This contribution reports FURNAS’ [1] experience in the usage of opening resistors, as well as, controlled switching for switching-off high voltage shunt reactors in Brazil.

**Shunt Reactor (SR) application philosophy** - In FURNAS, as well as in other utilities, the SR are used in power system transmission overhead (OH) lines for 2 main purposes: (a) switchable SR at bus-bars or tertiary-windings of power transformers, for steady-state voltage control issues; (b) fixed SR at the OH line ends to deal with switching transient overvoltage requirements, related to the line closing and/or opening operation (including fast auto-reclosing issues). Referring to the switchable SR, for mitigating/controlling the switching transient overvoltages (generated when switching-off such SR), it is possible to use CB equipped with opening resistors or controlled switching devices (CSS).

In case of using circuit-breaker (CB) equipped with opening resistors, for optimizing the transient switching overvoltage control, the ohmic value in each phase should be of the same magnitude of the ‘characteristic impedance’ of the SR (surge impedance). In the FURNAS’ 800 kV level transmission system, a normal range of surge impedance values for SR is 2.000 Ohms to 4.000 Ohms.

For illustration purposes, the 800 kV switchable SRs of FURNAS transmission system, in the 1980’, have air-blast CB equipped with opening resistors for transient switching overvoltages mitigation, as it has been defined by the planning and design works, developed in the late 70’ and early 80’.

In the next schematic diagram, shown in Figure 1, one can see the existing SR application philosophy installed in such transmission system.

![Figure 1– Fixed and bus-bar switchable Shunt Reactors application philosophy in the Brazilian 800 kV transmission system owned by FURNAS.](image)

The design criterion for dimensioning the CB opening resistors was to use the same ohmic-value-range of the SR surge impedance, meaning it was necessary to provide CB with opening resistors in the range of 3.000 ~ 4000 Ohms [2]. The nominal reactive power of such SR at industrial frequency is 330 Mvar/765 kV.

In this case, there was no control over the arcing time of the SR current within the CB chambers during the switching off procedure. Therefore, this could lead to reignitions when the arcing time was too small, causing new overvoltages with very high front steepness.

For the above mentioned case, computer simulations and field tests have been performed in order to demonstrate the project effectiveness such as good sharing of voltages and currents by the main and auxiliary (with the opening resistor) chambers of the circuit breaker, and very low probability of occurrence of reignition within the circuit breaker chambers.

The design of the circuit breaker has been optimized so that the insertion of the 4000 Ω opening resistor is given by the contacts opening in the main chamber, corresponding to a current chopping of 80 A, and, after an insertion time of 15ms, the contacts of the auxiliary chamber then open, corresponding also to a similar current chopping of 10 A.

The one-line diagram, shown in Figure 2, represents shunt-reactor switching scheme and circuit data used for computer simulations.
One can see at the graph on the upper part of Figure 3 the currents through the main and auxiliary chambers of the circuit-breaker in one phase (where the current chopping phenomenon is clearly seen). The maximum current and energy at the surge arresters are shown at the graph on the lower part of it, obtained from computer simulations.

Figure 4 shows the graphs of the voltage measured at the reactor terminals to ground obtained from both computer simulation and field test.

The current chopping, mean a sudden change to zero in the magnitude of the SR nominal current, and forces the ‘magnetic field’ energy, stored in the reactor coil, to be converted to ‘electric field’ energy, stored within the stray capacitances, causing, thus, sudden changes in the load-side transient voltage. The lower the stray capacitances are the higher the chopping overvoltages will be during the occurrence of current chopping.

This transient phenomenon is related to the fact that, during the SR switching-off, the nominal current is forced to zero suddenly, and prior to the natural power-frequency-zero-crossing, within the CB chambers, leading to such a phenomenon known as ‘current chopping’. Thus, the current chopping, meaning a sudden change to zero in the magnitude of the SR nominal current, forces the ‘magnetic field’ energy, stored in the reactor coil, to be suddenly converted to ‘electric field’ energy, stored within the stray capacitances, causing, thus, sudden changes in the load-side transient voltage. This energy-transfer-phenomenon is known as ‘chopping overvoltage’, shown in Figure 5.
The related current chopping switching transient can lead to a transient recovery voltage (TRV) across the circuit-breaker chambers that should be investigated, in principle, as a big concern, in order to avoid undesirable damages to the SR, or even to the CB.

One must have in mind that the lower the stray capacitances are, the higher the chopping overvoltages will be during the occurrence of current chopping. For higher EHV levels, there are higher stray capacitances values related to the SR and CB. Therefore, for 800 kV, at a first sight, the chopping overvoltages (suppression peak overvoltage) would not be such a big concern as in lower voltage levels, since there are significant stray-capacitances related to such equipment.

The field experience in FURNAS has shown it was much more reliable and secure to have a complete control over the possibility of no-reignition during the SR switching off, by means of using CB equipped with controlled switching [3], compared to the increase in current chopping overvoltages. In the case of 800 kV switchable SR, the increase of chopping overvoltages, derived from the increase of minimum arcing time (given by the CB with controlled switching), is very small, due to the fact that the stray capacitances of the SR windings are quite significant.

The application of controlled switching technology in this case showed to have a very good performance for transient switching overvoltages mitigation, avoiding completely the possibilities of reignitions during the switching off procedure of SR, since the convenient minimum arcing time could be properly controlled for that purpose. The extensive field tests/measurements performed by the company proved such expected performance during several switching off operations of the existing 800 kV busbar SR. Figure 6 shows switchable 330 Mvar/765 kV Shunt Reactor installed at the bus-bar of Itaberá Substation, as part of Itaipu AC Transmission System.

![Figure 5 - Current chopping and suppression peak overvoltage](image1)

![Figure 6 - Shunt Reactor of 330 Mvar/765 kV at Itaberá Substation](image2)
[1] FURNAS Centrais Elétricas S. A. - Brazilian state-owned power utility for generation and transmission of bulk energy
