21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Challenges to Overcoming Technology Limitations when Applying Present Day Standards to Grid of the Future (GOTF) High Voltage Circuit Breaker Applications – Capacitor Switching

R. A. YORK
Mitsubishi Electric Power Products, Inc.
USA

SUMMARY

As transmission and distributions networks migrate towards advanced network configurations, challenges with meeting existing standards with new and advanced technologies become a concern for certain applications. Capacitor switching is a well-established means of achieving robust levels of system stability, voltage and power control as well as load flow. Advancements being made and implemented for future system conditions in GOTF requires system operators, utility purchase specifications, OEM's and standards writing organizations to address limitations being encountered with new technologies. Specifically, as vacuum interrupters are being applied to higher rated maximum voltage circuit breakers, limitations to this interrupting technology with respect to their capacitor switching capabilities will need to be addressed. This paper discusses the history of capacitor switching standards for high voltage circuit breakers, the historical approach for capacitor switching applications as technology migrated from oil to SF6 to vacuum as the interrupting medium of choice, the limitations and future actions needed associated with vacuum interrupter technology.

KEYWORDS

Capacitor switching, vacuum interrupter, vacuum circuit breaker, Class C1, Class C2

Richard.york@meppi.com

Capacitor switching has been a required performance duty for circuit breakers since the dawn of the power transmission and distribution industry. The severity of capacitor switching duties arises from the fact that in capacitive loads, voltage and current are 90°out of phase with each other. Current in an AC circuit can only interrupt at a current zero crossing, which results in a voltage peak remaining as a trapped charge on the capacitor bank. The system voltage continues at its normal power frequency of 50 or 60 Hz. Therefore, the maximum voltage that the breaker must withstand will occur in ½ cycle following current interruption.

There are a variety of influences that will affect the exact voltage the breaker will be exposed to depending on the type of capacitive load. There are shunt capacitor banks, which can be grounded or ungrounded. Transmission lines have mutual phase-phase capacitance, cable circuits may be individually shielded and grounded or not. The system grounding conditions will also influence the peak capacitive recovery voltage as well. This topic is well covered in many textbooks and publications; this paper will not go into further details of the application.

The industry standards define required capacitive switching ratings and test requirements for capacitor switching. ANSI/IEEE and IEC standards each define required ratings and test procedures to prove a breakers capacitive switching capability. From an historical perspective, the standards originating prior to and including the 1979 publication of IEEE C37.04 and C37.09 were based on oil insulated circuit breaker technology. Oil circuit breakers possess a unique sensitivity to capacitor switching applications when compared to their modern day SF6 breaker replacements. Oil breakers had lower magnitudes of capacitive current switching capabilities. Also, when exposed to the inrush currents associated with back-to back current switching, physical damage to the interrupter may have resulted if the values were too high. Standards addressed these limitations by establishing inrush current peak and frequency limits in the preferred ratings values.

This also necessitated accommodations to be made by the users to apply oil circuit breakers on their systems. For those back-to-back capacitor bank applications, there was a recommendation in the standard to limit the product of the inrush current peak and frequency to a value of $2x10^7$. Capacitor bank installations based on oil circuit breaker capabilities strictly adhered to this requirement. With the advent of SF6 circuit breaker technology, the limitations of oil breakers were easily recognized to be not applicable. SF6 offered superior switching capabilities with respect to voltage withstand, current magnitude, inrush current peak and frequency limitations, endurance. While many of these limitations were of no consequence to the SF6 breaker, if an oil breaker were in the same substation as an SF6 one switching shunt capacitor banks, the application restrictions still applied. In this case, the oil breaker could still be exposed to carrying those high inrush peak and frequency currents associated with back-to-back switching. Under a fault condition, the outrush current fault contribution from the energized capacitor bank would still expose the oil circuit breaker to this damaging condition.

The history and evolution of the capacitor switching ratings and test requirements specified in IEEE standards have been thoroughly described in the CIGRE Technical brochure published by WG A3.38 in 2020: "Shunt capacitor switching in distribution and transmission systems". A brief summary of this evolution will only be provided here.

Two classes of circuit breakers were defined in previous editions of the standards: General Purpose and Definite Purpose. General Purpose circuit breakers were not specifically designed for capacitor switching duty while Definite purpose breakers were. The capacitor switching test requirements specified for the Definite Purpose classification required only 24 Open and 24 Close-Open operations to be performed at each of two capacitive current values, 30% and 100% of the rated capacitive switching current. These test specifications for numbers of operations were the same for single phase and three phase tests. No restrikes were permitted during the test sequences. This led to the term 'restrike free' circuit breakers, meaning no restrikes were allowed to be experienced during the tests.

IEC standards at that time were less onerous as only 12 open and 12 close-open operations were required at two current levels. As the number of shunt capacitor banks being placed in service and the numbers of operations increased, the industry recognized the need for a more robust ratings and test method for Definite Purpose circuit breakers. Presently, the Class C1 and C2 ratings for capacitor switching are defined in both IEEE and IEC standards. C1 is defined as 'low probability of restrike' and C2 'very low probability of restrike'. The test requirements are structured to differentiate between the various types of capacitor switching applications, these being Line Charging (LC), Cable Charging (CC) and Bank Charging (BC). The numbers of operations and required voltage factors are defined separately for each of these three applications for the Class C2 rating. Class C1 test requirements are nearly identical to the 'Definite Purpose' ratings as defined in previous versions of the IEEE standards.

In addition to a greater number of switching operations specified in the type test requirements for the Class C2 rating, the requirement that the circuit breakers interrupter contacts be 'pre-stressed' before commencing the capacitor switching type test program. This 'pre-stressing' consists of performing three (3) medium level fault switching operations, T60, or 60% terminal fault switching operations. This is known to degrade the capacitor switching capabilities of some interrupter types, SF6, for example.

The standards requirement to limit the product of the inrush current peak and frequency to a value of 2×10^7 also did not necessarily apply directly to the SF6 breaker switching ability and performance. However, it was discovered when ignored, if this value were to be exceeded, problems may be encountered in secondary protection relay, control, and instrumentation circuits. In some cases, current transformer secondary terminals could flashover due to overvoltages caused by the high peak and high frequency primary inrush or outrush conditions.

As SF6 breaker technology advanced to completely replace oil circuit breaker availability in the industry, and an industry recognition of all the advantages over oil breakers, an aggressive replacement program had begun. The standards' Preferred Rating for inrush current peak and frequency, 20 kApeak, 4250 Hz, were often discarded from consideration when replacing older oil breakers with SF6 and when designing new substations completely free of oil breakers. This led to a wide variety of capacitor bank installations with various combinations of inrush current peak and frequency. This was a common industry practice, accepted and perhaps encouraged by switchgear manufacturers, since it resulted in a lower first installed and total life cycle cost without sacrificing performance. By disregarding the inrush current peak and frequency limits as published in the C37.06 tables of 'Preferred Ratings', users were free to design each installation in whichever manner that best fit their needs.

This evolution of SF6 breaker technology was occurring at the higher range of rated voltages and currents, both continuous and rated short circuit interrupting currents. During this same time, vacuum interrupter technology was also advancing. At the lower range of voltage, roughly 38 kV and below, and 20 kA interrupting, 1200A continuous currents, the vacuum interrupter took over the industry. The reliability and performance afforded by vacuum made this the obvious technology choice for these classes of breakers. However, when it came to capacitor switching, vacuum technology had its own performance characteristics. The closing operation to energize a capacitive load will usually expose the breaker to a pre-strike before the contacts touch. The prestrike will be a high frequency current that is a function of the load side capacitance and the inductance between the breaker and load. Current limiting inductors have been routinely applied to limit the peak inrush currents to accommodate vacuum circuit breaker sensitivities.

Vacuum interrupters possess a sensitivity to high frequency inrush currents during the pre-strike phase of back-to-back switching duties. Therefore, capacitor bank installations designed for vacuum interrupters will often include a CLR to limit the inrush peak and frequency. SF6 breakers, in contrast, have routinely been thought to be somewhat immune to the prestrike current peak and frequency. It became a user decision if controlling the inrush current on closing was necessary or not. This led to a divergence of the types of installations with and without inrush control over the years.

The prevailing IEEE standards accommodate this variety of inrush current characteristics in the ratings with the establishment of Alternate 1, 2 and 3 combinations of inrush current peak and frequency in C37.04-2018. These three alternate sets of ratings are in addition to the same traditional ‘Preferred’ values. These values originated and have been carried over from the 2009 publication of IEEE C37.06. Notes to the tables for capacitive switching inrush current and frequency ratings identify how these various combinations of values were derived. (Tables 4, 8 and 14, notes 8 and 7, respectively):

> The preferred rating lists the previous values listed in ANSI C37.06-2000 and represent the usual values that have historically been used for circuit breakers previously referred to as definite purpose circuit breakers.
>
> Alternate 1 rating was added in particular for some ratings of vacuum and some other circuit breakers. The values of inrush current magnitude and inrush frequency are generally lower than the preferred rating (historical values).
>
> Alternates 2 and 3 ratings represent alternatives of exceptional maximum capacitance switching values as seen in a survey of users and manufacturers in world-wide applications.
>
> Alternate 2 rating was developed by taking the 90th percentile of the inrush current frequency seen in the survey and matching it with the corresponding inrush current magnitude at that 90th percentile inrush frequency.
>
> Similarly, alternate 3 rating was developed by taking the 90th percentile of the inrush current magnitude seen in the survey and matching it with the corresponding inrush current frequency at that 90th percentile inrush current magnitude. These values of inrush current magnitude and inrush frequency are generally higher than preferred rating (historical values).
>
> *(excerpt from C37.06-2009 Table 14, note 7)*

Design features of what we call the ‘Grid of the Future’ continuously evolves and new technologies and operating philosophies are implemented. As automated control systems progress, micro-grids develop, generation sources expand in both numbers and locations, it is apparent the quantities of capacitor bank installations at all voltage levels are increasing. The number of daily switching operations also increase. Proliferation and location of green energy sources, such as wind and solar, relative to load centers will compound the issue. The need for highly reliable switching devices is critical. Restrike overvoltages may damage sensitive control systems and utility customer equipment and have adverse effects on power quality.

Vacuum breakers and interrupters have proven to be highly reliable since their original development. There are, however, limitations that must be considered. Vacuum interrupters may be able to interrupt the high frequency inrush of the pre-strike during closing. The high frequency current may affect the contact surface condition, reducing the maximum voltage withstand capabilities. Field emissions from contact welds and release of microparticles during contact separation are known to affect the insulation withstand capability of vacuum interrupters. Contact surface micro projections and irregularities associated with anode and cathode spots also challenge the capacitor switching recovery voltage capability. This can result in difficulties to achieve capacitor switching Class C2 performance for vacuum breakers technology. A survey of available Class C2 ratings for vacuum breakers across all voltage ratings and manufacturers indicate this difficulty. Class C2 Capacitor Switching ratings has become an expectation for SF6 breaker technology. Vacuum technology has not yet achieved this threshold of expectations or capabilities.

Elimination of SF6 for insulation from high voltage equipment, specifically circuit breakers, is an ongoing endeavor. Significant achievements have been made but challenges remain. To apply F-gas free equipment for capacitor switching applications, many questions must be resolved. If, as expected, greater numbers of capacitor banks will be installed and switched more frequently, Class C2 ratings will be needed. Many questions remain:

- How to achieve this performance?
- Are new vacuum interrupter contact technologies being developed to improve the capabilities?
- Do standards need to be changed?
- If yes, how?
- Will newer technology, such as distribution STATCOM's, replace reactor and capacitor banks for substation applications?
- Will this limit single switched and back-to-back voltage control inside the substations?
- Can the industry support equipment with higher voltage ratings applied at lower voltages?
- At what cost?

These are ongoing issues that will continue to be addressed within the industry. We all anxiously wait for how they are ultimately resolved.

BIBLIOGRAPHY

[1] Working Group A3.38 CIGRE. “Shunt capacitor switching in distribution and transmisión systems”
[2] IEEE C37.04-2018
[3] IEEE C37.06-2009
[4] Vacuum Switchgear, Allan Greenwood, Institution of Electrical Engineers, London, 1994
[5] The Vacuum Interrupter, Theory, Design and Application, Paul Slade, CRC Press, 2008
[6] Effect of Arcing Time with Capacitive Making Current on Contact Welding in Vacuum, Taiki Donan, et. al., 2018 28th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), IEEE 2018