EXPERIENCES WITH IMPROVING POWER QUALITY BY CONTROLLED SWITCHING

Michael Stanek*
ABB Switzerland Ltd, High Voltage Technology
Switzerland

Includes contributions by

A.C. Carvalho, ABB Brazil Ltd, Brazil
J.H. Sawada, D.F. Peelo, B.C. Hydro, Canada
P. Alatalo, Avesta Polarit Oy, Finland
W.J. Bergman, PowerNex Associates, Canada
G.T. Bowden, AltaLink, Canada

1 Introduction

Switching operations in power networks are a common cause of transient disturbances. Depending on the network configuration and the characteristics of the switching condition, these transients can cause undesirable effects, not only on the switched load, but also on the entire network. As a consequence, the power supply can be drastically affected, as for example by nuisance protection operation due to high inrush currents, or undervoltage due to transformer energization. Such disturbances can in turn provoke interruption of power supply to certain loads or parts of the network. Also, sensitive industrial processes can be severely impacted even if no power supply interruption occurs. Therefore, it is desirable to eliminate these potentially dangerous switching transients as far as possible.

Various means of reducing switching transients, such as pre-insertion resistors or inductors as well as metal oxide surge arresters, have been used traditionally. In the 1990s, a very competitive method has become widely available, namely the application of controlled switching [1,2]. It is generally agreed that utilization of this technique can significantly reduce switching transients and thus improve power quality.

Controlled switching is applied to limit the consequences of a switching event on the switched equipment, on the circuit breaker, and/or on the power system. It has been successfully applied to closing on shunt capacitor and filter banks, unloaded transformer switching, shunt reactor switching, and to energization and high-speed auto-reclosing on EHV transmission lines. A summary of the value of controlled switching for power quality in these applications is shown in Table 1.

Power quality can be described in terms of voltage as any deviation of the magnitude, frequency, or purity from the ideal sinusoidal voltage waveforms. Typically, the deviations are classified as follows [4]: transients (impulsive or oscillatory), interruption, voltage dip (sag) or undervoltage, voltage swell or overvoltage, voltage unbalance, waveform

Table 1: Applications and consequences without and with controlled switching

Application	Consequences on Power Quality	
	Without Controlled Switching	**With Controlled Switching**
Closing on shunt capacitor or filter banks	Severe voltage dip and recovery transient at station bus; transferred surges to other parts of the system including customer owned stations.	Virtually eliminates the voltage dip and subsequent transients and surges.
Closing on unloaded power transformers	Severe voltage dip at station bus can occur; in addition, inrush current may cause protection misoperation.	Virtually eliminates the voltage dip, inrush current limited to almost steady state value.
Transmission line auto-reclosing	Switching overvoltages and possible unsuccessful reclosing caused by breakdown of line insulation.	Limits switching overvoltages, thus reducing the probability of unsuccessful reclosing with its associated consequences.
Shunt reactor switching	Reignitions which can be damaging to the shunt reactor and some circuit breakers; reignitions may also cause protection misoperation.	Eliminates reignitions.

* ABB Switzerland Ltd, High Voltage Technology PTHS-T, 8050 Zurich, Switzerland. Email: michael.stanek@ch.abb.com

distortion (i.e. DC offset, harmonics, interharmonics, notching, noise), voltage fluctuations (flicker), and power frequency variations. In the context of controlled switching, it is the deviations and consequences associated with voltage sag, transients, and interruptions that are of interest. Energization of shunt capacitor banks and power transformers has a direct influence on power quality, while that of transmission line reclosing is directly or indirectly dependent on the nature of the power system.

2 Capacitor Bank Energization

Together with lightning, capacitor switching is one of the two main sources of transient overvoltages on utility systems [4]. These overvoltages, in conjunction with the inrush currents, will manifest themselves locally in the substation as well as at remote locations on the power system [1,5]. Local effects include mechanical and dielectric stresses on substation equipment, transient potential rise of the substation earthing, and transient surges coupling to control and protection wiring. Remote effects include transfer of capacitively coupled fast transients through transformer windings, overvoltages on open ended or transformer terminated lines, and excitation of near resonant portions of the power system by the oscillatory transient frequency. These effects can in turn cause nuisance trip of protection relays with all its associated consequences.

Controlled closing at voltage zero across the circuit breaker can almost completely eliminate the switching transients, for both single bank and back-to-back switching [1,5].

A Canadian utility has been using controlled closing for 138 kV capacitor banks since 1985. Two 55 MVAr capacitor banks are installed at Lamoureux substation, which is located close to Edmonton, Alberta, Canada. Fig. 1 shows energization of a single capacitor bank without synchronized closing. Fig. 2 shows the effect of synchronized closing for the same switching case. The distinct reduction in inrush currents and transient overvoltages with the use of synchronized switching can be clearly seen from these oscillograms.

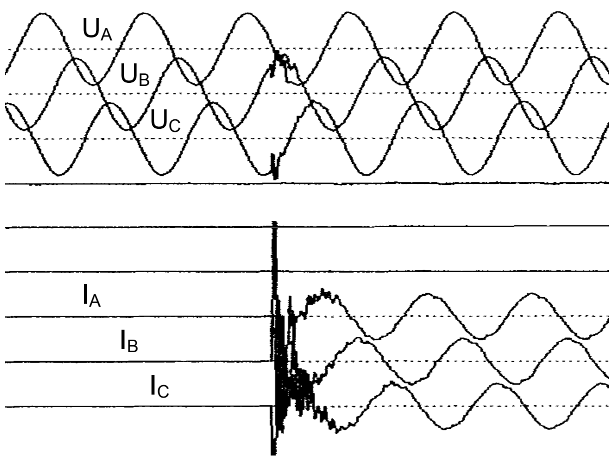

Fig. 1. Non-synchronized closing of capacitor C_2 at Lamoureux with no other capacitor bank energized. Top three traces: busbar voltage. Bottom three traces: capacitor current.

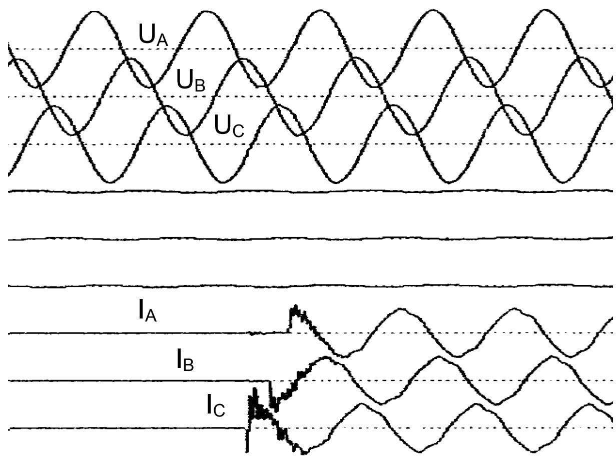

Fig. 2. Synchronized closing of capacitor C_1 at Lamoureux with no other capacitor bank energized.

Before the introduction of controlled switching, energization of a capacitor bank occasionally caused problems at an industrial supply substation located approximately 17 km from Lamoureux. In one event, a switching transient from Lamoureux was sufficiently high to result in surge arrester operation at that substation. This in turn caused two bus differential protection relays to trip out a large refinery in the middle of the winter. This single incident involved commercial losses of the customer in the range of several million US Dollars.

This utility now installed synchronized closing control on most capacitor banks in its network. (Some capacitor banks have pre-insertion closing reactors.) With that, power quality during capacitor bank energization has been significantly improved by reducing transient overvoltages and inrush currents with their associated effects on system customers.

3 Energization of Arc Furnace and Static Compensator

A stainless steel plant in Finland uses electricity as the primary energy source for production. The plant employs its own industrial substation with an average consumed power of 240 MW at 20 kV general distribution voltage. It has a production output of 550,000 tons of steel per year.

3.1 Arc Furnace

In this plant, an arc furnace rated 55 MVA (40 MW average) at 20 kV is used for refining Ferro-chrome steel. The same 20 kV bus that supplies the energy for the arc furnace also feeds other industrial equipment such as a cold rolling mill and an annealing and pickling line. A harmonic filter (3rd harmonic) is the only means of improving power quality on this busbar.

A long standing problem had been energization of the arc furnace, which is essentially a power transformer with load: in many cases switching on created high inrush currents, in conjunction with voltage sags. This is demonstrated by the oscillogram in Fig. 3, where inrush currents of almost 10 kA and a voltage drop down to 0.7 pu. were observed. These effects often caused tripping of protection devices and thereby a forced outage of several production areas. The financial loss from these situations amounted up to $50,000 US per year.

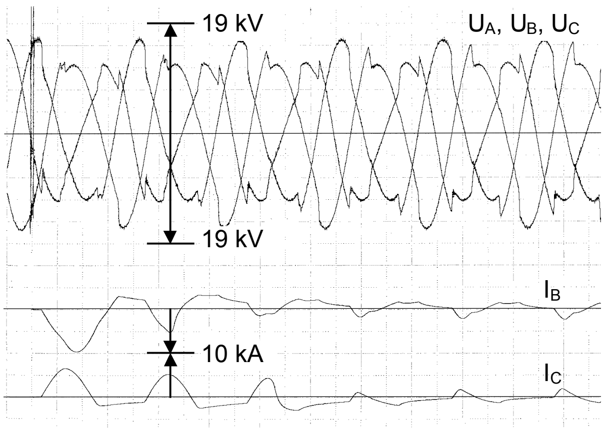

Fig. 3. Uncontrolled energization of arc furnace.

3.2 Static Compensator

In the same stainless steel plant, a static var compensator (SVC), rated 65 MVAr, is connected to another 20 kV busbar. Its purpose is to supply reactive power to the large motors of the hot rolling mill, in order to keep the feed rate, and thus product quality, constant.

Energization of the compensator negatively impacted power quality because of the switching transients. Fig. 4 shows a typical energization with inrush currents in excess of 6 kA and a voltage swell to more than 1.5 pu. Again, the result of such an event often was tripping of protection relays with all its negative consequences.

3.3 Energization Procedure

In order to cope with the switching problems described above, a special energization procedure was adopted: Production in all rolling mills as well as in the Ferro-chrome processing area had to be reduced to 50% of its normal power consumption, then the arc furnace or static compensator was connected to the busbar, and finally production was resumed in all areas.

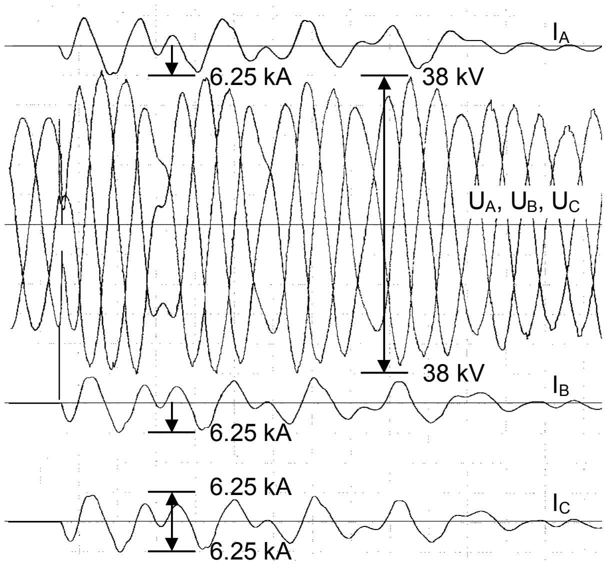

Fig. 4. Uncontrolled energization of static compensator.

This procedure took about ten minutes and had to be performed weekly. It resulted in a yearly loss of 9 production hours or 600 tons of steel per year. It is evident that this situation was not satisfactory from both economical and technical points of view.

3.4 Improvements by Controlled Switching

A permanent solution for both energization problems was found in controlled switching, using special medium voltage circuit breakers with independently operated poles. The scheme was put into service in September 1997 and has brought tremendous improvements in power quality:

- inrush currents reduced to less than 1 kA for the arc furnace (Fig. 5) and less than 4 kA for the static compensator (Fig. 6);
- sags or swells of the busbar voltages practically eliminated;
- no more production outages (forced or operational) when energizing either component.

The total savings in this plant by the use of controlled switching are estimated in the range of $100,000 US per year. Considering a period of 20 years (estimated life time of the installation) and an annual interest rate of 7%, the present value of the savings amounts to approximately 1 million US Dollars.

Encouraged by the success with the two installations described above, the stainless steel plant also installed a controlled switching system for a new 110 kV arc furnace (75 MVA, 65 MW). It has been in service since September 1998 and has been giving similarly positive results.

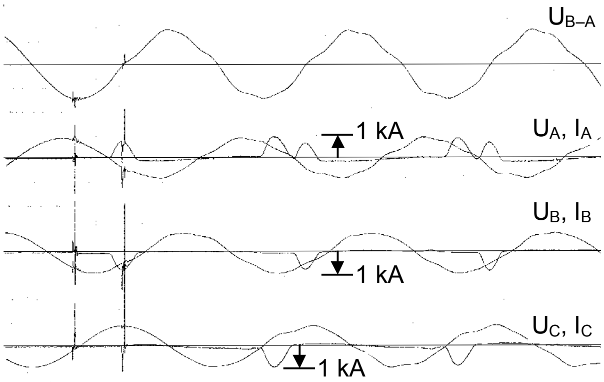

Fig. 5. Controlled energization of arc furnace, not taking into account the transformer core's residual flux.

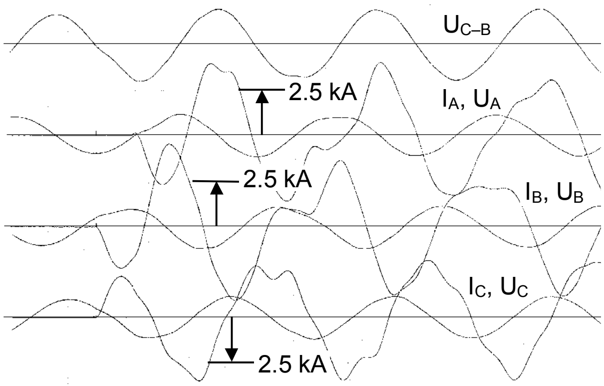

Fig. 6. Controlled energization of static compensator.

4 Transmission Line Energization and Auto-Reclosing

Due to the capacitive behavior of an unloaded transmission line, normal energization of a line is similar to the case of capacitor banks described above. An additional benefit of controlled closing can be found when used in EHV or UHV networks, where the line insulation level is determined by the switching rather than by the lightning overvoltages. The value of controlled transmission line auto-reclosing lies in limiting the switching overvoltage transient level, which may otherwise assume values up to 4 pu on a long line. Thus it enables—in combination with appropriately applied line surge arresters—switching overvoltage control along the entire length of the line. It was shown that by implementing such a combination it is possible to reduce the line insulation level to values as low as 1.7 pu, as was demonstrated elsewhere [2]. A lower insulation level can result in lower costs for the towers, which in the cited example amounted to more than 1 million US Dollars.

Fig. 7 shows a controlled auto-reclose trace from a field test on a Canadian 500 kV system. In this situation, the optimum moment for reclosing is at a voltage zero across the circuit breaker ($U_B – U_L$). Although the trace is too slow to capture very short transients, it can be seen that the busbar voltage shows practically no distortion around the making instant. With current making in a beat minimum of the differential voltage, the probability of a prestrike is also very low.

It is conceivable that without controlled switching the switching overvoltage may lead to an unsuccessful reclose in a previously healthy phase, as happened to a Canadian utility many years ago. (Unfortunately, no details on this event are available any more.) In a meshed system it is assumed that all customers, while not necessarily suffering a service interruption, will be exposed to voltage sags, system swings, and possible generation shedding and more system swings; and even possible travelling wave effects elsewhere in the system. The scenario assumes an unsuccessful reclose due to the switching transient, and the value of controlled switching is to eliminate the unsuccessful reclose and the subsequent trip and reclose with all associated power quality consequences.

5 Conclusions

The practical examples presented in this paper demonstrate the effectiveness of controlled switching as a means to reduce the effects of switching operations in various applications. For energization of capacitor banks, the transient switching overvoltages can be practically eliminated. This is also true for energization of unloaded transmission lines, where the extra benefit of a reduced line insulation level can be gained in EHV networks. In addition, controlled auto-reclosing of transmission lines reduces the risk of unsuccessful reclosing. On arc furnaces and other transformers, controlled switching significantly reduces the inrush current and possible associated voltage dip, which otherwise may cause nuisance trip of protection circuits. Similar benefits can be gained for controlled energization of a static VAR compensator, where the voltage swell is practically eliminated. Thus, controlled switching presents itself as an ideal solution for power quality problems associated with switching operations in high voltage networks.

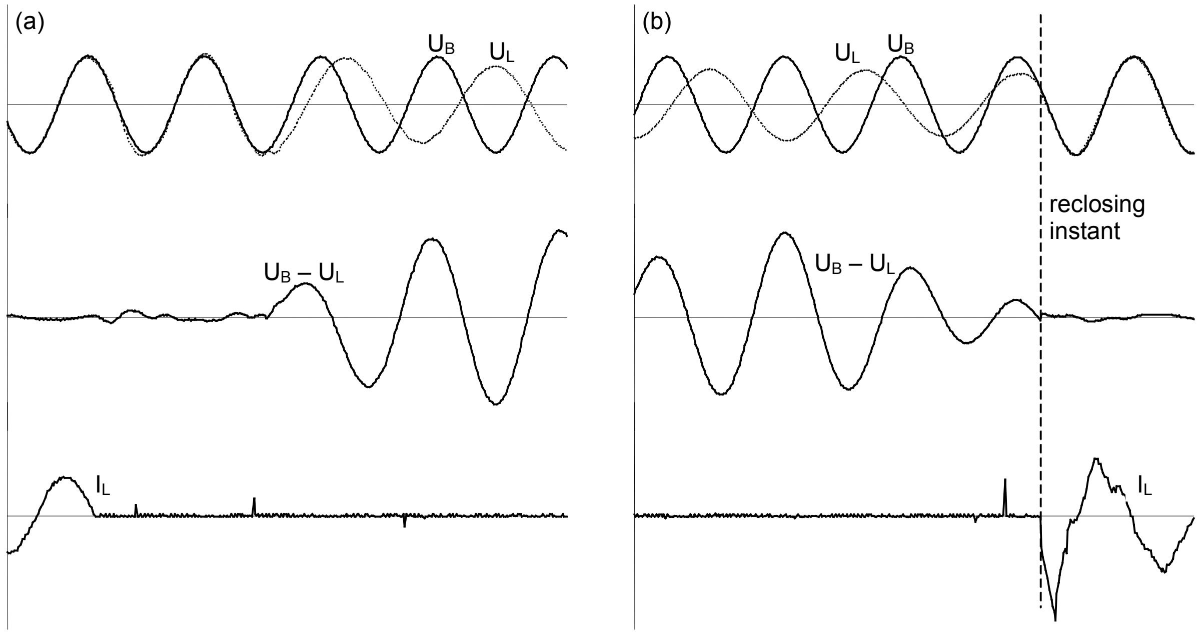

Fig. 7. Circuit breaker opening (a) and controlled auto-reclosing (b) on shunt compensated transmission line (Phase A only). U_B = busbar voltage. U_L = line voltage. I_L = line charging current. Note the beat voltage signal across the circuit breaker ($U_B – U_L$).

6 References

[1] CIGRE WG 13.07, "Controlled Switching of HVAC Circuit Breakers. Guide for Application: Lines, Reactors, Capacitors, Transformers." Part 1, *ELECTRA* No. 183, April 1999, pp. 43-73. Part 2, *ELECTRA* No. 185, August 1999, pp. 37-57.

[2] K. Fröhlich, C. Hölzl, M. Stanek, A.C. Carvalho et al, "Controlled Closing on Shunt Reactor Compensated Transmission Lines. Part I: Closing Control Device Development. Part II: Application of Closing Control Device for High-Speed Autoreclosing on B.C. Hydro 500 kV Transmission Line." *IEEE Transactions on Power Delivery*, Vol. 12, No. 2, April 1997, pp. 734-746.

[3] D.F. Peelo, J.H. Sawada, "Experience with Controlled Transmission Line Autoreclosing and Controlled Shunt Reactor Switching on B.C. Hydro System." *CIGRE 1998 Session*, Paper No. 13-101.

[4] R.C. Dugan, M.F. McGranaghan, H.W. Beaty, "Electrical Power Systems Quality." McGraw-Hill, 1996.

[5] A. Bosma, W.J. Bergman, "Switching of Capacitive Currents—Capacitor Banks." CEPSI, Pahtaya, Thailand, November 1998.