload.

According to the results of these studies the reactance value is 20 Ohms per phase.

The operation time of this CLR is short and during this period there was short-circuit only 120 km far from Tucurui substation in the transmission line to Vila do Conde substation. The flow through the CLR isn't high, especially during this period of motorization of Tucurui power plant second stage.

Table III shows basic characteristics of ELETRONORTE 550kV CLR.

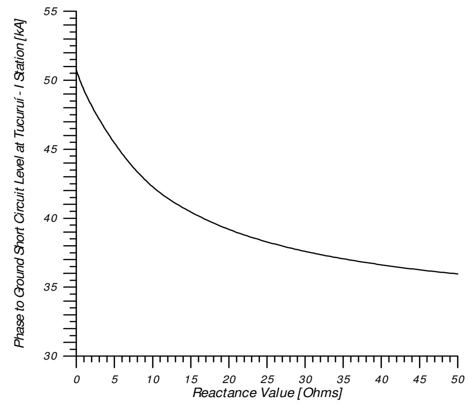

Fig. 6 – Effectiveness of the Short Circuit Current Limiting Reactor

TABLE III
CHARACTERISTICS OF ELETRONORTE 550kV CLR

- rated voltage (kV):	550/√3
- rated frequency (Hz):	60
- reactance per phase (Ω)	20
- per phase inductance (μH):	53050
- rated current (A):	2600
- maximum voltage drop (kV, RMS):	52
- rated power (MVAr):	135
- rated short-circuit current (kA, RMS):	10
- impulse insulation level (kV, peak)	1550
- switching insulation level (kV, peak)	1180
- quality factor:	400
- type of installation:	external

Figure 7 shows ELETRONORTE 550kV CLR at site.

Fig. 7 - ELETRONORTE 550kV CLR at site

V. IMPACT ON TRV REQUIREMENTS FOR CIRCUIT BREAKERS

Whenever the circuit breaker (CB) interrupts a fault (or steady state) current, a voltage appears across its terminals, starting from a value corresponding to the arc voltage and rising, in an oscillatory (transient) way, until the steady state system voltage. Hence its designation as Transient Recovery Voltage - T.R.V.

Although dry type air core series reactors are very powerful in controlling system faults, they tend to introduce a very fast component to the system TRV, which could exceed the circuit breaker TRV characteristic. As it will be shown, the main reason for this is the fact that an air core series reactor tends to have very large surge impedance.

Figure 8 shows a simplified diagram of a system where a CLR has been installed. The symbols used in the figure are self-explanatory.

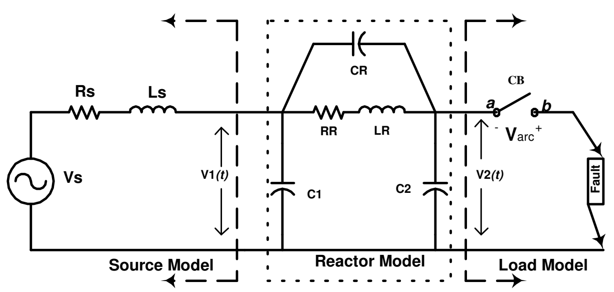

Fig. 8 – Equivalent Circuit with CLR

The reactor model consists of a pure inductance (**L_R**), in series with its total high frequency resistance (**R_R**) and capacitors connected between each reactor terminal to ground (**C_1, C_2**) and a capacitor connected between the reactor's terminals (**C_R**). For simplicity, the capacitors connected between the reactor terminals and ground have already been associated with other capacitance to ground (stray or otherwise) which always exist in the bus (equivalent of the source side) or the circuit breaker.

The capacitance associated with the reactor and the breaker are usually very small (up to a few hundred Pico Farad) while the capacitance associated with the bus (system equivalent) is much larger, being in the order of tens of nano Farad or higher. In short, **C_1 is much larger than either C_2 or C_R.**

Although a TRV analysis of a real circuit would invariably require a suitable computer simulation, for the purpose at hand a simple qualitative analysis will suffice. Inspection of figure 6 suggests that the circuit's response consist of the superposition of two distinct frequencies, which are determined by the combinations of L's and C's.

By performing a delta - star transformation on the capacitance's of the circuit, two linearly independent meshes can be determined, corresponding to the two frequencies and their associated damping factors:

$$f_1 = 1 / \{2\pi * \sqrt{L_S} * [C_1 + C_R*C_2/(C_R + C_2)]\} \; ; \; e^{(-Rs/2Ls)\,t}$$

$$f_2 = 1 / \{2\pi * \sqrt{L_R} * [C_R + C_1*C_2/(C_1 + C_2)]\} \; ; \; e^{(-Rs/2LR)\,t}$$

Since **L_S** and **L_R** are typically of the same order of magnitude, and **C_1** is large as compared to either **C_2** and **C_R** (which also are of the same order of magnitude), **f_1** is essentially determined by **C_1** while **f_2** is controlled by **C_R**. It results then that **f_1** is much lower than **f_2**.

Therefore the voltage across the breaker contacts should start from **V_{arc}** at t = 0 and reach its final value **Vs** through a superimposed double frequency oscillation, each having its own damping characteristics.

In fact, **f_1** has the same order of magnitude as the corresponding frequency of the TRV without the presence of the reactor in the circuit while **f_2** represents the impact the reactor has caused in the circuit's TRV

Figure 9 shows a superposition of two TRV waveforms, obtained in actual laboratory tests, with and without reactors. It clearly shows the effect that a reactor has on the breaker TRV.

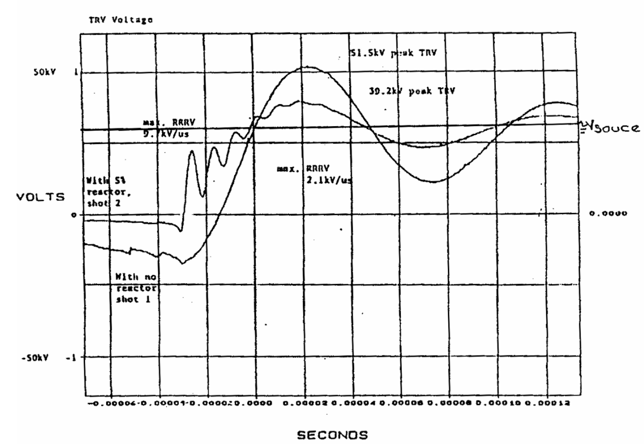

Fig. 9 – Superposition of system responses with and without the CLR

The presence of the reactor in the circuit has two basic consequences: (i) it reduces the peak value of the TRV; and (ii) it drastically increases the R.R.T.R.V. While the first effect is welcome, the second is very negative, as the rate of rise usually is the most critical parameter.

From the foregoing discussion it is reasonable to conclude that, to minimize the effect a CLR on the breaker TRV it is necessary to lower frequency **f_2.** To do so there are two alternatives: (i) increase **C_2**, for instance by installing a 'large' (bigger than few nano Farads) capacitor from (close to) the breaker terminal or from the reactor terminal to ground or (ii) increase **C_R**, the intrinsic reactor capacitance.

In some cases it might be necessary to use a combination of these methods in order to bring the system TRV to within the breaker characteristics.

Option (i), although feasible, could increase the cost of the installation somewhat since, besides the cost of the equipment itself, other expenses, such as foundation / installation would have to be accounted for. Note that this capacitor must be fully rated to the system where it will be connected. It should also be pointed out that, for some types of circuit breaker, the installation of a capacitor close to the breaker terminal may lead to a phenomena referred to as "Current Chopping" which may give rise to severe over voltages on the series reactor.

On the other hand, $\mathbf{C_R}$ would have to be rated to only the maximum voltage drop across the CLR (under short circuit conditions) and, in some cases, could be made an integral part of the reactor itself (i.e. minimum installation costs).

VI. CONCLUSIONS

With the deregulation of the Brazilian electric sector, the connection of independent power producers to the basic network causing the increase of short-circuit levels not included in previous long-term planning forecasts requires more and more knowledge of techniques for short-circuit limitation at High-Voltage (HV) levels of the existing network.

Up to now, for HV applications at the Brazilian interconnected network the adopted solution has been the usage of air-core current-limiting reactor (CLR), both in series with the incoming feeder circuit and in bus tie/coupling.

For such applications important aspects must be analysed as the transmission system performance under steady-state and transient conditions, the definition of the physical dimensions for the equipment, the specifications of the electrical characteristics and the special cares with respect to the possible damages caused by the magnetic flux generated by the CLR to human life, directly or through contact with metallic structures in the vicinities.

The position of the CLR at the substation busbar to meet better the needs for the specific case must be analised.

The presence of a lumped inductance in an electric circuit could lead to an increase in the severity of the transient recovery voltage (TRV) across the circuit breaker (CB) contacts, associated with the interruption of the circuit current. The installation of a suitable capacitor across the reactor may easily solve this problem. In some cases it might be necessary to also install capacitors from each side of the reactor to ground.

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VIII. BIOGRAPHIES

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