Delayed Current Zero Crossing Phenomena during Switching of Shunt-Compensated Lines

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***Abstract*—** There are a number of 345kV transmission lines in the Midwest region that have installed shunt reactors on the transmission lines for voltage control. Studies conducted on several of these lines indicate that there is a risk of Delayed Current Zeros (DCZ) during some switching scenarios. Transient studies indicated that under some switching cases, the line and in some instances reactor breakers may not see current zero crossings for several cycles. If the line breaker tries to open immediately after line energization, while the line currents are in a transient state, the breaker currents will be offset with slow decaying DC. It will fail to open if there is no current zero within the interrupting time. The magnitude of the DC offset is governed by the point on the voltage wave where the breaker contacts close, line resistance, line inductance, and reactor inductance.

The paper analyses the effect of degree of compensation on the DCZ phenomenon and discusses various mitigation methods. It also highlights some suggested protection and automatic control practices that can be employed to minimize DCZ transient effects on the equipment.

***Index Terms*—Shunt Reactors, Delayed Current Zero, Shunt-compensated lines, Line Protection**

I. INTRODUCTION

CAPX2020 projects initiated by eleven Utilities of five states in upper Midwest, have built nearly 800 miles of transmission at 345 kV and 230 kV. This is the largest transmission project in recent years to improve the reliability of the grid in upper Midwest. Long transmission lines during light load conditions needed shunt reactors to control system voltages to be within the acceptable limits. They were installed either on transmission transformers tertiaries or on transmission lines. Shunt reactors on transmission lines were installed at both ends on lines longer than 100 miles or installed at only one end on shorter lines. Circuit breakers or circuit switchers were used on several shunt reactors and some were directly connected to transmission lines.

Long transmission lines can be represented as infinite sets of series connected elements made up of series resistance R, series inductance L and shunt capacitance C as shown in Figure 1.

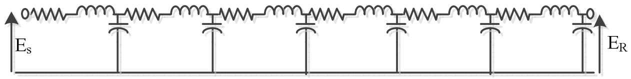

Figure 1: Long Transmission line Representation

Resistance is usually much smaller than the inductive reactance and can be ignored for our discussions. The receiving end voltage, E_R is dependent on how much current is flowing on the line.

Unloaded or lightly loaded lines tend to exhibit the Ferranti effect where the receiving line end voltage, E_R, is elevated compared to the sending line end voltage, E_S.

Transmission lines that require voltage control are energized with shunt reactors connected to keep the receiving end or system voltage at the required operating level. Degree of compensation (Shunt Reactor MVAR compared to Charging MVAR considered as 100%), location and number of shunt reactors on a line is determined through planning studies.

Application and sizing of shunt reactors is explained in detail in T.J.E Miller's book [1].

II. SWITCHING OF SHUNT COMPENSATED LINE

A. Effect of Degree of compensation on breaker currents during normal switching – Mathematical analysis

Degree of compensation, M is defined as $M = \frac{\text{MVAR\_R}}{\text{MVAR\_C}}$ (1)

where, MVAR_R is the rating of the sum of all shunt reactor MVAR ratings installed on the line and MVAR_C is the charging MVAR of the line.

Capacitive current I_C leads the voltage by 90^0 whereas the inductive current I_L lags the voltage by 90^0 and is out of phase with respect to capacitive current.

Assuming voltage waveform as V sin (ωt), capacitive current

$$I_C = I \sin(\omega t + \varphi + 90) = I \cos(\omega t + \varphi) \quad (2)$$

Where, φ is angle delay on the voltage waveform from zero crossing when the breaker is closed.

Shunt reactor current with degree of compensation equal to M will be $I_L = M\, I\, [\sin(\omega t + \varphi - 90) + \cos\varphi\, e^{-t/\tau}]$

$$I_L = M\, I\, [-\cos(\omega t + \varphi) + \cos\varphi\, e^{-t/\tau}] \quad (3)$$

It is to be noted that the reactor current will have an additional term corresponding to the decaying DC. DC sign will depend on whether the voltage is increasing or decreasing at the instant of switching.

Breaker current is given by $I_{BR} = (I_L+I_C)$

$$I_{BR\varphi} = (1-M)\, I*\cos(\omega t+\varphi) + MI*\cos\varphi * e^{-t/\tau} \qquad (4)$$

Assuming maximum DC offset when switched at voltage zero crossing, $\varphi=0$, the breaker current will be

$$I_{BR0} = (1-M)\, I*\cos(\omega t) + MI* e^{-t/\tau} \qquad (5)$$

If the AC component peak is greater than the DC value at the instant of switching (t=0), it can be concluded that the AC current waveform will always cross the zero current line.

$$(1-M)I > MI; \quad M<0.5 \qquad (6)$$

The degree of compensation, M from equation (6), has to be less than 0.5 to avoid delayed current zero (DCZ) on shunt compensated lines during switching.

If the degree of compensation is greater than 50%, the current zero is delayed until time t when $(1-M) = M*e^{-t/\tau}$. This is when AC waveform peak exceeds the DC value.

Solving for time to get first current zero, $t = \tau \ln \frac{M}{(1-M)}$ (7)

Shunt reactors used on the transmission line can either be of air-core construction with a typical X/R of 350 (time constant, τ =0.928 seconds) or oil filled type with X/R around 600-750 (τ up to ~2 seconds).

Assuming a time constant of 2 sec (X/R ~750), time to get first current zero variation with the degree of compensation is shown in Figure 2.

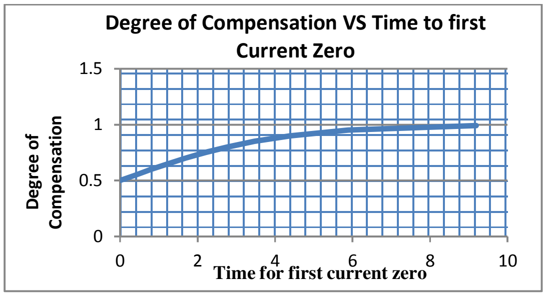

Figure 2: Time to first zero based on degree of compensation

B. Line breaker current on 100% compensated line

To understand the switching issues associated with shunt compensated lines, single phase circuit of a 345 kV line as shown in Figure 3 is used for our discussions. The line is represented using lumped parameter model with half the total charging MVAR (50) connected at both ends. 50 MVAR shunt reactor is connected at the switching end. Infinite source is assumed at this point.

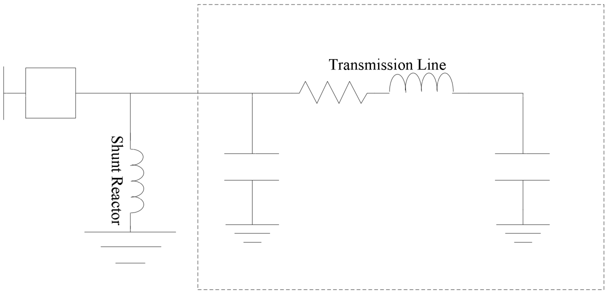

Figure 3: Single Phase 100 % shunt compensated line – shunt compensation: 50 MVAR

The voltage relationship between steady state capacitive and inductive currents and the resultant breaker currents of 100% shunt compensated line are as shown in Figure 4.

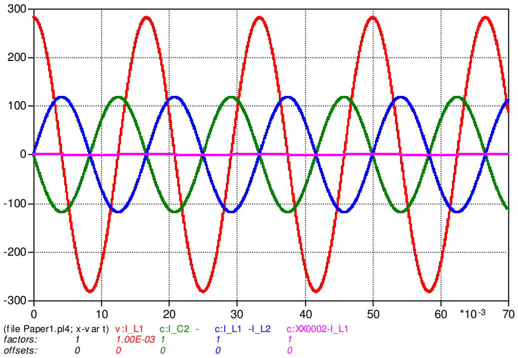

Figure 4: Steady state Reactor current (Blue), Capacitive Current (green) and resultant current through the line breaker (Magenta). Voltage in kV (Red); All Currents in Amps

The resultant current through the breaker would be the sum of these two currents which is actually difference between the two currents (I_C-I_L) as they are out of phase. The compensation is 100% indicating $I_L = I_C$, the resultant current through the breaker is zero. For other ratings of shunt reactor, breaker current is either capacitive or inductive depending on whether the charging MVAR is greater than or less than the Shunt reactor MVAR.

As discussed earlier, shunt reactor transient currents during line energization has additional DC component depending on the point on voltage wave switching. Maximum DC offset is when the shunt reactor is energized along with the line at voltage zero point as shown in Figure 5.

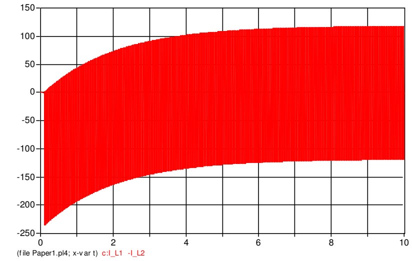

Figure 5: Shunt reactor current - switching at Voltage zero

Line breaker current as shown in figure 6 has initial switching transients due to capacitance and slowly decaying DC current decaying with time constant, τ of 2 seconds.

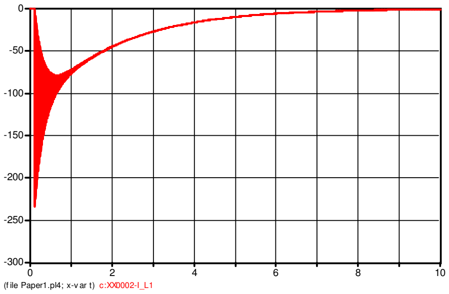

Figure 6: Breaker current during Switching at Voltage zero with X/R= 750

Breaker current never sees a current zero for almost 8 seconds. The delay in the appearance of first current zero is dependent on the degree of compensation as discussed in the previous clause.

C. Effect of source impedance on DCZ

Time constant, τ in equation (7) is the overall time constant of the energizing circuit which includes the source impedance. Source impedance with lower X/R reduces the overall X/R of the circuit under study. As an example, with Fault MVA of 2500 MVA at the bus, source impedance is (2.491 +j47.5) ohms assuming X/R of 17.

50 MVAR Shunt reactor impedance = (3.174 +j2380.49) assuming X/R of 750.

Total impedance = 5.665 +j2428. This has an X/R of 428.6. The time constant reduced from 2 seconds to 1.137 seconds.

Time constant of the circuit reduces with decrease in source strength.

Figure 7 shows the plot of breaker current with X/R of 428.6.

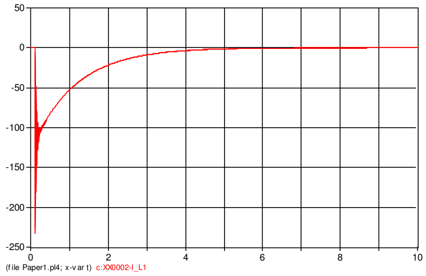

Figure 7: Line breaker current with X/R of 428.6

D. Energizing faulted line – Impact on DCZ on healthy phases

Voltages on un-faulted phases increase due to ground faults and maximum change is at the fault location. Increase in voltage is dependent on the effectiveness of system grounding as seen from the fault location.

Effectiveness of grounding, K is defined as $K = Z_0/Z_1$

Where, Z_0 and Z_1 are the total zero sequence impedance and positive sequence impedance of the system at the fault location.

For a single line to ground fault at the shunt reactor location, un-faulted phase voltage increases by a factor $\frac{(K-1)}{(2+K)}$

For Double line to ground fault, the voltage increases by $\frac{3K}{(1+2K)}$.

As an example, for A-G fault at the reactor location in a system with K=2.8, the voltage on the B-phase (in PU) will be

$$|V_B| = \left|e^{-j240} - \frac{(2.8-1)}{(2+2.8)}\right| = |-0.5-j0.866 - 0.375| = 1.231$$

For a B-C-G fault, A-phase voltage (in PU) will be

$$V_A = \frac{3*2.8}{(1+2*2.8)} = 1.273 \text{ PU}$$

Double line to ground fault produces higher voltage shift on the un-faulted phase.

Analysis to determine the time to get first current zero is the same as discussed in previous clauses except that the voltage on the healthy phase will be higher than the value during normal energization and the DC offset is higher.

Since line capacitance is distributed over the entire length, voltage shift at the fault location will not result in proportional increase in capacitive current as seen on the shunt reactor. Inter phase capacitance also influences total capacitive current. Transient studies are required to determine how much M needs to be reduced below 0.5 to prevent DCZ.

III. CASE STUDIES

A simplified 345kV, 135 mile shunt compensated line, shown in the figure 8, is used in the following switching studies.

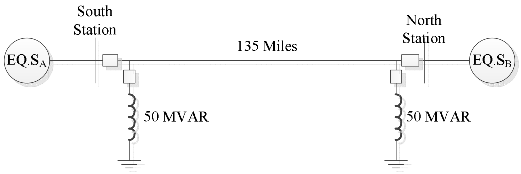

Figure 8: Simplified system model used for transient studies

Line Data: Line: 345 kV, 135 miles; Line charging MVAR: 117 MVAR; Line impedance (6.82+j79.6) ohms

Shunt Reactor Data: 50 MVAR connected at both ends of the line. Shunt Reactor impedance (3.83+j2424) ohms;
X/R =632.91 (τ =1.67s).

A. Energization of a shunt compensated line

First, South to North line radial energization from South substations was studied. The south line end breaker currents following line energization with both line end shunt reactors connected (86% percent shunt compensation) are shown in figure 9. Line end breaker A- and B-Phase poles are simulated to close at their corresponding phase voltage zero crossings.

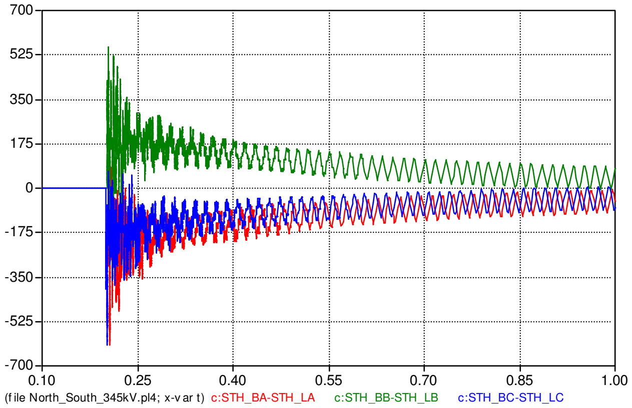

Figure 9: South line-end breaker currents following radial line energization with both shunt reactors connected.

Breakers equipped with pre-insertion resistors have been used to reduce switching over voltages. Selection of resistor value and duration of insertion in discussed in detail in the reference paper [2]. To minimize DCZ severity shown in figure 9, utilization of pre-insertion resistors during energization was studied. Typical pre-insertion resistor value of 425 ohms was used. Simulation studies found that to eliminate missed current zero crossings, a minimum of 13ms pre-insertion time was required. Figure 10 shows the resulting South end breaker currents.

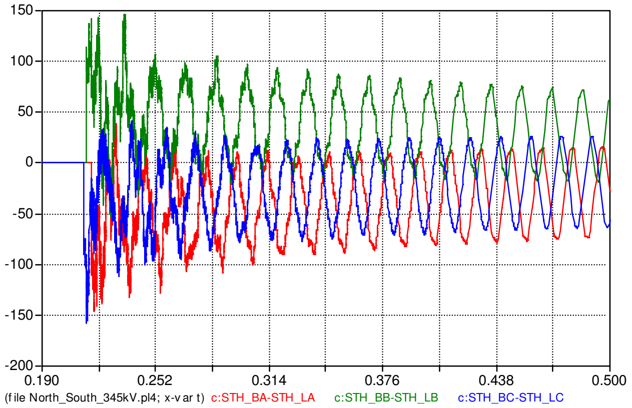

Figure 10: South line-end breaker currents following radial line energization using 425 ohm resistors pre-inserted for 13ms.

The impact of increasing the pre-insertion resistor values was also studied. Using a pre-insertion resistor of 600 ohms did minimize the severity of DCZ line-end breaker currents experienced.

Radial energization of the line with only the North end shunt reactor connected (43% compensation) was considered next. Figure 11 shows the South line-end currents following line energization.

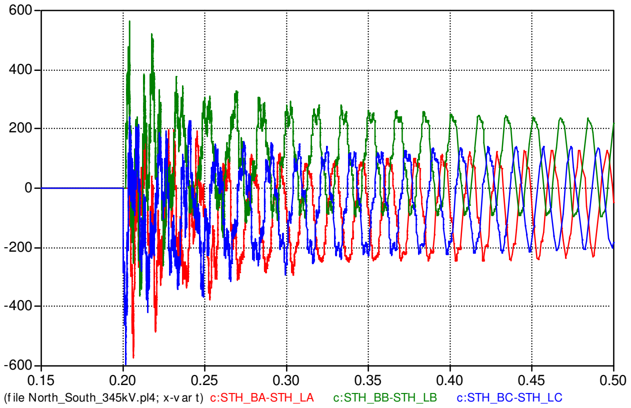

Figure 11: Radial energization of the line, with only North line-end reactor connected

Figures 9 and 11 demonstrate that if M < 0.5, line breaker currents don't experience delayed current zeros during energization. Similar results were observed when the line was energized from North substation.

Energizing of a shunt compensated line into a fault may also result into delayed current zeros on the un-faulted phase (s). A close-in double line to ground fault, as stated earlier, generally results into the highest voltage rise on the un-faulted phases at the fault location. This fault type is considered for the simulation results shown in figure 12 below.

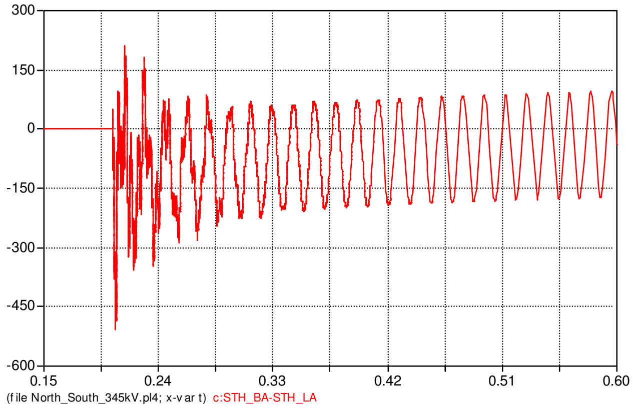

Figure 12: Radially energizing line from South into a close-in BC-Ground fault, with only South line-end shunt reactors connected.

Simulation study results, shown in Figure 12, with only one shunt reactor connected (M~0.43) did not result into missed current zero crossings on the un-faulted phase. Line energization into a fault with both line reactors connected resulted into several seconds of missed current zero crossing. Utilization of 600 ohm pre-insertion resistor, during energization of the line, with 86% compensation, into a double line to ground fault, didn't not mitigate the DCZ transient on the un-faulted phase.

The severity and degree of current offset on the un-faulted phases depends on the fault type, system parameters, and line configuration, all of which may vary from line to line. This makes every case different and perhaps unique. For this line, the M value of about 0.43 was found to be adequate to eliminate DCZ for all switching scenarios. Therefore, transient studies to determine the degree to which M needs to be reduced from 50%, to mitigate DCZ are recommended.

B. Switching of shunt reactor on energized system

Shunt reactors are typically switched in during light loading conditions and switched out during heavy loading to keep the voltage within the required limits. Figure 13, 14, and 15 show simulation study results used to evaluate the impact of switching a shunt reactor on to a closed through transmission line. Figure 13 shows the South substation line end breaker currents following energization of the South line end connected shunt reactor. Reactor breaker B- and C-Phase poles are simulated to close at their corresponding system zero voltage crossings. Initially, limited or no power is considered to flow on the line.

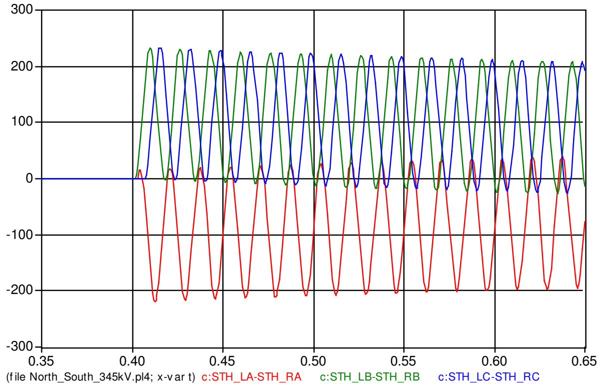

Figure 13: South substation, shunt reactor breaker current

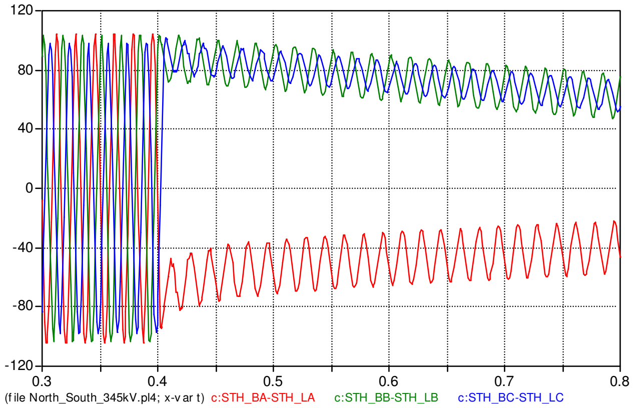

Figure 14: South Substation line breaker current following reactor switching with limited power flow on the line

Simulation study is repeated with the South reactor breaker getting switched on to the closed through transmission line, with about 46 MW flowing from South to North.

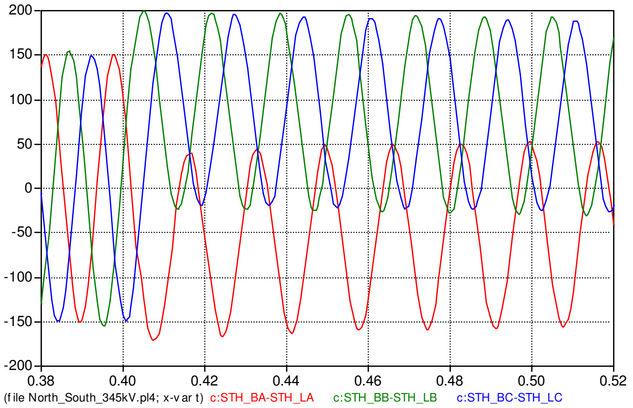

Figure 15: South line end current following energization of South line-end shunt reactor on a closed through transmission line with North line-end reactor connected. Approx. 46 MW are flowing on the line

The studies show that closing of the reactor at voltage zero creates DC offsets whose magnitude largely depends on the reactor value being switched. The generated current DC offset is distributed between the two sources from the reactor bus. The strongest source side experiences the most DC offset. As explained earlier, if $M < 0.5$, line breaker currents experience delayed current zero for several cycles.

Figure 15, however, shows that if there is sufficient amount of power flow on the line, the extra phasor component (line load current) adds to the I_{BR} (previously defined as I_L+I_C) current component to create a net sinusoidal current component that is at least equal to the peak DC current component. In this case, a minimum of 46MW, power flow from South to North, is found to be adequate in mitigating the delayed current zeros when energizing the second shunt reactor. As a rule thumb, it's therefore recommended that at the minimum, the line is loaded to the value corresponding to the shunt reactor power rating (in MW) that's being considered for switching. This helps mitigate the DCZ phenomenon on line end breaker currents. Switching of a shunt reactor doesn't create delayed current zeros on reactor breaker currents themselves. In the worst case switching scenario (poles closing at system voltage zero), the reactor breaker current just gets fully offset for a few cycles.

C. Switching of line/shunt reactor for transmission line fault events

Transmission lines are designed to be automatically switched out by protection schemes during fault conditions and reclosed back in after a predefined time if the fault is not permanent. In some instances, planned system may drive the need to switch out lines. The former is considered first. The current flowing through the South reactor breaker is shown in figure 16, following an A- phase to ground fault at system voltage zero.

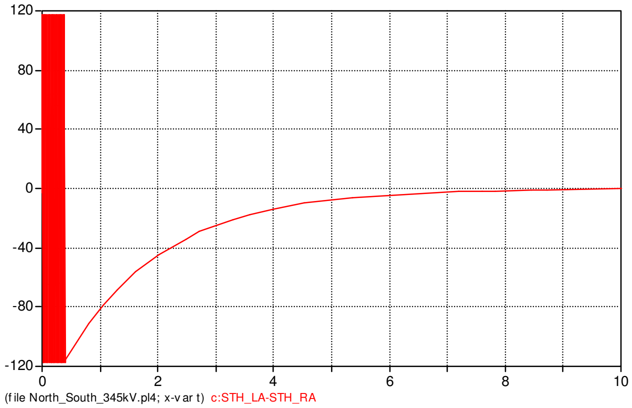

Figure 16: South line end current for an A-Phase to ground fault on the reactor bus at A-Phase system voltage zero

Since the reactor current lags the system voltage by 90 degs, the reactor current is at its peak at the instant of the system fault occurrence. Simulation studies show that due to a large X/R (~633), the reactor current takes several seconds to decay to zero. In this particular study, the reactor current takes in excess of three time constants to decay to about 2% of its peak value.

Secondly, a case of line de-energization under no-fault conditions is considered. Figure 17 shows voltage transients on the transmission line following line de-energization (only B-Phase is shown). The exchange of trapped energy between charging capacitance and the transmission line shunt reactors may last several cycles before it's damped out.

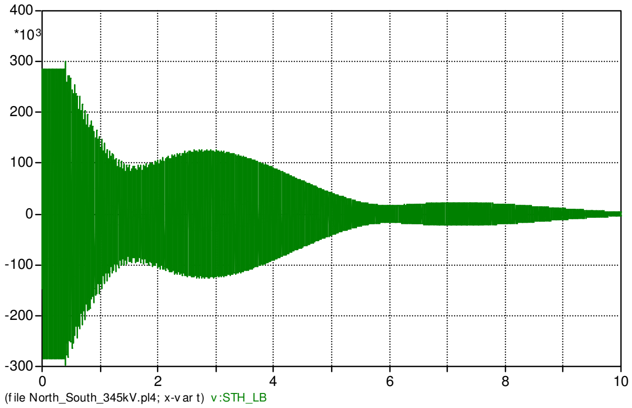

Figure 17: South line end B-Phase voltage following line de-energization under no fault conditions

From the simulation study results in figure 16, and 17 above, it is recommended to not trip the reactor breakers for transmission faults. Following a system fault condition, reactor breaker current(s) in the faulted phase (s) may take several seconds before it decays to zero. Also depending on the severity of the voltage transients on the transmission line and how long they last following line de-energization, high-speed reclosing may not be recommended.

IV. DELAYED CURRENT ZERO MITIGATION METHODS

A number of methods, suggested for mitigating the DCZ phenomenon and their shortcomings, are discussed:

A. Use of pre-insertion resistors on line breakers

Pre-insertion resistors, typically sized to match the transmission line characteristic impedance, are sometimes recommended as a way of mitigating DCZ. This method however, has some limitations among which include:

- Transient studies have shown that longer pre-insertion times are required to mitigate DCZ occurrence than can be guaranteed by some breaker manufacturers. Breaker manufacturers typically guarantee 8-12ms. Pre-insertion time of at least 13ms was required for normal line energization.
- Much as using pre-insertion resistors may minimize the DCZ phenomenon, studies have shown that this method may not be adequate under all the switching scenarios especially those involving reactor switching on an already energized transmission line
- Depending on breaker switching mechanism, increasing the pre-insertion resistor value may create new transients once the main contact by-passes the pre-insertion resistor.

B. Limit degree of line compensation during line energization

Studies have shown that limiting the degree of line compensation to less than 50% during line energization minimizes DCZ. For lines that have more than 50% compensation, reducing the compensation before line energization is recommended. Extra shunt reactors may be added on the line after energizing it. Reducing the compensation temporarily during energization does however lead to elevated remote end voltages. Remote end connected equipment like Coupling Voltage Transformers and surge arrestors need to be adequately rated.

C. Utilization of controlled closing for switching reactors

To mitigate possible missed current zeros resulting from switching in shunt reactors on connected through transmission lines, controlled closing is suggested. Since shunt reactors are switched in during light load periods, it becomes particularly vital to minimize instances of closing of any of the reactor breaker poles at voltage zero crossing. Implementation of this may however, be challenging on existing shunt reactor breakers as this may require breaker replacement or upgrade.

D. Consider moving reactors (or some of them) from transmission line to substation buses

Addition of shunt reactors or some of them on the bus may help minimizes DCZ when the reactors are switched. Depending on the bus size, the number of elements connected to it, and the level of each element loading at the time of reactor switching, DC offsets get distributed among the elements connected on the bus. And as far as the reactor breaker currents are concerned, the worst case scenario typically just results into full offset of the shunt reactor current. Existing sites may have physical limitations which makes implementation of this challenging. Also as previously mentioned, reduction of shunt reactor MVARS leads to elevated line end voltages. Remote end line connected equipment must be sized adequately.

V. TRIPPING AND RECLOSING CONSIDERATIONS FOR SHUNT COMPENSATED LINES

Delayed Current Zero phenomenon associated with the switching of shunt compensated lines has been demonstrated to be a slow decaying transient. This has a number of implications on line reclosing. Given below are some of the operational recommendations associated with switching shunt reactors:

A. Radial energization of transmission line

It has been demonstrated that energization of shunt compensated line with more than 50% compensation may result into delayed current zeros on line breaker currents. A definite time delay is recommended to allow for decay of transients before synch closing the line end remote end breaker.

B. Disable high-speed reclosing

Transient simulations have been used to demonstrate that ground faults occurring at or near system voltage zero crossing may result into shunt reactor currents that may take several seconds to decay to zero. Transmission lines that require a reduction in the shunt compensation before re-energization do therefore require adequate time, which is several times longer than recommended for high-speed reclosing, before some reactors can safely be switched out. Additionally, adequate time delay before line re-energization also allows for transient oscillations involving exchange of energy trapped between the reactor and the shunt capacitance to decay.

C. Delay line breaker tripping for transmission lines

Ground faults occurring at or near system voltage zero crossings, on lines with more than 50% compensation may result into missed current zero on line breaker currents for several cycles. This is depends on the zero sequence currents flowing on the healthy phases or the minimum load on the healthy phases at the instant of fault occurrence. A close-in A-phase single line to ground fault at South substation, occurring at system voltage zero crossing, with 46MW flowing from South to North, is simulated and studied. Figure 18 shows the South un-faulted phases' line-end breaker currents.

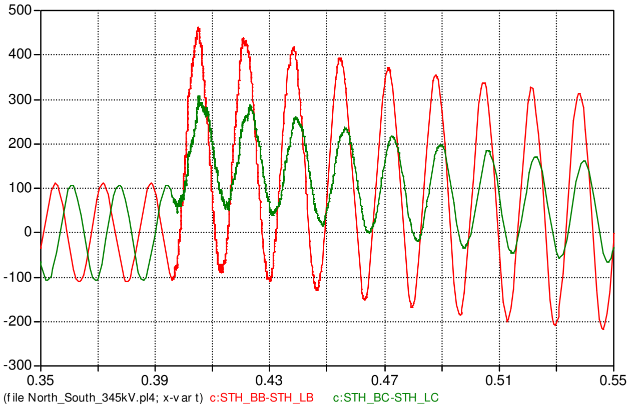

Figure 18: South line end currents of the un-faulted phases following an A-phase SLG fault

Current zero crossings on the C-Phase don't appear until at least five cycles after fault inception. Similar current behavior is observed at North substation on un-faulted phases. Therefore intentionally delaying tripping for transmission faults may be suggested. This would allow for currents zeros to appear.

CONCLUSIONS

Energization of Shunt Compensated line with over 50% compensation or energization of shunt reactors greater than 50% of the line charging current on transmission lines will result in large DC offsets in line breaker currents. The delay in the appearance of current zeros can be as late as a second due to high X/R of shunt reactors. Opening of these breakers immediately following energization of such shunt compensated line or shunt reactor will result in line breaker failure due to delayed current zeros (DCZ). The DCZ effect is dependent on the degree of shunt compensation and also on the point on wave switching.

Several mitigation methods and line operational recommendations have been discussed:

On line energization to prevent DCZ:

- If shunt reactor(s) on the line is not required to limit open end voltage to acceptable level, energize the line without shunt Reactors.
- Keep Shunt Compensation below 50% during line energization.
- Energize the line through breakers equipped with pre-insertion resistors that provide enough damping to produce current zeros within breaker interrupting time. This is dependent on the resistor value and duration of insertion. It may not work under all the cases if the degree of compensation is close to 100%.

On Shunt reactor energization onto energized lines, to prevent DCZ:

- Switch shunt reactors less than 50% of the total charging current.

- Switch shunt reactor at voltage maximum point on the wave.
- Switch shunt reactors if their inductive MVAR is not more than the minimum load on the line, in MW.

Tripping for line faults:

- Trip only the line breakers and not shunt reactors.
- Shunt reactors need to be tripped only after several seconds delay to allow full decay of reactor current on the faulted phase.
- Total interrupting time of faults on lines with shunt compensation greater than 50% may need to be at least few cycles to allow presence of current zeros on healthy phase(s) during faults. This is dependent on the zero sequence currents flowing on the healthy phases or the minimum load on the healthy phases.

Tripping for shunt reactor faults:

- Trip the shunt reactors only if they are equipped with breakers.

Reclosing on Lines:

- Instantaneous reclose is disabled on lines where shunt reactor switching is required to reduce the degree of compensation.
- Time delay reclose is enabled after the reactor is switched out.
- Synch-check reclosing at the other end after energizing the line may generate offsets on the currents. DC offset is dependent on the load picked up after restoration.

ACKNOWLEDGMENT

Authors sincerely thank American Transmission Company study group for bringing up DCZ issues during the line design studies on one of the CAPX lines. This finding resulted in studying all other lines by other CAPX members to evaluate appropriate mitigation methods for several lines.

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[2] D.E. Hedman, I. B. Johnson, C. H. Titus, D. D. Wilson, “Switching of Extra-High-Voltage Circuits II-Surge Reduction with Circuit-Breaker Resistors.”, IEEE Trans. on Power Apparatus and Systems, Vol.83, Issue 12, December 1964, pp 1196-1205