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Development of non-intrusive monitoring for reactive switching of high voltage circuit breaker

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ABSTRACT

High-voltage circuit breakers are among the most important equipments for ensuring the efficient and safe operation of an electric power system. On occasion, circuit breaker operators may wish to check whether equipment is performing satisfactorily and whether controlled switching systems are producing reliable and repeatable stress control. Monitoring of voltage and current waveforms during switching using established methods will provide information about the magnitude and frequency of voltage transients as a result of re-ignitions and restrikes. However, high frequency waveform measurement requires shutdown of circuit breaker and use of specialized equipment. Two utilities, Hydro-Québec in Canada and Powerlink Queensland in Australia, have been working on the development and application of a non-intrusive, cost-effective and flexible diagnostic system for monitoring high-voltage circuit breakers for reactive switching. The proposed diagnostic approach relies on the non-intrusive assessment of key parameters such as operating times, prestrike characteristics, re-ignition and restrike detection. Transient electromagnetic emissions have been identified as a promising means to evaluate the abovementioned parameters non-intrusively.

This paper describes two complimentary methods developed concurrently by Powerlink and Hydro-Québec. Also, return of experiences on the application to capacitor bank and shunt reactor switching is presented.

Introduction

Field experience has shown that capacitor and shunt reactor switching are among the most severe duties of high-voltage circuit breakers (CBs) because of frequent dielectric and mechanical stresses that may lead to failures compromising personnel and equipment safety. Shunt reactors and capacitor banks are generally switched frequently, often daily. Overvoltages may occur due to inrush current or restrikes in the case of capacitor banks and current chopping or re-ignitions in the case of shunt reactors [1,2]. Significant oscillatory transient overvoltages due to internal voltage amplification in EHV transformers during capacitive bank switching have been reported recently [3,4]. It has also been reported that current-limiting reactors for fault current protection can also generate transient recovery voltages (TRV) exceeding the CB's ratings [5]. Therefore, it is of interest to monitor the condition of these stressed CBs.

Monitoring of system voltage and current waveforms during switching can provide, if acquisition is performed in sufficiently high resolution, valuable information about the magnitude and frequency of re-ignitions or restrikes that could be a precursor to interrupter failure. It is possible to undertake full voltage and current site tests to record voltages during switching. While tests yield significant information they require expensive equipment and considerable shutdown time. De-engergization of lines or substation equipment is more and more difficult in today's generally loaded HV networks.

Moreover, the decision to install an on-line monitoring system on a high-voltage CB is not straightforward, either, as it is not always economically effective. In fact, typical monitoring systems are not well suited for CBs already in service since they involve

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expensive retrofitting in order to add intrusive sensors such as pressure and contact travel sensors.

Therefore, there is a need for a simple and cost effective CB monitoring system that will provide information about interrupter performance at high-voltage levels, such as re-ignitions, and not limited to operating mechanism timing measurements.

Experiences of failures of high-voltage CBs during shunt reactors and capacitor bank switching, combined with increasing restriction on the availability of high-voltage equipment for investigation and inspection have led two utilities, Hydro-Québec in Canada and Powerlink Queensland in Australia, to explore new non-intrusive methods to assess CB condition [6,7].

Failures of HV SF_6 circuit breakers during reactive switching

Issues for capacitor switching

CBs installed on capacitor banks are frequently subjected to severe dielectric stresses during current interruption. The TRV peak can reach twice the nominal voltage across each pole in the case of a grounded neutral capacitor bank and two times and a half across the first-pole-to-clear in the case of a non-solidly grounded capacitor bank. Most modern CBs are designed with a very low probability of restrike (class C2) [8]. However, degradation with age and wear may lead to a deterioration of dielectric withstand of the CB and may increase the restrike probability up to an unacceptable level over the years. On some occasions, restrikes lead to overvoltage which could potentially damage neighboring equipment [3,9].

Over the last several years, some critical failures of SF_6 live tank CBs switching capacitor banks have occurred on Hydro-Québec's transmission network in Canada. These critical failures were the result of an incomplete closure [6] or restrike of the CB causing an internal arc fault. For example, Hydro-Québec has experienced a case of a catastrophic failure of an SF_6 CB which exploded after switching off a 120-kV shunt capacitor bank. The investigations based on digital fault recorder data and visual inspections of interrupter fragments made clear that multiple restrikes in two poles had occurred. These repetitive restrikes led to overvoltages slightly higher than 4 p.u. Such restrikes may cause important damage on CB's main contacts and nozzle.

Issues for reactor switching

Bachiller et al. [10] conducted a series of field tests to examine the performance of a high-voltage CB during shunt reactor switching. Switching tests were made on a 110-Mvar, 420-kV shunt reactor and re-ignitions were observed in 25% of 68 three-phase switching operations. Tests on a 150-Mvar, 420-kV shunt reactor resulted in six re-ignitions for 26 switching operations. In the review of experience from the UK National Grid Company [11] Reid et al. commented that they have observed very fast re-ignition transients of up to 5 p.u. in the 400-kV system. They suggest that in the calculation of re-ignition currents and voltages, it may be necessary to use distributed circuit parameters to represent the reactor and the busbar-side connections.

Work by Spencer et al. [12] identifies causes of CB failures under reactor switching applications has shown that modern single-interrupter SF_6 CBs may be affected over time by high frequency-arcing produced by repeated re-ignitions. The tendency of arcs to occur outside the nozzle was shown to be affected by the ability of the polytetrafluoroethylene (PTFE) nozzle material to absorb and store small quantities of negative charge. The stored charge distorts the field around the nozzle and causes re-ignition arcs to occur external to the nozzle. Spencer found that charge trapped in PTFE nozzles could be stored for up to 2 years.

Powerlink has as well experienced several catastrophic failures of high-voltage SF_6 CBs used in shunt reactor switching operations on its 275 kV network.

A 300-kV dead tank SF_6 CB catastrophically failed in the open position several hours after switching off of a 30-Mvar, 275-kV shunt reactor. The CB had completed about 1800 switching operations when the fault occurred. One pole exploded and was completely destroyed by arcing while the two other poles remained in their entirety. An internal view of one of the surviving interrupter nozzles showed that the inside of the interrupter nozzle was severely degraded by arcing. There was also clear evidence of arc damage on the moving contacts outside the nozzle and puncture of the nozzle appeared to have occurred at a point close to the contacts.

In another case [13], failure to ground occurred within an interrupter of a 275-kV dead-tank CB switching a 5-limb, star-connected, line shunt reactor earthed via a neutral earthing reactor. During a routine opening operation, the dead tank CB failed to clear on phase A and subsequently faulted internally to ground. This CB had been in service for over four years and had been operated almost daily.

During the fault investigation and breaker disassembly, clear indications of severe arcing puncture were found in the nozzles of the interrupters in A and C phases. This nozzle damage appeared to have occurred prior to failure possibly due to re-ignitions during opening operations. It was deduced that failure of the last pole to open was due to a puncture of the PTFE insulating nozzle between the moving main contact and the fixed arcing contact of the interrupter. The 50 Hz current within the nozzle was extinguished but ionized gases were considered to have been forced though the puncture by pressure rises due to the puffer. It seemed that subsequently a power-frequency arc established between the main contacts outside the nozzle and out of the effective area of arc cooling and control and the catastrophic failure followed.

Catastrophic failure modes

In case of an unsuccessful opening or an incomplete closure of a live tank CB, the arc current could remain across a gap in the interrupter limited to normal load level and could last until the rupture of the enclosure due to an overpressure or a thermal shock to the porcelain insulator. The presence of an internal arc could remain undetected by the grid protective relays because there is no significant current disparity between the normal and fault condition. Generally, live tank CBs do not have any pressure relief device. An internal arc in an interrupter of high-voltage live tank CB with porcelain insulators can cause major consequences: risk of compromising personnel safety, system outage and damage to surrounding equipment.

For dead tank CBs the risk of major consequences is reduced as any internal arc fault will rapidly develop to a line-to-ground fault and will be cleared by the grid protection. In case of overpressure the gases will be released through a pressure relief device. Nevertheless, the catastrophic failures are possible because of high arc energy due to fault current which could be released inside a CB enclosure.

Transients electromagnetic emissions due CB switching or electric discharges

Previous work

Transient electromagnetic emissions (TEE) due to CB switching in substations were studied in the 1980's and the 1990's. This