BENEFITS OF CONTROLLED SWITCHING OF MEDIUM VOLTAGE CIRCUIT BREAKERS

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ABSTRACT

This paper describes the benefits of using controlled switching technology on medium voltage circuit breakers. Although this technology has been used on high voltage networks for over 30 years, recent technological advances have permitted the development of a new generation of controlled switching devices for medium voltage. This paper reviews controlled switching device approaches, describes medium voltage applications and shows some research results.

INTRODUCTION

Controlled switching (CS) of circuit breakers (CB) has become a widely accepted means of reducing transients in high-voltage (HV) power systems. The availability of affordable control switching devices (CSD) has allowed this technology to be deployed in medium voltage applications (MV). Technical and economic benefits can be expected, similar to those experienced by transmission or generation utilities.

With the increasing worldwide demand for energy, most power systems, including distribution systems, must be operated close to their maximum rating. Since security margins are reduced, transients resulting from voluntary CB switching operations can cause unwanted protection trips of the entire system. Controlled switching of circuit breakers is an approach used by several utilities to mitigate voltage and current transients, therefore improving customer service.

The CSD mitigates transients by synchronizing the CB's mechanical operations with the power system, at a precise electrical target. To achieve this function, the CSD must accurately predict the CB's timing based on its technical specifications, operating conditions and performance measurements from previous operations. The target point for electrical opening and closing is set according to what type of load needs to be switched. For example, the basic strategy in regards to discharged capacitor banks is to energize it near the voltage zero crossing. Also, a power transformer's acceptable opening/closing target point could be near the voltage peak. In addition, in order to eliminate inrush current, the remaining residual core flux that results from the previous de-energization must be taken into account.

There are numerous benefits to using this technology in medium voltage applications, as a CSD:

- Improves the system's power quality by mitigating voltage transients and inrush current;
- Decreases risks of electrical apparatus failures caused by stresses induced by electrical transients;
- Decreases probabilities of power outages caused by equipment failures or undesired protection trips;
- Lowers maintenance costs;
- Protects equipment investments by extending the lifespan of existing assets;
- Allows optimized protection settings for maintenance, operation and personal safety;
- Increases energy capacity of commercial and industrial transformers by using better fusing and protection coordination functions;
- Optimizes specifications for equipment procurement.

Among economic benefits provided by applying the controlled switching approach for MV applications, the increased delay between maintenance operations means significant savings considering the large number of installed MV circuit breakers. In some cases, a CSD could also expand the CB's lifespan by a large factor: The CSD has monitoring functions that can help the system owner improve his approach of apparatus maintenance.

Another economic advantage is directly related to better sizing of all equipment. Usually, several pieces of equipment are uprated to handle inrush current. When transients are almost eliminated, equipment-rating specifications can be decreased, therefore, lower-cost equipment can be used.

Recently, controlled switching was used successfully for arc furnaces and distributed energy resources (DER) integration: this paper presents related strategies and results. Several other projects using CS are under development, and we believe that this transient mitigation approach will be generalized for medium voltage applications.

CONTROLLED SWITCHING PRINCIPLES

In medium voltage capacitor bank applications, inrush current and voltage transients are direct results of energizing the load at the wrong electrical moment. These phenomena are a threat to the reliability, availability and quality [1][2] of electrical energy supplies.

Controlled switching permits precise control of the CB opening or closing to minimize disturbances [3]. According to solutions offered by CSD manufacturers, this control can be simple and decrease transients to a reasonable level. Furthermore, it can use sophisticated algorithms that allow for the optimum mitigation of disturbances.

Figure 1 shows a typical controlled switching device implementation. For a basic implementation, the CSD measures the power system's voltage to synchronize the CB's mechanical operations. In order to control the electrical target with utmost accuracy, the CSD must correctly predict the CB's timing behavior. This calculation is based on the CB performance specifications and timing correction algorithms. They take into account the influence of operating conditions such as ambient temperature, the CB’s control voltage level and idle time since the last operation. Recording of measured performance for all operations plays an important role in achieving automatic correction of the CB’s timing variation caused by electrical and mechanical wear.

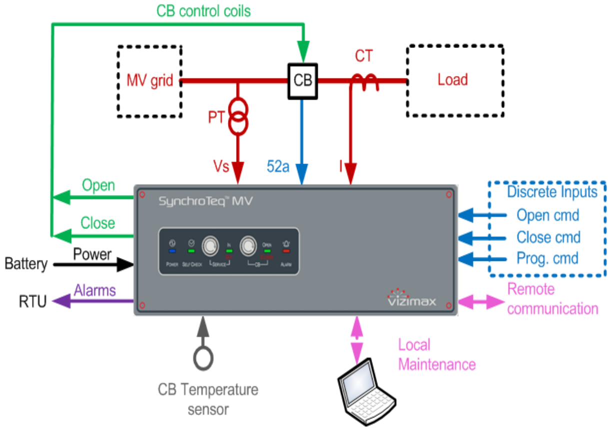

Figure 1—Basic CSD installation

For distribution systems applications, remote communication is of utmost importance since the CSD is not only used for optimum switching of the load, but also for monitoring of assets. Data collected by the CSD and stored in its memory is used extensively to detect CB problems and determine long-term trends in the CB’s behavior. Using Ethernet connectivity, the CSD can be connected to almost any communication media for centralized control and data analysis.

MV CAPACITOR BANK APPLICATIONS

Capacitors are devices that oppose to rapid voltage changes by absorbing current. When energizing a grounded discharged capacitor bank, the optimum electrical target is consequently at the zero voltage crossing (for an ideal CB). Closing the CB at any other moment would cause inrush current and voltage disturbance on the grid, decreasing power quality and increasing risks of power outages caused by undesired protection trips [2].

Because there is a 120° phase difference in MV systems, the controlled switching strategy requires that each CB pole be operated independently (Independent Pole Operated—IPO). Also, excessive contact bouncing of the CB shall be avoided because the resulting switching point departs from the ideal target. This is a problem when selecting a capacitor-switching device (CB or switch), since most of them are of vacuum type in MV applications. Vacuum technology is more susceptible to contact bouncing, which in turn causes excessive inrush current. Furthermore, pre-ignition at contact closing and subsequent inrush current heavily erode contacts, creating detached particles that lead to the device’s premature failure. These particles cause late breakdowns (restrikes) which appear as NSDD (non-sustained disruptive discharge) [4][5].

Consequently, besides improving power quality and reducing power outages, the use of a CSD to control capacitor banks increases the switching device’s operating life, especially when vacuum technology is involved.

The use of fast switching CSDs in Static VAR Compensator (SVC) and STATCOM applications is essential for rapid availability of these systems after a grid blackout. When a Mechanically Switched Capacitor bank (MSC) is disconnected from the grid by the CB, up to ±1 PU of residual voltage can be trapped in the capacitor bank. This trapped charge will decay to 0 V within approximately 15 minutes, and energizing the MSC with a standard CSD before that period would cause inrush current. To avoid such undesirable transients, the SVC or STATCOM installation must be blocked until the capacitor bank is discharged. This system downtime problem, that could increase network unavailability, is however solved using a fast switching CSD. It calculates the residual charge remaining in the capacitor bank at any time and dynamically adjusts the CB’s switching moment to avoid inrush current. When using this fast switching CSD technology, an SVC or STATCOM full compensation capacity can be made available immediately after a blackout, helping smooth power restoration.

Introduction on the market of new independent pole operated CBs and switches will certainly help increase the number of CSDs in MV applications.

POWER TRANSFORMER APPLICATIONS

Energizing a power transformer without a mitigation technique can cause excessive inrush current and significant temporary overvoltage surges in the grid. This inrush current is mainly related to the CB's closing time and to the remaining residual flux in the transformer's core after its previous de-energization.

The controlled switching solution aims to eliminate this problem by controlling the CB's switching on the proper point on the wave. A CSD offers several mitigation techniques to reduce a transformer's inrush current, such as in the following examples:

1- Using a basic CSD (Figure 1) to control both the opening and closing switching points in time of the CB. This technique reduces inrush current when using a simultaneous pole operated CB (gang operated: GO). However, excessive inrush current may appear after an uncontrolled CB protection trip;

2- Using an enhanced CSD (Figure 2) to energize the transformer according to the residual flux measured during the previous de-energization. This technique works as well as the previous example when there is a controlled opening of the CB (simultaneous pole operated), as it also reduces inrush current in case of uncontrolled trip of the CB. The inrush current is reduced to the lowest possible magnitude obtainable when using a gang operated CB;

3- Using an enhanced CSD to measure the residual flux [6] and to energize the power transformer using an independent pole operated (IPO) CB. This technique reduces inrush current to negligible levels in most cases, even in uncontrolled tripping situations.

Figure 2 shows an enhanced CSD implementation for a power transformer.

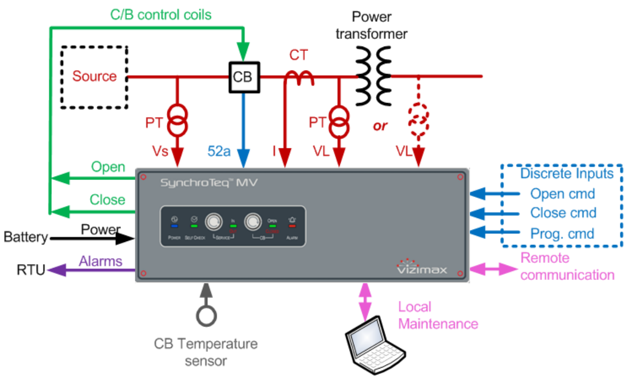

Figure 2—Enhanced CSD installation

The CSD functionality is identical to the one described in Figure 1, with the exception of the transformer voltage that is measured using a PT on either its primary or secondary winding. The voltage measurement is used to calculate the residual flux in the transformer's core resulting from the transformer de-energization. When re-energizing the transformer, the CB's closing point in time is dynamically changed according to the residual flux pattern. As stated previously, the use of an IPO CB provides the best mitigation results, especially when re-energizing the transformer after uncontrolled trips.

The development of a low cost enhanced CSD for power transformers opened a new broad range of MV applications, including:

- Grid code-compliant interconnection of DER on the grid, eliminating excessive inrush current, overvoltage transients and voltage dips related to energization of DER installations. In several countries, temporary voltage drips cannot exceed 3% on the transmission system and 5% on the distribution grid. Furthermore, due to the fairly large capacity of the step-up transformers involved in DER facilities, the probability of false protection trip on the feeders is reduced, avoiding power outages for other interconnected customers;

- Improvement of commercial and industrial protection schemes with optimized protection settings and fuses values reduction. Using a CSD, the transformer maximum inrush current is considerably reduced, avoiding the need for time-delayed protection, over-rated protection settings or fusing. This allows safer protection schemes and lower risks of personal injury due to arc flash in switchgears;

- Increase of the transformer's capacity for a new or existing commercial or industrial installation. The major limiting factor regarding the maximum transformation level that can be connected to a distribution system is the transformer's protection that has to coordinate with the utility's fuse that feeds the site. The coordination issue is not in the overload area of the fuse but towards its instantaneous area where the customer side protection has to be set to allow transformer energization (8-12 x FLA) while coordinating with the utility fuse. Using a CSD to reduce the transformer's inrush current can increase a typical installation capacity by 60%, while keeping the same fuse: same interconnection, more available power;

- Reduction of maintenance costs and production downtime while improving the CB's operating life in arc furnace applications. This can be achieved by reducing the transformer in rush current and controlling the arcing time during tripping which are responsible for wearing the CB's electrical contacts. An ongoing field experiment is showing that a CB's life can be extended by over 3 times (still increasing).

REAL CASE STUDY

The integration of Distributed Energy Resources (DER) involves major technical challenges because of the inrush current resulting from switching of the plant transformer. Different techniques are used to mitigate transients. Three different approaches have been tested and results are presented here. These tests were done on 25 kV circuits using the CSD approach for MV applications [7].

The first tested mitigation approach is the pre-insertion resistor technique. A resistor is temporarily connected in parallel with the circuit breaker to limit current during the first moments of the transformer's energization. This approach uses random opening and closing.

The second approach is similar to the previous one, but it uses an inductor instead of a resistor, with two transformers mounted back-to-back. The pre-inserted inductor internal impedance limits the inrush current until the CB is closed.

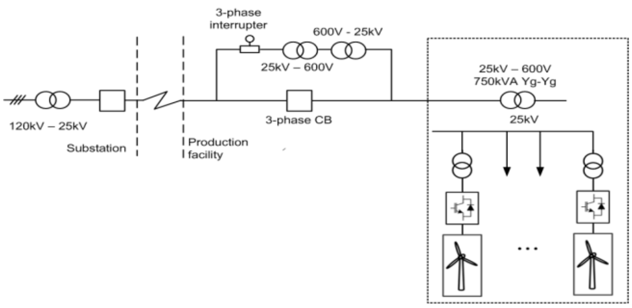

Figure 3—Mitigation with pre-insertion inductor

The third tested approach is based on the use of a CSD. During the tests, two different control strategies were used:

1. Delayed controlled strategy using an independent pole operated (IPO) CB. For Yn connected transformers, the phase with the highest residual flux is closed first at an angle that would produce a prospective flux of the same magnitude as the residual flux. The two other phases are closed simultaneously around 4 ½ cycles later;
2. Simultaneous closing strategy using a gang operated (GO) CB: the opening of the CB is controlled in such a way that the residual fluxes are sufficiently known in the 3 phases. The CB is then closed at an angle that minimizes inrush current.

Figure 4 illustrates the average maximum inrush current between three tested inrush current mitigation techniques. The figure's 4th column shows that the most effective inrush current mitigation technique uses a CSD that takes residual flux into account.

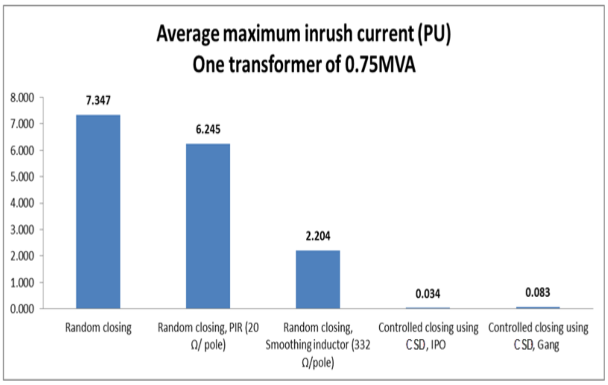

Figure 4—Comparison of inrush currents (in PU)

TECHNICAL BENEFITS OF CS

Controlled switching has many technical advantages [8]:

- Reduces wearing of equipment;
- Allows breaker performance monitoring;
- Facilitates predictive maintenance approaches;
- Allows equipment remote monitoring.

Since controlled switching techniques eliminate transients, equipment experiences less stress. For example, inrush current inside the power transformer causes mechanical vibrations that reduce the equipment's lifespan. Moreover, transients can cause dielectric degradation, which impacts the equipment's reliability.

In order to fulfill an accurate controlled switching operation, the controller must take into account changes in breaker behavior to adjust time delay for breaker control. The CSD monitors the process and the controller can signal any changes that exceed a certain threshold and report them to Maintenance. With all the CB's behavior information in hand, Maintenance can plan maintenance operations prior to more severe breaker problems. Consequently, maintenance can be scheduled at the optimal moment for minimal impact on system operations.

During breaker operations, controllers can record information such as voltage signal, current signal and CB timing performance. This information is of great value for equipment troubleshooting and maintenance planning, as it permits comparison and analysis of the CB's performance trends. Those trends help maintenance scheduling decisions.

Controlled switching devices offer other remote monitoring functions [9] including a web-based HMI that experts can use to remotely execute system commissioning. Therefore, it is possible to view the history of all operations and determine performance variations.

ECONOMIC BENEFITS OF CS

Controlled switching also has many economic advantages:

- Optimal assets management;
- Reduction of maintenance costs;
- Reduction of unavailability time;
- CAPEX optimization.

Because controlled switching operations reduce stress on equipment and thus reduce equipment failure, availability of the overall system increases. Fewer failures mean reduced maintenance costs. Furthermore, since controlled switching techniques eliminate transients on the system, safety margins can be lowered to allow a higher power flow to operate equipment in place.

Since the controller records behavior of the CB and related equipment, maintenance strategies can be reviewed. It is possible to replace a periodic maintenance approach with conditional maintenance. This has another positive impact on maintenance costs. Moreover, maintenance can be planned to minimize impacts on system operations. In summary, the controlled switching approach increases the power system's reliability while augmenting its power capacity for the equipment in place.

The controlled switching approach also has a positive impact on capital expenditures (CAPEX). Since the equipment's lifespan is increased, its replacement can be delayed for many years. This prevents the several months of delay for the manufacturing and commissioning of a new transformer and the resulting impacts on the power system's equipment. Finally, since the safety margins can be lowered and the system's power capacity increased, major investments for construction of power lines and substation modifications can be delayed or eliminated.

CONCLUSION

Thirty-year experience has demonstrated that the CSD approach is reliable and economical for high voltage networks over the long term. Similar technical and economic benefits are expected for MV networks, especially for capacitor bank and power transformer applications.

Used primarily to reduce or eliminate switching transients to improve power quality and reliability, the controlled switching technology also offers: new and improved network operating strategies, easier implementation of predictive maintenance, low-cost breaker performance monitoring, reduction of maintenance costs associated with equipment wearing, optimal assets management, reduction of unavailability time and optimization of equipment purchasing specifications.

Looking forward, the number of CSD's in medium voltage applications should increase notably, considering the introduction of new independent pole operated CBs and switches and low cost enhanced CSDs.

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