Tertiary Reactor and Switcher Design Advancements Result in Improved Grid Reliability

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***Abstract*—Tertiary Shunt Reactors have long been used as a cost effective method of providing reactive compensation for transmission lines. Increasing failure rates has brought into question the viability of this approach. This paper examines the interaction between the reactor and the switching device, highlighting the high frequency transients caused by different switching technologies. Recent advances in switching technology and reactor design approaches may significantly reduce the exposure to these transients, extending the life of the equipment and improving reliability of the tertiary reactor solution resulting in improved Grid reliability.**

***Index Terms*—shunt reactor, air core shunt reactor, tertiary, reactor switching, interrupter design, grid reliability, re-ignition**

I. INTRODUCTION

The increase in Renewable Generation along with the increased regulations applied to traditional power generation have created new challenges for utilities to control the flow of power over existing and new transmission lines. This has resulted in a need for more Reactive Power to both maintain the proper voltage level on the line as well as to insure that the power is flowing to the location it is needed. The constantly changing load profile of the line along with the length of the transmission line requires a dynamic method of introducing reactive power (inductive or capacitive). The blackout, experienced in the Midwest and Northeast in 2003, has been attributed to a severe shortage of reactive power in Northern Ohio that resulted in power plant and transmission line failures setting the blackout in motion.

Reactive power compensation can be provided through the use of generators, capacitors, reactors, or shunt and series compensation FACTS (Flexible AC Transmission Systems). The utilization of reactive shunt reactor compensation is an appropriate measure to balance the reactive power demand during low-load conditions, resulting in the ability to control the voltage level within acceptable levels along the power line.

II. SHUNT REACTORS

A. Oil or Dry Type Shunt Reactors

There are two types of shunt reactors: the oil immersed, iron core type that is very similar to a power transformer, and the air core or core-less type. In general, the main differences between iron core reactors and air core reactors are the applied voltage levels, kVA ratings, space requirements, weight, losses, potential environmental impact, controllability, protection of the reactor, current rating during operation, and the substation grounding layout as impacted by the magnetic field. Compared to oil-immersed reactors, air core reactors have the advantage of lower life cycle costs, lower weight, the absence of insulating oil, environmentally more friendly, less spare parts, easier to transport and mount, simplicity of insulation to ground and air core reactors are almost maintenance free [1].

B. Connection to the Power System

Figure 1 shows three different shunt compensation methodologies which are used among different utilities. Line connected shunt reactors are directly connected to both ends of HV transmission lines. Direct Bus connected shunt reactors connect to the bus in a substation. Tertiary connected shunt reactors are installed on the secondary side of a transformer and is separate from the low voltage load windings.

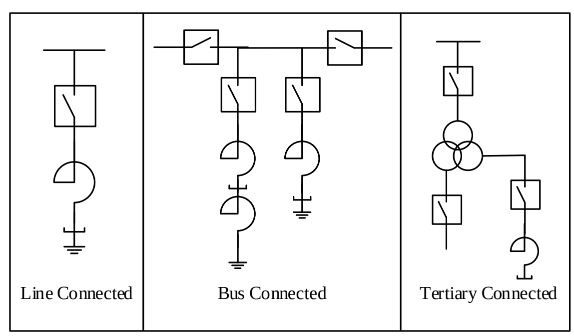

Figure 1 Shunt Reactor Application [1]

Tertiary winding connected reactors are usually limited to voltages below 72.5 kV and are mainly medium voltage (15.5kV-38kV) ungrounded air core reactors in a wye configuration [2]. The advantage of this kind of shunt compensation lies in lower cost for reactors and switchgear compared to direct connected reactors. It also allows for the use of a less complex protection scheme, provides higher flexibility to control when installed in small units, and helps in the suppression of ferroresonances [3].

The switch can either be located on the neutral side or on the supply side between the power transformer tertiary windings and the tertiary reactors themselves (see Figure 2). The neutral point location may not allow for clearing short circuits of a phase to phase nature should they occur. This location has slightly higher transients when switching as seen by the switching device. The alternative location is able to clear phase to phase faults should they occur. It has slightly lower transients seen by the switching device. This alternative location however imposes these transients directly on the tertiary bushings of the power transformer.

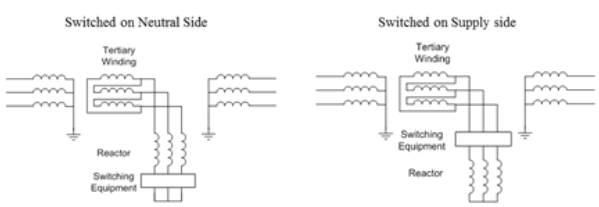

Figure 2 – Switch Locations [1]

C. *Tertiary Reactor Design and Failure Modes*

A typical air core shunt reactor construction widely used in tertiary applications is shown in Figure 3. The rating of tertiary air core reactors for voltage levels up to 72.5 kV is in the range of 20-60 MVAr per phase. Hence the design of this kind of air core reactor is most likely a multi-layer winding with currents up to 2kA.

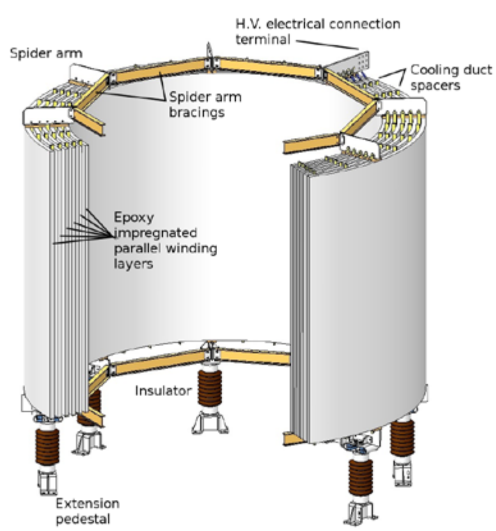

Figure 3 – Modern Tertiary Air Core Shunt Reactor

Three types of switching related faults occur in tertiary air core shunt reactors. These faults consist of low probability modes like phase-to-phase and phase-to-ground failure and also turn-to-turn failures. Turn-to-turn modes are the most common and most challenging failure modes. Improper design, poor quality in manufacture, the use of insulation material with low hydrolytic stability, and transients caused by switching can all lead to insulation deterioration resulting in turn-to-turn failures. These failures normally have severe impact on the faulty reactor and may damage reactors on healthy phases as well, since a breakdown in one phase can lead to an increase up to ≈ 2 times the rated phase current [4] in a healthy phase. Methods, such as the use of a split phase protection scheme, can be utilized to help minimize the damage to healthy phases.

System data (frequency, operating voltage, maximum voltage, BIL, inductance value or reactive power rating, available fault level, etc.) as well as Environmental data (ambient temperature range, outdoor/indoor application, altitude above sea level, wind conditions, seismic requirements, etc.) all are important and can impact the design and performance of the shunt reactor.

The turn-to-turn insulation has to be designed to withstand the highest stress to be expected. Therefore the most severe transients have to be considered as well as their frequency of occurrence. Without detailed information from the utility, manufacturers often have to make assumptions when completing the design. Since, for air core shunt reactors, the turn-to-turn insulation can make up to 10% of the total costs there is an opportunity for possible cost improvements but also a risk that the insulation utilized may not be sufficient for the application.

The location of the turn-turn fault is most likely in the windings closest to the ends of the shunt reactor. Each winding on the shunt reactor can be seen as an inductance parallel with a leakage capacitance and capacitance to ground. The inductive part acts stiff on inrush currents, and the capacitive part causes an exponential distribution of voltage over the winding, with max at the top due to high frequency.

The modeling and simulation for these turn to turn voltage calculations can be seen in Figure 4, where L is the inductance of each turn of the reactor, R is the resistance of each turn, Cs is the series capacitance between two turns, Cg is the capacitance to ground of each turn, Rd is the dielectric resistance of the insulation material and M is the magnetic coupling between turns. For the sake of convenience not all elements are labeled and not all magnetic couplings are shown. Moreover capacitive coupling elements and the resistive part of turn-to-ground insulation is not given since these elements have insignificant influence on the voltage distribution along the reactor winding [7]). The provided model is for a multilayer air core reactor with n parallel cylindrical layers consisting of m turns in the innermost layer and z turns in the outermost layer.

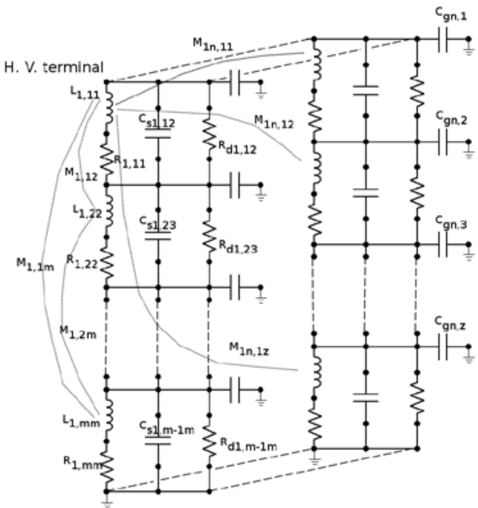

Figure 4 - Multi-Layer Air Core Transient Model

Figure 5 shows visually that a sharp voltage change will create a large turn to turn voltage that progresses through the windings. There hence are traveling waves generated from reflections. At reflection points, these will compound increasing stress on the turn to turn insulation.

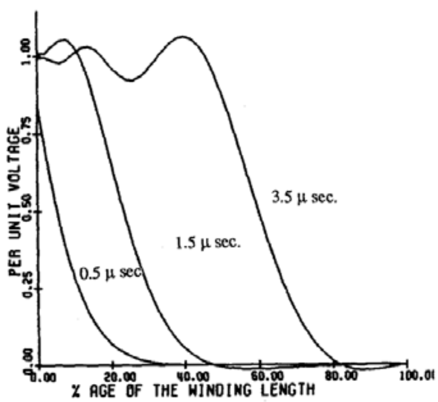

Figure 5 - Air Core Reactor [8]

Voltage related failures are typically the result of reduced insulation withstand levels, switching surges, high magnitude re-ignitions, or lightning impulse events. Transient overvoltages exceeding the insulation BIL can cause immediate failure while partial discharge energy, over time, can lead to localized breakdown of insulation material eventually leading to the reactor failure. Shorted turns which increase the current through those shorted windings of the reactor, restricted air flow in cooling ducts, and higher than expected ambient temperatures are typical causes temperature related failures. This results in accelerated aging and the failure mode usually results in more widespread damage to the reactor than a voltage related failure.

D. Impact of tertiary reactors on the tertiary winding of Power Transformers

While voltage transients and turn to turn voltages are significant on the tertiary reactors themselves, it is unlikely that they are an issue to the tertiary windings of the transformer itself. This is because the transformer tertiary windings and entrance bushings are an order of magnitude higher capacitance than that the tertiary reactors themselves. This will allow very little of these external voltages transients to get inside the transformer.

While not often discussed, consideration should be given to the fault current rating of the transformer tertiary winding. It should be designed to handle fault current levels that may occur if there is a failure of a tertiary reactor. While this capability may have been designed into the transformer tertiary windings, it is not commonly available from the nameplate information on the transformer. Lack of an adequate short circuit capability can cause undue risk to the long term performance of the power transformer and shorten its life, through failure of insulation in case of a fault external to the transformer.

E. Impact of Transients due to Switching

It is the author's opinion, based on review of published documents and discussions with users, that with a properly designed and applied shunt reactor, the most common cause of turn-to-turn failures can be attributed to transients caused by switching. Overvoltages from current chopping, restrike, re-ignitions, and prestrike can be generated during the highly inductive switching operations.

There is no published reliability database available for tertiary shunt reactors to the authors' best knowledge. Likewise, there is no published data on reduced reliability of transformers with tertiary reactor applications but there is circumstantial evidence that this exists by utility engineers. Experienced engineers have said that 80% of major breaker failures occur on reactor switching applications but this accounts for less than 2% of all breaker applications. The statement "Shunt reactor switching by circuit breakers seem to be the most unreliable application of circuit breakers" is supported by a CIGRE study [5]. Although this high failure rate is common knowledge by those with a number of reactors that are actively switched, it is not realized by those without reactors or those who have them but do not switch them except on an annual basis.

Current Chopping is when the current is forced to zero prior to a natural current zero. This creates an overvoltage from the energy stored in the reactor. $E = \frac{1}{2} L \times I^2$ The energy is a constant both before and after the chopping event occurs. The energy is converted into voltage as occurs with a conservation of this energy. The voltage is then stored in the capacitance as in $E = \frac{1}{2} C \times V^2$. Thus overvoltages occur on the reactor windings at the point of this current chopping event. Figure 6 shows the relative effects of this voltage surge in terms of typical current chopping magnitudes. Higher current chopping values are characteristics of some interrupter technologies and designs. Typically, vacuum interrupters have the higher values. Additionally ones with fault current interrupting capability have significantly higher chopping currents than those specifically designed for switching only. This is problematic as many users want to have the same device to switch the reactor and to protect is. The paradox is that this higher current switching device is causing overvoltages and likely damage to the very device that it is protecting. This effect is what creates the voltage difference between V_m and V_o which represents the voltage surge from current chopping and can be seen in Figure 7. SF6 devices typically have lower chopping currents. As can be seen, this also produces lower chopping overvoltages resulting in less stress on the reactor itself.

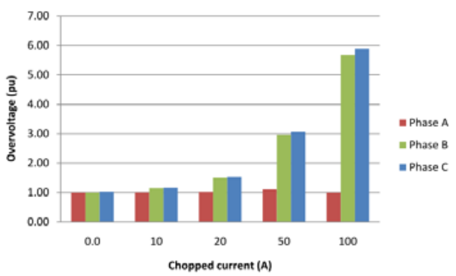

Figure 6 – Overvoltage vs Chopped Current Magnitude [8]

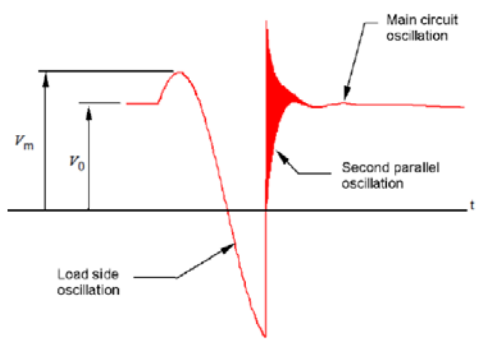

Figure 7 - Typical Waveform of Re-Ignition overvoltage [8]

Re-ignitions are likely to occur during the race between the voltage rising after interruption and the separating of the interrupter contacts. While the voltage rise for iron core reactors is extremely fast, the voltage rise for an air core reactors can be more than 10 times faster. In both cases, there is virtually no movement of the contact positon between actual current interruption and when the voltage reaches its maximum value. Hence, if the contact gap is too small when the current interruption occurs, then the contacts cannot withstand the recovery voltage. This results in a re-ignition.

The issue with a re-ignition is that it is an extremely fast collapse of voltage. Commonly this is faster than the voltage rise that occurs from direct lightning strikes and can result in higher turn to turn voltages in the windings of the reactor. The primary difference here is that reactors are switched daily in many applications and lightning strikes close to the device are quite rare. Hence, the likely hood of having insulation failures in service is much higher from re-ignitions than it is from electrical thunderstorms.

A likely sequence of events leading to reactor failure is that these high re-ignition voltage collapse rates cause turn to turn insulation failures. The shorted turn then decreases the inductance of the air core reactor dramatically and increases the local current in windings that then are carrying currents well in excess of their rating hence overheat.

One method used, with some success, to reduce the magnitude of the transient voltage during switching is to apply an RC filter or “Snubber Circuit” between the switch and tertiary shunt reactor. While this may limit the extreme voltage magnitudes of overvoltages, there appears to be a higher number of re-ignitions when this is used with some vacuum interrupters. It should also be noted that while the Snubber circuit reduces the voltage rate of rise, it does not impact the rate of change of the voltage collapse during the re-ignition. Figure 8, below, shows the choppy nature of such occurrences common in many vacuum interrupter designs. As can be seen, the circuit is interrupted, then a re-ignition occurs, a current zero is interrupted and another voltage excursion is created. This sequence is repeated until there is sufficient dielectric strength between the contacts to prevent further re-ignitions. Should the frequencies be close to the resonant frequency of the reactor itself, this can cause a further stress on the turn to turn windings.

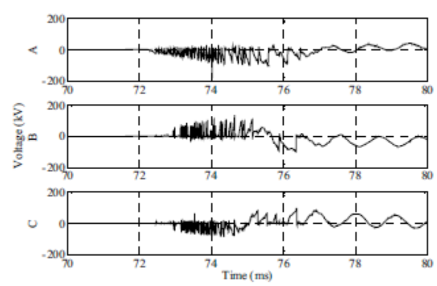

Figure 8 - TRV Waveform with Snubber Circuit [9]

F. Other Interrupter Technologies and their Impact on Tertiary Reactors

Interrupter technologies have varying capabilities when it comes to interrupting high frequency zeros which will result in either more or fewer high frequency current oscillations. Vacuum intrinsically has the capability to interrupt these high current zeros which can lead to repeated re-ignitions. SF6 interrupter technology is much less likely to do so and as a result causes fewer re-ignitions and fewer high dv/dt events, resulting in less electrical voltage fatigue to the turn to turn winding insulation

SF6 circuit breaker interrupters, by standard, are general purpose devices and are not specifically designed to withstand the re-ignitions and current flow generated by the fast voltage rise created by switching reactors. As a result, the arc can take undesirable paths causing damaged voltage shields, punctured nozzles, and other damage degrading of the capability of the interrupter. At times, these arc paths can venture outside of the designated arcing chamber leading to a major failure. CIGRE breaker reliability surveys reveal that the reactor switching duties cause failure rates 10 times that of conventional breaker installations.

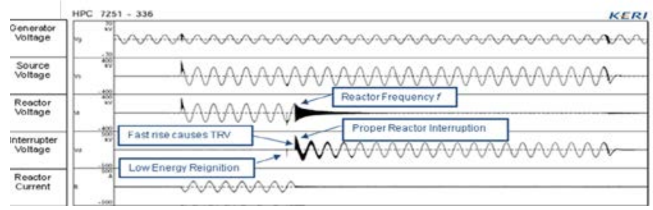

Figure 9 - Switching Test with Low Energy Re-Ignition [10]

G. *Special Purpose Reactor Switching Device*

An improved SF6 interrupting technology is now available that is purposefully designed for shunt reactor switching. It is one that intrinsically has lower chopping current, does not interrupt high frequency zeros and is designed to be able to withstand a partial discharge to minimize the likelihood of a re-ignition and dramatically reduce the number of re-ignitions that may occur on a single interruption event. Additionally, because of this design, it is able to withstand many re-ignitions over its lifetime without puncturing the nozzle extending the life of the switching device. This is achieved through modified gas flow that delays interruption until contacts are sufficiently apart from each other to withstand voltage. The geometry of the arcing contacts and gas nozzle are specifically designed to better control the interaction between the gas, contacts, and nozzle material during switching a purely reactive load out of the circuit. A minimization of the likelihood of a re-ignition results because of this controlled interruption process. Additionally, this approach also further eliminates the possibility of interrupting the high frequency current zeros which in themselves cause further turn to turn voltage stresses from voltage escalations.

The design of the interrupter is counter intuitive to breaker designers. Breakers are designed to interrupt at the first possible point in time. Interrupting in the first cycle is very important to a protection scheme, but makes the breaker more likely to experience re-ignitions. A switch, designed specifically for interrupting reactive loads on the other hand can take advantage of extending this minimum arcing time. The new interrupter design is unique in that it is designed to delay the first interruption until the gap is large enough to avoid high energy re-ignitions (see Fig 9). The delay is accomplished with a special interrupter design that will not allow the interrupter to sustain an interruption until the contacts have developed sufficient gap [6].

Special purpose reactor switchers have the following advantages:

- Delays current interruption until interrupter contacts are able to withstand fast recovery voltages
- Interrupter designed to withstand reignition without damage or life reduction
- Mitigates high turn to turn voltage stresses on reactor
- Reduces current chopping
- Eliminates voltage escalation from high frequency current zero interruptions caused by multiple re-ignitions.

III. Summary

Tertiary shunt reactor applications typically lead to the use of multilayer, parallel winding air core designs. Their behavior should be incorporated in transient studies in order to accurately model the interaction between the switching device and the air core reactor. It is also noted that the more useful information shared, by the user, with the equipment manufacturers, the fewer costly safety margins have to be added to the design.

A well designed interrupter system can reduce the excessive turn to turn voltages, that otherwise occur, and can allow the reactor manufacturers to offer a design optimized to survive the user's switching environment. As the reactor is more expensive than the switching device, perhaps a more even distribution of costs can achieve a more reliable and less expensive overall solution for these applications.

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