ON-LINE PARTIAL DISCHARGE MEASUREMENT AND CONTROL

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ABSTRACT

By means of voltage injection into the neutral, the RCC Ground Fault Neutralizer can control phase-to-ground voltages, immediately quench partial discharge activity and thus prevent the further development into full dielectric breakdown. Full control of the phase-to-ground voltages also admits on-line PD testing at levels above normal operating voltage, enabling systematic fore-checking strategies for the early detection of defective system components. This is done without at all affecting the power supply to end-users.

INTRODUCTION

The energy system ranks amid society's most critical infrastructure and the demand for reliable electricity of highest quality is ever increasing. Deregulation among utilities and network operators, combined with elevated consciousness on matters of operational efficiency and cost-effectiveness, put intelligent means of managing plant assets into focus. Condition based maintenance, a collection of predictive strategies and knowledge rules to target repair and refurbishment efforts, is gaining popularity in the industry. With these methods, asset renewal programs can be based on the actual condition of the equipment instead of age. However, these strategies presuppose reliable ways of pinpointing where faults have an increased probability of occurring.

The partial discharge phenomenon (PD) has been identified as a reliable indicator of incipient dielectric collapse. PD activity can be measured off-line and on-line, both methods offering their respective advantages but also, to date, exhibiting inherent limitations. To catch all impending insulation breakdowns, a continuous monitoring system would be necessary, but the detection of PD activity at normal operating voltages (U_0), as it is done in the on-line systems today, often raises the warning signal much too late. The avalanching development of partial discharge into a complete fault can be a matter of hours. It would therefore be of great interest to find ways to increase the predictive power of the already promising field of on-line PD measurement.

THE PARTIAL DISCHARGE PHENOMENON

If a strong enough electric field is applied across a dielectric which contains a defect like a void, the gas inside the void will ionize and a current will flow temporarily, leading to a resistive voltage drop across the void. If the discharge occurs in the insulation of an electric cable, it will cause small pulses travelling the length of the cable, one in each direction from the discharge site. The pulse duration is very short, typically in the nanosecond range and the pulses travel at approximately half the speed of light, i.e. some 150 meters per microsecond. Sustained discharge exposure affects the dielectric and causes electrical treeing which will ultimately lead to full breakdown of the insulation. A PD inside a void will cause the surface charge of that void to redistribute during the discharge process. The surface charge will, during the reversed polarity of the next AC half-cycle, cause an additional electric field added to the external field. This is one of the contributing factors that make the voltages at which PD is initiated and extinguished differ [2].

PD levels, customarily measured in total pulse charge, vary greatly between cable types. In oil-paper insulated cables, the insulation can withstand thousands of picocoloumbs for extended periods of time whereas in polymer insulated systems, discharges of orders of magnitude lower can prove fatal. Even though polymer cabling is designed to be PD free, discharge is still found in e.g. terminations and joints [4].

OFF-LINE PD MEASUREMENT

Off-line partial discharge measurement has been utilized at manufacturing, commissioning and also during the cable operational life the last couple of decades. The measuring techniques have matured into a reliable method for determining the dielectric condition, but the obvious drawback is that the cable needs to be disconnected which inevitably incurs cost, both for the network operator as well as the end customer. A further disadvantage is that when the cable is not operating under normal load, the PD test is not performed under operating conditions. This is problematic since PD exhibits strong temperature dependence. An unloaded and cooled cable can withstand an off-line test to later fail when reconnected and put back in operation. Moreover, PD is not always a linear phenomenon, but often has an avalanching development and can also appear intermittently. This in turn means that it is not certain that weak points will have been identified when testing off-line, since it is not feasible to test at the short intervals needed for reliable monitoring.

It has been debated at which voltage off-line testing should be performed [2]. Testing has been done at up to over 3 times U_0, but this has in many cases led to permanently damaged cables. The ideas regarding safe testing voltage appears to vary country by country but there seems to be consensus that raising the voltage over U_0 when performing off-line testing is the way forward. If the voltage stress duration can be kept short, it will not harm the insulating material.

When testing off-line, the pulses originating from the PD event will get a clear reflection from the cable ends. Therefore, it is relatively easy to correlate the difference in time-of-flight between the first pulse arriving and the reflected one, to the distance to the discharge site and thus the fault site can be determined accurately.

To restrict the size of the test equipment voltage source, which needs to be able to cover the power required by the cable capacitance, testing is often done at frequencies lower than the operating frequency. This means that one has altered a system parameter from what the equipment is normally exposed to and PD characteristics are dependent of frequency. Testing at operating frequency shows the equipment condition in its true operating environment. To limit the rating of the voltage source, operating frequency resonant systems can also be employed in which an inductance is added in parallel to the capacitance of the cable. This coarse inductive compensation lets the voltage source simply cover the losses of the circuit, but the inductive test reactor is often bulky and its use impractical.

The extensive measurement devices needed for measuring off-line PD are often integrated into a specially designed vehicle, which is moved between test sites. This method is not only costly but also very time consuming. A permanently installed system would be the optimal condition monitor.

ON-LINE PD MEASUREMENT

The last couple of years have seen increased use of non-intrusive on-line PD sensing technology which measures discharge activity on circuits under normal operation. On-line trials have been conducted in countries like the UK, the Netherlands and Italy. The systems and methods are refined year by year and not only trending and classification of PD activity, but also localization is now possible on-line. Since the harsh noise environment is one of the limiting factors, considerable signal processing has to be employed to filter out the pulses, and single ended localization measurement is difficult due to the very limited size of the reflected pulse.

Sensors can be put in each end of the cable, which then have to be synchronized very accurately [5]. Another solution is to put a transponder in the far end of the cable which detects the pulse travelling away from the busbar. When sensing an incoming pulse, the system emits a pulse of larger magnitude back to the cable, a pulse which travels back to the busbar and can easily be detected [3]. With these systems, accurate localisation on cable lengths of up to 5 km is achievable.

CORONA

Not only in voids of solid dielectrics but also in other gaseous environments like e.g. free air will electrical fields cause PD. For over-head lines, most of the electromagnetic radiation from the ionization process is emitted as ultraviolet radiation, but some can also be found in the visible spectrum. At some instances, the phenomenon can be observed by the naked eye in the form of a glow around the conductors in over-head systems at night. Corona can be used as an indicator of broken or dirty insulators, and special cameras have been developed to detect the ultraviolet pulses emitted. With these cameras, an operator travelling in a helicopter can very efficiently survey the condition of the network and deficient gear can be identified and repaired.

THE RCC GROUND FAULT NEUTRALIZER

Figure 1: RCC Ground Fault Neutralizer, 110kV railway transmission system (courtesy Deutsche Bahn).

The RCC Ground Fault Neutralizer (cf. Fig 1), developed originally for safe post-fault protection in resonance grounded overhead networks [6], offers - combined with on-line PD measurement - a novel possibility for true pre-fault detection.

The RCC Ground Fault Neutralizer can be seen as a logical extension of the traditional arc suppression coil (ASC, cf. Fig 2), invented by Waldemar Petersen (1880-1946) in the early 20th century. The arc suppression coil forms, analogous to the case of PD off-line test reactors, a parallel resonance circuit with the phase-ground leakage capacitances (C_0) of the network. This resonance circuit increases the source impedance for single phase-to-ground faults and thus limits the fault current.

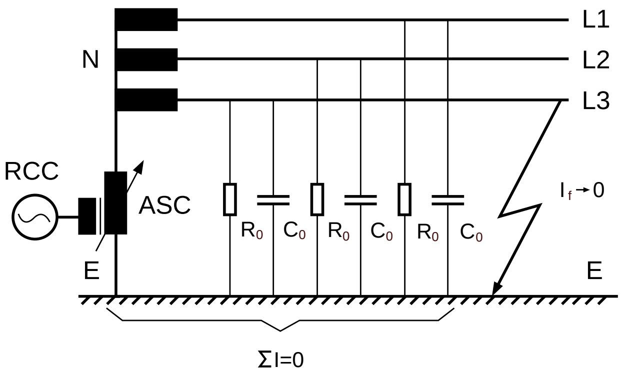

Figure 2: The RCC Ground Fault Neutralizer, outline schematic.

However, despite the arc suppression coil, there is still a current in the fault, caused by the network's phase-ground resistive leakage (R_0), as well as other losses in the system. This remaining current can be of considerable size and causes risks of fire and personal injury on overhead lines as well as harmful restriking mechanisms in cabled networks.

The RCC Ground Fault Neutralizer simply does to the active residual current, what the arc suppression coil does to the capacitive fault current, i.e. it injects a 180 degree phase opposite complement into the neutral. Due to Kirchoff's current law, this will increase the source impedance for single-phase to ground faults to infinity, and hence no current will flow in the fault site. Since the equipment is based on solid state power electronics, this de-energizing of the fault site takes place faster than it is possible to open the feeder circuit breaker.

The benefits of Petersen's basic idea of limiting the fault current cannot be overstated, and since ground faults constitute the majority of faults experienced by the transmission and distribution grid, introduction of the RCC Ground Fault Neutralizer greatly improves system performance. Running short circuit currents over the fault site, even during short periods of time, causes significant stresses to transformers and switchgear. Moreover, the energy release in the fault site, as well as ground potential rises resulting from this, both create personal injury and property damage hazards.

The first RCC Ground Fault Neutralizer was commissioned in Sweden in 1992 and to date, more than 70 systems have been installed in different European countries. A first pilot installation in the Southern Hemisphere will be commissioned this year in New Zealand.

ON-LINE PD MEASUREMENT AND CONTROL

As a bridge to better understanding the new idea presented in this paper, one should consider what occurs in the case when a ground fault is fully neutralized and the physical fault actually disappears. Nothing will happen. The fault site is maintained at ground potential irrespective of whether there is a galvanic connection to ground or not. The RCC Ground Fault Neutralizer simply maintains the equilibrium and, since the coarse compensation is done by the arc suppression coil, the additional power needed to achieve this is relatively limited. Thus, the RCC Ground Fault Neutralizer is not only a current compensator, but can also be seen as a means to control phase-to-ground voltages.

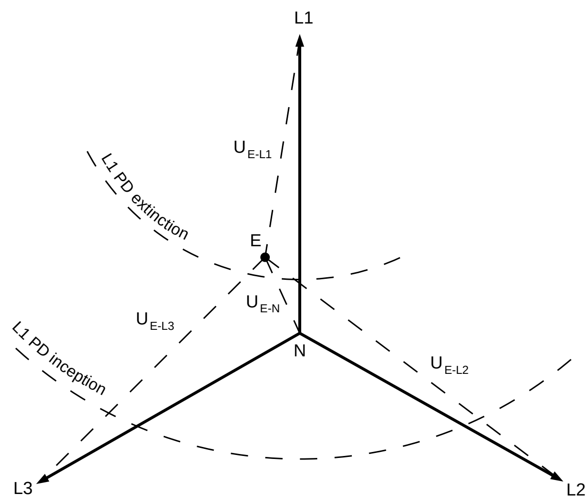

Figure 3: Quenching PD activity by controlling the ground potential (E) position relative to the three phase system.

This option opens a range of new possibilities. If the system experiences detrimental PD, in e.g. phase L1, that consumes the insulation and will eventually lead to full dielectric collapse, the voltage control will enable that phase to be put on a lower voltage (cf. U_{E-L1} Fig 3) than the PD extinction level. The PD hysteresis phenomenon, i.e. the difference between inception and extinction levels, permits the system to return the three-phase system to normal symmetry without the PD reigniting. This can be utilized to quench any PD activity that has been triggered by transient over voltages resulting from e.g. atmospheric lightning or network switching operations.

The possibility to stop PD in its development will provide the network operator with plenty of time to plan and organize countermeasures. As payload is conveyed in the positive and negative sequence only, altering the position of the three phase system with respect to ground potential has no impact on the power supply to end-users.

Increasing phase-voltages individually and on-line, will also enable on-line PD testing at voltage levels presently only used in off-line testing. Until now, the on-line phase-ground (cf. U_{E-L1} through U_{E-L3}, Fig 3) voltage has been U_0, but unlocking the symmetry of the three-phase system will make the continuous study of PD inception levels possible. This new monitor will likely to be a robust indicator of equipment condition. If the inception voltage (cf. PD inception, Fig 3) reaches as low as U_0, the insulation is not stable even in fault free condition and will quickly deteriorate into a fault. Another critical level should be 1.73 times U_0, which is the voltage the equipment will experience in the healthy phases when there is a ground fault present in the network. Note that it is theoretically possible to also go beyond 1.73, the limiting factor being the power rating of the neutral equipment. The correct decision schemes are a matter of on-going research.

Another possible application is the voltage control during corona camera operation. Raised ground-phase voltage levels will enable the detection of defective or dirty insulators much earlier in their development into complete flashovers.

The case of trees lying on covered over-head lines is another problem that might find its solution with this new cross-breeding of technologies. If one can raise the ground-phase voltage in each phase selectively, it should be possible to determine if there are any fallen trees present in the system. Inciting PD over the tree trunk will likely enable accurate localization of its location.

CONCLUSIONS

Voltage injection into the backbone of the three-phase system, the neutral, provides a host of new possibilities. This new option of controlling phase-to-ground voltages - without at all affecting the power supply to end-users - allows the immediate quenching of destructive partial discharge activity as well as on-line PD testing at voltage levels exceeding U_0. Moreover, new ideas like strengthening the predictive power of corona camera imaging and solving storm-related tree problems of covered over-heads can be considered.

Combining the RCC Ground Fault Neutralizer with on-line PD measurement technology enables systematic fore-checking strategies for the early detection of defective system components to be developed and enhanced [7].

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