USE OF CONTROLLED SWITCHINTG SYSTEMS IN POWER SYSTEM TO MITIGATE SWITCHING TRANSIENTS. TRENDS AND BENEFITS – BRAZILIAN EXPERIENCE

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Abstract– Switching transients in power systems have always been a matter of concern in studies of power equipment insulation coordination. However, considering the new institutional, environmental and economic existing constraints in most of the power systems all arround the world, and, still, with the growing of the use of sensitive loads - from home digital clocks to fully automated industrial production lines, in the last few years -, these power system transients could become, more and more, a big issue.

This paper aims to present some aspects regarding relevant switching transients in power systems and the means to mitigate them. It will present the classical means of mitigation, such as circuit breakers with pre-insertion resistors, etc. However, the main focus will be on controlled switching systems (CSS), since it is becoming more and more an atractive way, technically and economically speaking, to mitigate such switching transients and to improve power quality (PQ), in order to cope with the new power system requirements and constraints.

In the case of Brazilian interconnected power system, supply is usually provided by long EHV transmission lines, not only to connect far hydroelectric power plants to the main load centres, but also to interconnect power systems of different regions. Due to the long distances between load centers and generation plants, several transmission lines and substations of 550kV up to 800 kV had to be built in the country, soon after these voltage levels started to be used by utilities in other parts of the world. And, as a consequence of such peculiar characteristics of the Brazilian power system, there is the need of many voltage control equipment, such as shunt capacitor banks and reactors. Still, the switching of long EHV transmission lines and power transformers in such system has become a special issue. Examples of switching transients problems occurred in the Brazilian interconnected power system and how they can be mitigated will also be presented.

Whenever possible, it is also presented available data considering cost reduction regarding power equipment, due to the use of such controlled switching systems. The cost reduction is possible, mainly, by reducing insulation levels of large capacitor banks, eliminating circuit-breakers auxiliary chambers, reducing transmission lines costs, due to a possible compaction and reducing arresters rating..

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I. INTRODUCTION

Brazilian power supply is usually provided by long EHV transmission lines due to the power system characteristics in this country, not only to connect far hydroelectric power plants to the main load centers, but also to interconnect power systems of different regions. Due to the long distances between load centers and generation plants, several transmission lines and substations of 550kV up to 800 kV had to be built in the country, soon after these voltage levels started to be used by utilities in other parts of the world.

It will be presented some aspects regarding switching transients in Brazilian power system, in the context of insulation coordination and also power quality. It will be seen the means to mitigate them, such as circuit breakers with pre-insertion resistors, controlled switching systems (CSS), current limiter reactors and zinc-oxide arresters.

It will also be made a performance comparison among the devices used to reduce switching transient over voltages and over currents, emphasizing which is the best solution for each case presented.

But special attention is given to the nowadays available technique used to mitigate these switching transients in power systems, i.e., controlled switching systems (CSS) using synchronizing devices.

To illustrate, some examples of costs reduction, regarding power equipment, due to the use of controlled switching, mainly reducing insulation levels of large capacitor banks, circuit-breakers auxiliary chambers elimination, arresters rating reduction and transmission lines costs, due to a possible compaction will be shown.

The paper deals with the main characteristics, the typical voltage and current wave-shapes and amplitudes of switching transients, basically in the following four situations of interest in power systems:

-switching on of large power system capacitor banks;

-long EHV transmission lines energization and automatic reclosing;

-power transformers energization;

-shunt reactors de-energization.

II. COMMENTS ON CONTROLLED SWITCHING

Controlled switching, as a technical solution for switching-surge limitation, is not a new idea. This possibility and its benefits had already been investigated almost 30 years ago, particularly for no-load line and capacitor banks switching on. However, satisfactory technological solutions to put in practice the idea of synchronous-switching could only be developed in more recent times, thanks to the evolution of high-voltage circuit breaker designs and to the development of micro-electronic devices applied to power systems. The experiences acquired with the use of synchronous-switching in power systems have shown that this technique can be very efficient to control switching transients, having thus become a powerful means at the disposition of utilities to help them meet both stringent insulation coordination requirements and power quality improvement.

The basic idea of controlled switching devices is to comand precisely the mechanical closing or opening of circuit breaker contacts at optimal instants or angles, regarding power frequency voltage and current respectively. In this way, switching transients could be greatly reduced, eliminating stresses within system equipment and also improving power quality supply levels. Such device consists basically of a zero detection module, a delay-time calculation module and the power module, which receives the comand from the second described module and send a power signal to the breaker close coil or open coil.

It is relevant to say that, for closing switching performance, the statistical characteristics of breaker contacts scatter and the behaviour of dielectric strength between closing contacts (withstand voltage decay) are very important parameters. These two characteristics will determine the maximum making voltage between breaker contacts, specially in compensated transmission lines reclosing application and, thus, the mitigation level of switching transients.

III. TRANSMISSION LINES SWITCHING

The energization and automatic reclosing of EHV transmission lines can cause high transient overvoltages. As mentioned before, this has always been a matter of concern in studies of insulation coordination. Going ahead in nowadays challenges, and taking into account the power quality issues, these transient overvoltages may contribute to sensitive load supply interruption. This could occur if the technique used to reduce and control switching transient overvoltages does not limit the overvoltage values in acceptable levels, regarding the protection operation of the substation equipment or of other lines connected to the sending end point of the switched transmission line. This could happen specially in unusual system configurations, as during restoration procedures.

To meet modern challenges in transmission systems, compacted line designs have been indicated as a solution for the ever-increasing need to transmit great amounts of power, since a reduced number of transmission lines is required (which also means less right-of-way). Comparing to conventional lines, the compact ones warrant a considerable power transmission increase and also, in some contexts, a series compensation reduction. The conventional and compact tower differ basically in the phase-to-phase distance. For compact towers it can be 50% shorter, according to insulation coordination criteria, which leads to a lower line surge impedance and, consequently, a higher surge impedance loading (SIL). Since the phases in compacted lines are closer, the insulation failure risk increases, hence effective overvoltages control devices must be used.

To avoid such problems, some switching overvoltage reduction techniques are widely used, such as metal-oxide arresters (MOA) and/or breakers with closing resistors (PIR). The usual closing resistor and insertion time values are around 400 Ohms per pole and 8 to 12 milliseconds, respectively. This closing resistor values correspond approximately to the surge impedance of EHV transmission lines.

More recently CSS and ZnO arresters became available to be used together. As the initial amplitude of voltage wave propagation at the instant of line energization, due to the closing of the circuit-breaker contacts, depends on the voltage across these contacts, the switching transient overvoltage can be effectively limited by means of the control of the instant the breakers close in each phase, regarding the instantaneous values of system voltage and residual line voltage (due to line trapped charge), in case of reclosing.

The closing resistor is still the most used conventional way for reducing the transient overvoltages in this case. Although controlled switching seems to be a comparable solution, for line switching overvoltage control it has not been applied widely up till now, since development in this area is very recent. The controlled switching basic characteristics (circuit-breaker and synchronizer scatters) must assure, at least, the same results obtained with the PIR, regarding switching transient overvoltage mitigation.

A performance comparison among these transient overvoltage reduction techniques can be done using the results of a TNA study, where it was simulated the circuit showed in Fig. 1. The simulated conditions consisted of the following operations:

- line energization;
- tripolar high speed line reclosing;
- monopolar high speed line reclosing

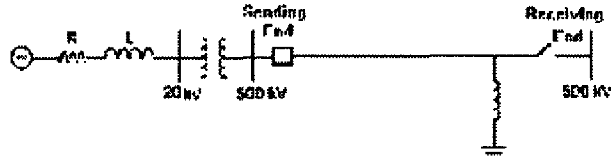

Fig. 1. Schematic one-line diagram of the studied system

Table I shows the maximum values obtained for several system configurations Three different ways of overvoltage control were tested: only surge arresters (MOA); MOA plus pre-insertion resistors (PIR) and MOA plus synchronizers or controlled switching system (CSS).

Another performance comparison amongst these transient overvoltage reduction techniques was done using the results of statistical digital simulations with the aid of the Alternative Transients Program (ATP) for two different tower designs, i.e., conventional and compact ones.

The simulations were based on the same statistic criteria of TNA study, to the same system described in Figure 1. The circuit-breaker main requirements are the rate-of-decay of the withstand voltage of the contact gap for closing operations (du/dt | CB) and the scatter (□1) of the mechanical closing time, defined in terms of a standard deviation of a Gaussian distribution. The requirements for the controller performance itself can be generalized in terms of the standard deviation (□2) of the scatter of the real switching instant, determined by the controller, in relation to the optimum instant, which would eliminate the switching stresses [6]. Controlled switching requirements values normally used are presented below:

- du/dt | CB > du/dt of the power frequency voltage at zero crossing (allowing to close at zero voltage);
- □1 = 0.5 ms (typical value according the nowadays circuit breakers technology [3]);
- □2 = 0.6 ms (for no-load line auto-reclose [4]);
- □2 = 0.15 ms (for no-load line energization [4]).

A resume of the statistical ATP results is presented in Figure 2. The results are related to the middle of the line, where the highest overvoltage levels occur, since overvoltages at both ends of the line are limited by the MOA plus compensation provided by shunt reactor.

From the results showed in Table 1 and Figure 2, it is possible to observe the effectiveness of the application of closing resistors or CSS, regarding the control or limitation of phase-to-ground switching overvoltages. These devices effectively control transient overvoltages and keep the energy absorption levels of arresters far below their capacity. It can also be seen, by the results obtained, that this effectiveness of PIR and of CSS in controlling transient overvoltages are quite comparable, with a small advantage for closing resistors, which are more efficient, mainly in automatic reclosing. The advantages of CSS in this comparison is the cost reduction of line breakers, by elimination of some components as auxiliary chambers, and an improvement of this equipment reliability, since many utilities often report problems with pre-insertion resistor mechanisms during the operational life of EHV circuit breakers.

TABLE I

Switching overvoltages during EHV line energization and auto-reclosing of Fig. 1. -

(1) - with MOA only; (2) - with PIR plus MOA; (3) - with CC plus MOA

Case description	Maximum peak overvoltage at line receiving end(p.u.)			Maximum peak overvoltage at half line (p.u.)			Arrester energy at line receiving end (MJoule)		
	Max	Mean	Standard deviation	Max	Mean	Standard deviation	Max	Mean	Standard deviation
energization (1)	1.81	1.74	0.02	2.20	1.93	0.09	1.70	0.43	0.23
energization (2)	1.70	1.63	0.03	1.80	1.62	0.07	0.25	0.05	0.04
energization (3)	1.72	1.68	0.01	1.86	1.74	0.02	0.46	0.25	0.04
3f reclosing (1)	1.85	1.76	0.04	2.80	2.20	0.23	2.10	1.03	0.43
3f reclosing (2)	1.68	1.57	0.07	1.78	1.50	0.1	0.33	0.18	0.03
3f reclosing (3)	1.80	1.71	0.05	2.35	1.90	0.21	1.20	0.44	0.28
1f reclosing (1)	1.80	1.69	0.08	2.30	1.83	0.25	1.40	0.56	0.43
1f reclosing (2)	1.68	1.47	0.12	1.63	1.36	0.11	0.28	0.19	0.03
1f reclosing (3)	1.78	1.70	0.04	1.90	1.60	0.09	0.55	0.34	0.14

IV. CAPACITOR BANKS ENERGIZATION

Closing switching of large capacitor banks in power systems may generate transient overvoltages and large inrush currents. Specifically in back-to-back configurations - where a capacitor bank is energized very near, electrically speaking, of other capacitor banks already energized - the transient inrush currents have a component of high frequency (up 10 kHz) which damps in about one or two cycles. These switching transients may cause local stresses to the substation's equipment and/or remote effects at the far end of transmission lines connected to the mentioned substation. During the switching off of capacitor banks, transients are not a problem normally. In this case the maximum overvoltage levels are quite well controlled by surge arresters and TRV (Transient Recovery Voltage) has a low slope. Also, the currents are not of great amplitudes and, thus, they do not represent a big issue.

Regarding local substation equipment stresses due to the transients generated during the switching on of capacitor banks, there may be mechanical and dieletric damages with capacitor bank cells or its circuit breaker, strong erosion of circuit breaker contacts, transient potential rise of the substation grounding mat and transient noise affecting control and protection systems. Remote effects may be overvoltages at the far end of radial connected transmission lines and/or overvoltages in secondary of transformers at the far end of these lines. These overvoltages depend on the amplification factors, applied over the voltage traveling waves injected into these lines by the capacitor bank switching, or possible resonances within this system.

Brazilian power system has experienced some of these related problems due to large capacitor banks switching. Some of them, and their consequences, will be described hereafter.

One of such examples, which is worth to mention, is the case of a capacitor island of 4 x 200 MVAr/345 kV sited at the far end of Itaipu power plant transmission system. It is foreseen that this island will have ten capacitor banks in near future, resulting in 2,000 MVAr of shunt capacitive compensation. In such case, the transient overvoltages were not significant, being the interest concentrated only in mitigating the transient overcurrents effects, since they indeed were causing equipment damage (erosion of breaker contacts and damage of many capacitor cells). These problems were resulting in equipment operating availability reduction (capacitor banks and their breakers) and system operation reliability reduction.

It has been also experienced problems related to strong flashovers between grounded parts of equipment structures in another substation of Brazilian interconnected system, when existing capacitor banks at the substation were energized in some back-to-back configurations. This was caused by transient potential rise of the substation grounding mat during these capacitor banks energization. In this case the use of CSS could eliminate the problem.

Sometimes, in order to reduce transient inrush currents when energizing a large power system capacitor bank it is used a current limiter reactor in series with capacitor bank. Although this alternative is one of lowest costs, it does not control transient overvoltages, besides it might have problems regarding resonances with power frequency current or voltage harmonics, which could flow into the capacitor bank. An advantage of this technique is to provide also short-circuit current reduction in the capacitor bank bay. This sometimes may be helpful in reducing the influence area of sensitive load disturbance. The common criterium to determine this area is to find the places in power system where a short-circuit aplication reduces the voltage under certain limits, for instance below 0.5 or 0.7 pu levels.

V. POWER TRANSFORMERS ENERGIZATION

Power transformer energization inrush currents can reach up 10 or 20 times the nominal current, reaching values near the magnitude of short-circuit currents. This phenomenum can affect greatly the power quality in the power system, since there may be protection system misoperation - of the switched transformer itself or of other transformers sited electrically near it (sympathetic interaction). The undesidered outage of power transformer due to this phenomenum can interrupt the supply of appreciable amounts of loads. The presence of high inrush currents fowing into the power system may cause also unacceptable voltage variations, regarding the sensitive loads supplied.

The usual mean to mitigate switching transients of power transformers is the use of closing resistors in their circuit breakers. More recently, the use of CSS is also becoming available.

The idea with the use of closing resistor is to reduce the instantaneous voltage values, during the first half-cycle of system voltage wave, applied to windings of the transformer which is being energized. Thus, the first sinusoidal flux peak would be much lower than it could be if no closing resistors were used, since the flux wave is obtained by integrating the voltage signal applied to the windings. This reduced flux peak added to residual flux will not allow strong saturations of transformer iron core. The usual values of closing resistors and insertion times used to switch on power transformers of 230 kV up to 800 kV are 400 to 800 Ohms per pole and 8 to 12 milliseconds respectively.

Nowadays we already can foreseen the use of CSS to reduce inrush currents when a power transformer is energized. The ideal situation is achieved when the residual flux in its iron core is well-known previouslly the energization switching. As the sinusoidal flux caused by the applied system voltage is superimposed upon the residual flux, the optimal instant of breaker closing can be achieve using the controlled switching, in order to add initially a sinusoidal flux with an opposite signal with respect to the residual flux. In this case, there will not be saturation, or it will be very weak, resulting in very low amplitudes of magnetizing currents during the first cycles (inrush currents), which is the desired result.

However, it is generally very difficult to determine the values or even the signals of residual fluxes, specially on transformers which have delta connections, normally with tertiary windings. For practical purposes, there is a general rule that can be applied, establishing the optimum closing instant around + 90 or -90 degrees, regarding the applied system voltage to the transformer winding.

In the Brazilian interconnected system it was already observed transformers trip out afterwards energization of other transformers. One of these events ocurred in 1997 during the execution of special field tests to obtain the real saturation curve of a 345/230 kV - 225 MVA power transformer. During these field tests, the 345 kV side breaker was closed at the system voltage wave zero-crossing level. Doing so at the appropriate moment, the sinusoidal flux was added to the known residual flux, previously set in the transformer iron-core. Thus, the total flux reached the level of 1.7 pu. This strong saturation of the transformer iron core had created a possible condition in order to produce transferred saturation (sympathetic interaction) amongst transformers, and it happenned in this case. Due to the transferred saturation, during the execution of such saturation curve measurements, it was registered undesired trip of two nearby SVC transformers, right afterwards the tested transformer breaker was closed by the controlled switching device commanded by the Furnas' on-site laboratory. This ocurred due to primary neutral overcurrent protection operation. If the parallel transformers' protection had operated also, there would have been interruption of a great amount of loads supplied by these set of 345/230 kV - 225 MVA transformers at this substation.

VI. SHUNT REACTORS

The switching off operation of shunt reactors generates transient overvoltages due to current chopping and reignition. The first one is created by the chopping of the reactor inductive current before its natural zero crossing. This occurs in all inductive loads switching off, in more or less degrees of severity. The last one is created when recovery voltage between breaker contacts exceeds the dielectric strength of the gap. The problem in this case is the rate of rise of recovery voltage, that may damage the windings insulation .

Synchronous opening of shunt reactor banks reduce almost to zero the probability of reignitions, by setting the mechanical opening instant of each breaker pole a little after the current zero crossing, in order to increase arcing time. This allows sufficient mechanical separation between breaker contacts at the instant the electric arc is extinguished, providing the breaker dieletric cold characteristc value will be high enough to guarantee there will not have reignitions, although longer arcing times increase chopping overvoltages.

This application is widely used in Furnas electric power system shunt reactors. There are shunt reactors of 150 MVAr/525 kV and 330 MVAr/765 kV which circuit breakers are openned by means of synchronizers since 7 years ago, with excellent results. In this case it was observed only a small overvoltage due to current chopping of the longer arcing times (about 1.1 to 1.2 pu of operating voltage). Before using this technique it was experienced shunt reactor insulation damage in Furnas power electric system due to reignition overvoltages. It resulted in equipment explosion, fault protection operation and unavailability of transmission lines. This occurrence affected strongly the power system reliability.

VII. EQUIPMENT COST REDUCTION DUE TO CONTROLLED SWITCHING

Regarding capacitor banks, the cost reduction that can be obtained using controlled switching can be illustrated with the capacitor island mentioned in item 4. Considering the final island configuration (10 capacitor banks), the elimination of auxiliary chambers in circuit breakers and the capacitor banks being specified with a higher electric field inside capacitor cells, permit a total reduction cost of about 8 million dollars of such equipment, besides allowing an increase of equipment availability and system reliability.

Regarding compacted transmission lines, besides several other advantages, line compaction brings also great benefits, in terms of cost reduction, since it permits a lower transmission cost per MW. This is possible since compacted lines have a higher SIL, allowing the transmission of the same amount of electric power with a lower number of circuits, although the compacted line cost itself is greater than the cost of a conventional one. It is expected that, with the technology evolution, the CSS effectiveness on controlling switching over voltages in transmission lines will increase, allowing the use of even more compacted towers' geometry.

In such compacted lines, the shunt reactors and metal-oxide arresters (MOA), and eventually CSS, would act controlling the phase-to-ground transient over voltages, as it could be seen in the given examples of Fig. 2. Since the phase-to-ground transient overvoltages are limited on both ends of the transmission line due to the application of MOA and CSS, the highest phase-to-ground transient overvoltage levels may occur in the middle of the line. In this case, the phase-to-ground overvoltages can be reduced by using MOA also in the middle of the line, as they are used on both ends of it.

But, in the case of CSS application in transmission lines, it is also possible to think that it may be able to control phase-to-phase transient overvoltages too. This last aspect, indeed, would be the „key" aspect to have the line compaction more feasible.

Of course we have to consider such costs in the context of each transmission system, which means that several parameters, besides those already considered above, would have to be taken into account in order to evaluate properly the cost reduction. Such parameters include the transmission amount of power, the electrical distance between phases considering corona effects, the voltage control requirements, environmental constraints to build up more transmission lines, right-of-way constraints-costs, etc.

Just to give an idea regarding general costs, considering an integration system which have to be build up to deliver power from a new hydro powerplant into an already existing transmission network, using a 500 kV transmission system, in the less optimist perspective, using 4 parallel circuits of compacted lines configuration would correspond to 5 circuits of the conventional 500 kV transmission line used in the past.

This, in the transmission alternative as a whole, would save .6 per unit of construction costs of one line, 30% to 40% less of right-of-way costs, and much less environmental interference.

However, it is important to point out that, even if the performance of CSS in transmission lines allows more and more control over switching transient over voltages, making it feasible to use higher degrees of line compaction, the corona effect will settle a physical limit to this compaction, due to the increasing of electrical field related to the approximation of line phases.

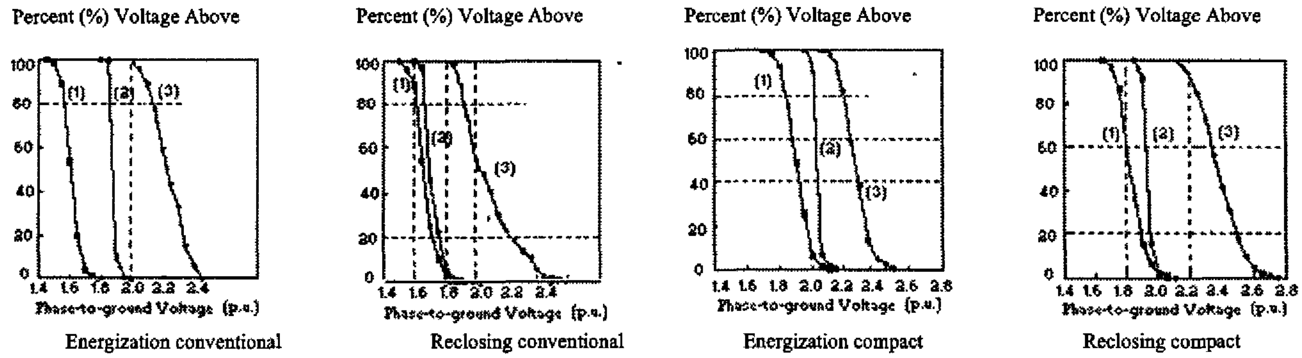

Fig. 2. ATP Statistical Overvoltages Results (1 p.u. = 408kV peak phase-to-ground) - (1) With PIR (2) Synchronous Closing (3) Only MOA

VIII. CONCLUSIONS

The use of switching transients mitigation techniques in power systems helps to improve power quality in general sense. Also can be stated that the controlled switching devices (CSS) are becoming more and more available to perform such role, besides allowing significant equipment cost reduction.

It is also relevant to point out that analyses of this nature (over switching transients mitigation) have always been a matter of concern in studies of equipment insulation coordination. Howerver, it is necessary nowadays to go ahead and take power quality issues also into account, since these power system switching transients may affect sensitive load supply.

It was seen that the application of CSS can afford a more wide use of compacted lines in power systems. In terms of capacitor banks the use of controlled switching permits to avoid equipment damage, voltage oscillation and sensitive load disturbance. Regarding power transformers energization, it is possible to avoid, mainly, the occurrence of sympathetic interaction and its undesired consequences. To shunt reactor switching off, there are benefits in terms of avoiding equipment damage due to re-ignition elimination.

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