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Series Capacitor Application Studies

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SUMMARY

Recently, the New York Power Authority (NYPA) with other New York utilities installed series capacitor banks on three existing 345 kV lines. A series of studies is conducted and brief summaries of select ones are presented in this paper. The selected studies are a) waveform analysis for subsynchronous resonance (SSR) concerns, b) line terminal breaker transient recovery voltages (TRV) and c) induced voltages and currents in the opened phases located in the vicinity of energized series capacitor compensated lines.

A screening study is performed to help identify the system conditions leading to potential SSR. Potential for SSR between a plant and the lines with series capacitors, for specific frequency range, are identified under different contingency conditions. The waveforms for the system fault events are analyzed to determine the magnitude of frequencies that may excite the SSR oscillation and also to use results for relay setting.

High breaker TRV, beyond capabilities of the existing terminal circuit breakers, are observed during studies when the conventional protection equipment for the series capacitors is utilized. The paper describes the studies covering the application of Fast Bypass Protective Devices (FPD) and Current Limiting Damping Equipment (CLDE) utilized for the reduction of overvoltages across the line terminal circuit breakers. The application of the FPD for mitigating potential development of the SSR is also discussed.

Some segments of the compensated lines utilize double circuit towers. When one of these circuits is opened the voltages and currents are induced in the open circuit from the energized circuit. The induced voltage and current levels, as well as, safety issues for the series compensated lines are also provided in this paper.

KEYWORDS

Series Capacitors, Sub-synchronous Resonance Frequencies, Transient Recovery and Induced Voltages

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I. INTRODUCTION

Recently, the New York Power Authority (NYPA) with other New York utilities installed series capacitor banks on three existing 345 kV lines.
A screening study is performed to help identify the system conditions leading to potential SSR. Potential for SSR between a plant and the lines with series capacitors, for specific frequency range, are identified under different contingency conditions. The current waveforms for the system fault events are analyzed to determine the magnitude of frequencies that may excite the SSR oscillations and if necessary, also to use results for relay setting.
The application of series capacitors in EHV systems can create excessive transient overvoltages across the contacts of the line circuit breakers for fault clearing. Such increase of the Transient Recovery Voltage (TRV) for the series compensated line circuit breakers has been studied for a number of years [1-5]. This TRV increase phenomenon is caused by the trapped charge on the series capacitors at the moment of current interruption. The TRV increase, if not mitigated, might become especially damaging when series capacitors are installed on existing transmission lines, with standard line circuit breakers. Conventionally, spark gaps, surge arresters (MOV) and damping circuits are connected across the series capacitors for their protection. Particularly, the spark gaps limit the line breaker TRV if they flashover prior to line breaker opening. However, for some fault types and current levels when the resulting voltage across the spark gap is not high enough, the spark gaps may not fire, leading to increased TRV across the line circuit breakers. In addition, during clearing of the ground faults, the gap associated with the faulted phases might spark over but not the gaps on the healthy phases. In such cases the fault clearing may result in excessive TRV on breakers associated with the healthy phases. The paper presents the TRV analysis for the three series capacitor compensated 345 kV transmission lines. The capacitor protection schemes for all three units are based on the Fast Bypass Protective Device (FPD), Current Limiting Damping Equipment (CLDE) and conventional metal oxide varistors (MOV). The application of the FPD for mitigating potential development of the SSR is also discussed.
Segments of the 345 kV lines are on double circuit towers. One of these circuits could be open. An energized circuit induces voltage and current in de-energized transmission lines in the vicinity. These voltages and currents may present serious equipment and / or work hazard for line crew personnel. The Occupational Safety and Health Administration (OSHA) requires temporary protective grounds (TPG) whenever work is performed on de-energized transmission lines where induction hazard could exist. However, during connecting or disconnecting the TPGs, if the induced currents and/or voltages are large, very long arcs may occur which could be lethal [6-8]. This paper presents the maximum induced steady state voltages and currents, discusses personal safety issues and provides recommendations.

II. WAVEFORM ANALYSIS FOR SSR CONCERNS

The SSR phenomenon might take place in the system with the series capacitors in service. As transmission line outages occur near plant P and Station A (Figure 1), the plant can become radially connected to the system through the series capacitor banks. This can create the potential for sub-synchronous resonance (SSR) occurring between the generator and the series capacitors. If resonance frequency of such connection aligns with one or more mechanical torsional modes of the generator and no preventive measures are utilized, damage to the turbine-generator shaft may take place.

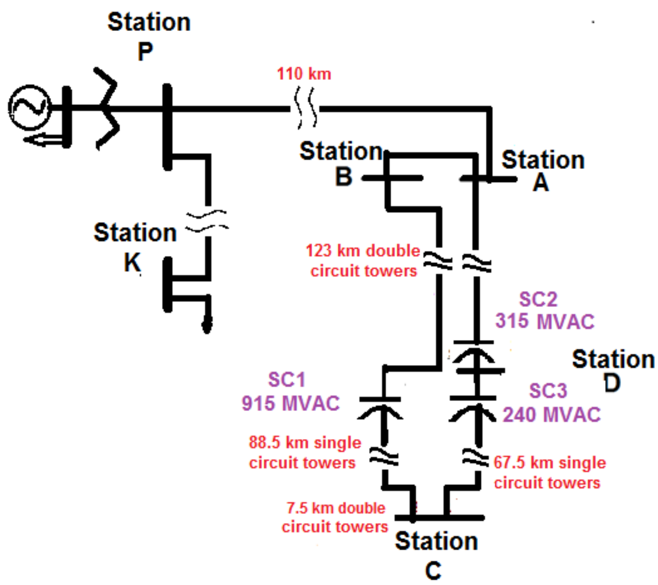


Figure 1. Simplified representation of the system with the series capacitors

A screening study is performed to help identify the system conditions leading to potential SSR. Potential for SSR between the plant and the lines with series capacitors are identified under different contingency conditions.

The modal damping coefficients represent the mechanical damping of the system. Concern with SSR arises when the total damping – mechanical damping plus electrical damping – becomes negative. Since the mechanical damping is always positive, the total damping becomes negative only when a negative electrical damping due to a system resonance overcomes the mechanical damping. Indeed, the actual destabilization depends on the mechanical torsional mode frequencies of the turbine-generator shaft system align with the regions of negative total damping.

It should be noted that the actual mechanical torsional modes of the generator K are not available. This fact required to perform an extensive system study covering the whole possible range of the generator/turbine parameters. The SSR screening evaluation is performed for a large number of contingencies. The pertinent results can be illustrated by Figure 2a, which presents the electrical damping coefficients vs. rotor frame frequency, for certain outage conditions. As can be seen, there is a group of outages for which the electrical damping coefficient always is positive (no possibility of SSR), and another group that has a small region of negative damping coefficients. It was observed that for all of the contingencies with negative electrical damping, one particular line, namely line P-K (Figure 1) is always included as an outage. A recommended solution is to bypass SC1 and SC2 series capacitors. Figure 2b shows that, with the line P-K open, bypassing the SC1 and SC2 series capacitors practically eliminates the SSR risk. Since the SSR doesn't develop every time when the line P-K opens, the signals to bypass the series capacitors can be sent only when the SSR currents are detected in the generator P. This should result in the prevention of unnecessary bypass operations of the series capacitors.

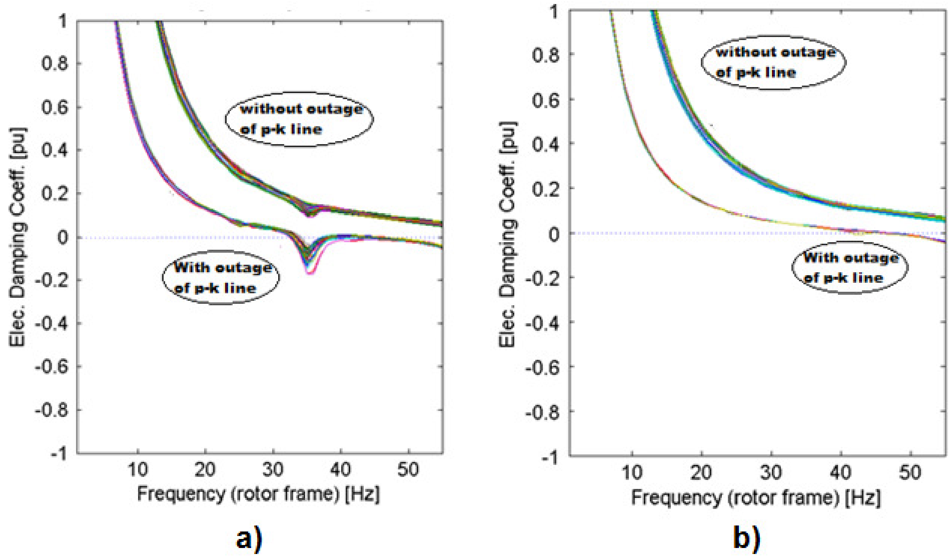


Figure 2: System Electrical Damping versus Rotor Reference Frame Frequency with SC1 & SC2 in service (a) and shorted (b).

The SSR Screening study shows (Figure 2) that the potential for SSR may exist, if rotor frame frequency (f_{or}) is within 30 to 40 Hz range. The relationship between rotor frame and electrical frequencies are as follows.

$$f_{or} = f_0 \pm f_e \qquad (1)$$

Where f_0 is the synchronous frequency (60 Hz) and f_e is the electrical system subsynchronous natural frequency. A simplified expression for f_e when a generator radially connected to a series compensated line is as follows.

$$f_e = f_0\sqrt{Xc / (X'' + X_l + X_T + X_S)} \qquad (2)$$

Where,

Xc = Series capacitive reactance
Xl = line reactance
X_T = generator transformer (GSU) reactance
X" = generator subtransient reactance
Xs =System equivalent reactance

Considering the observation from Figure 2 that shows the f_{or} range is within the 30 to 40 Hz, then from equation (1), the SSR potential exists if f_e (the electrical system subsynchronous frequency) is (60 – 30, and 60 – 40) within the 20 to 30 Hz range. The station P generator current waveforms are monitored and their FFT's are calculated. The frequency components within the 20 to 30 Hz range are extracted. This frequency range, therefore, can be considered as the potential SSR excitation and the magnitude can be used for the relay setting, as well.

The station P generator currents were analyzed for various system configurations and outage conditions. The station P generator and those in its immediate vicinity were modeled using the detailed information from the dynamic PSS/E databases. The extended system adjacent to the station P was simulated as well. The station P generator currents were monitored and analyzed, including the Fast Fourier Transform (FFT) for the 100 msec time span following the fault initiation or clearing. The simulations show that the maximum 20 to 30 Hz current level is 17 kA-peak for the N-1 and N-2 critical contingencies (primarily, for the faults in the vicinity of station P). The simulations for the N-3 contingencies resulted in the 20 to 30 Hz currents to maximum 9.7 kA-peak.

As it was stated earlier the main reason for such approach is absence of the actual data for the station P generator/turbine mechanical characteristics.

With inclusion of the mechanical generator/turbine shaft characteristics, several peaks symmetrically distributed above and below the fundamental frequency would appear [9]. The symmetrical distribution is a natural consequence of the modulation caused by torsional generator shaft vibrations. Several symmetrical peaks would appear because a unit shaft with multiple elements will have a number of torsional resonance modes.

Figure 3 shows the voltage and current frequency spectrum, as recorded at a generator terminals, after a switching transient [9]. The amplitudes are in percent of CT and VT rating. This figure shows several peaks, caused by SSR, around the fundamental frequency after the switching transient.

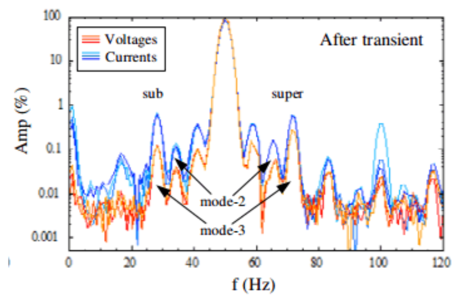


Figure 3. Short-time frequency spectra of voltage and current at a generator terminals, with SSR characteristics [9].

This is a good indicator of an on-going SSR phenomenon.

On the contrary, other non-SSR type events can cause current peaks below fundamental which lack the mirror peak above the fundamental frequency as shown in Figure 4.

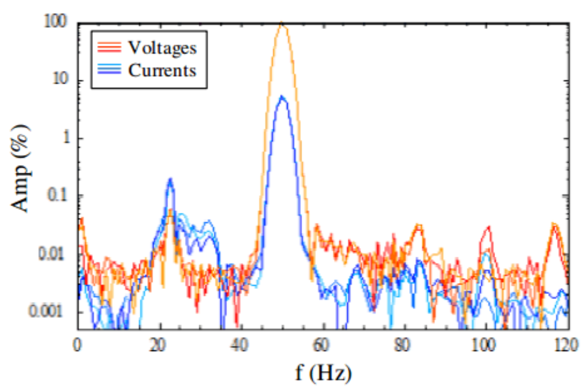


Figure 4. Spectra, similar to Figure 3, from a disturbance record that shows increased current below fundamental frequency of non-SSR type [9].

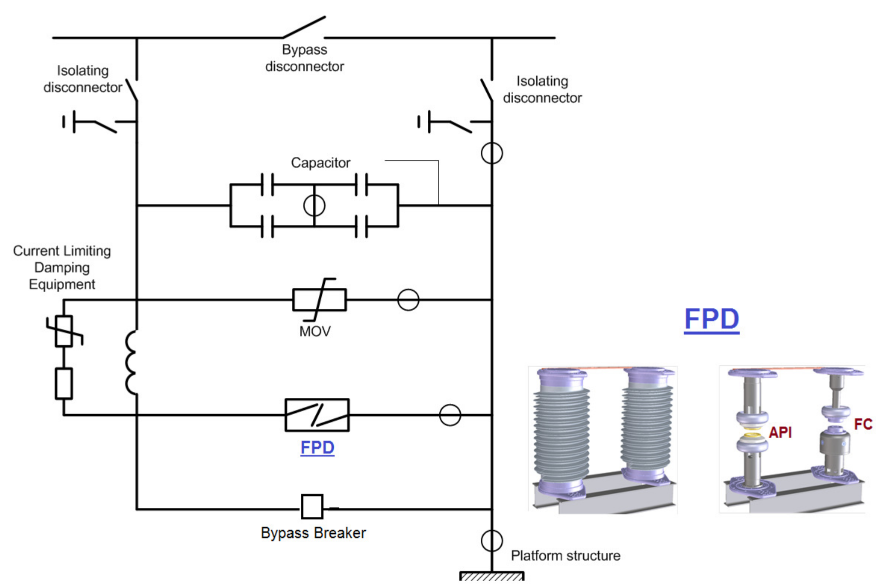
The study shows that SSR current excitations in the 20 to 30 Hz range of significant levels exist, for certain fault events. Thus, it is recommended to install the SSR relays at the station P generator terminals for monitoring the current FFT. The components in the 20 to 30 Hz, of the "non-symmetrical type," with respect to the fundamental frequency could be set to 17 kA-rms. The component of this type below 17 kA-rms would not require any operation. However the relays should be sensitive for operations to the "symmetrical" peaks with respect to the fundamental frequency, in the (20 to 30) / (90 to 100) Hz range.

III. LINE BREAKER TRV

For the line breakers TRV calculations the system is simulated using PSCAD transient program. In addition to the series compensated lines the model includes all 345 kV lines and components to at least one bus away from the compensated line buses and the system equivalent and transfer impedances at the remote buses. The accuracy of the PSCAD model is verified by comparing its short circuit currents at various busses to those from the PSS/E and ASPEN power system analysis programs.

The series capacitor overvoltage protection system consists of an MOV, a Fast Protective Device (FPD), and bypass breaker (BPB) as shown in Figure 5. The FPD is a forced triggered device that allows very fast bypassing of the series capacitor when an internal transmission line fault occurs. It has been applied on 725 kV, 500 kV and 400 kV systems [10-12]. The damping circuit is equipped with a resistor that adds considerable damping to the capacitor discharge process.

In order to limit the TRV across the line circuit breakers a bypass signal can be sent to the series capacitor from the line protection relays. When the series capacitor protection system receives this bypass signal it will immediately send close orders both to the FPD and the BPB (Figure 5). The FPD which is considerably faster than the BPB, will bypass the series capacitor, first. The damping provided by the CLDE ensures that the oscillating voltage across the capacitor will be effectively reduced "before" the line circuit breakers open to clear a fault.



a) b)

Figure 5. a) Series capacitor bank main circuit configuration, b) HV modules of the Fast Protective Device with and without housing: Arc Plasma Injector (API) and Fast Contact (FC).

The FPD is a switch consisting of an arc plasma injector (API), a very fast closing mechanical contact (FC) and an operation and supervision unit (OSU) [13, 14]. The FPD does not require presence of high voltage between the electrodes and does not need any electrode adjustments for project specific capacitor voltages or fault currents. The FPD also does not suffer from the conventional spark gap dilemma: the electrodes have to be close enough for secure operation and, at the same time separated enough to prevent unintentional spark over. It should be also underlined that the API and FC operations are initiated independently from each other.

TRV ANALYSIS FOR THE LINE TERMINAL CIRCUIT BREAKERS

The analysis of the line circuit breaker TRV on compensated lines was performed with the series capacitor protection scheme parameters for each compensated line, namely with the actual relay operation and communication times and various operation sequences of the line circuit breakers. Each compensated transmission line was represented by ten equal sections allowing to analyze the TRV values as a function of fault location along a given line. The points along the transmission lines are identified sequentially from F1 to F11 as illustrated in Figure 6 for the line between substations B and C. The line circuit breakers and substation buses in this figure are identified as S1, S2 and FB1, FB2 correspondingly.

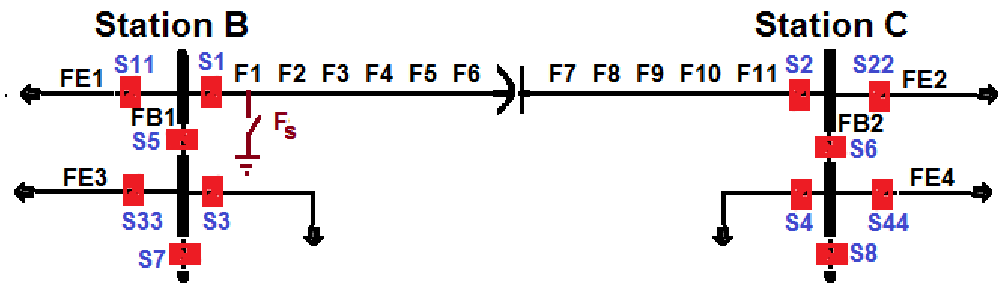


Figure 6. Fault locations on the compensated line between substations B and C

Various fault types are applied at the locations along the transmission line as well as at the external line points indicated as FE1 and FE2 and shown in Figure 6. At each of the identified locations for a given compensated line, various fault types, namely, three phase-to-ground and single phase-to-ground faults as well as the phase-to-phase and phase-to-phase-to-ground faults are simulated. Each fault type at every location is repeated twenty times over a 60 Hz cycle at equal angle intervals. Also, for each fault type, various sequences of breaker operations are simulated.

Conventionally, air gaps and surge arresters (MOV) are connected across the series capacitors for their protection. However, the air gap flashover takes place at certain voltage corresponding to a preset fault current limit through a capacitor. For example, the flashover voltages for the gaps across each series capacitor may be for fault currents that, at minimum, result in 85% of the corresponding surge arrester protective levels (that is, 195% of the rated capacitor voltage). However, such protective scheme could result in excessive breaker TRV's when the air gaps would not fire if the fault currents are lower than the preset limit.

The simulations are conducted for the implemented series capacitor protection system, namely, with the FPD and CLDE in service. The sequence of the line circuit breaker switching operations for each configuration is varied in order to determine the maximum TRV values. It was assumed in the simulations that the first breaker opening time (relay + CB) following fault application equals to 3.0 cycles. The opening time for the second circuit breaker on the series compensated line equals to 3.5 cycles and the fault path is cleared in 5 cycles after initiation.

The FPD is simulated with two parallel switches. The first switch simulates the Arc Plasma Injector (API) and all three phases close within 1.5 ms after any phase current through the corresponding MOV, connected in parallel with the series capacitors, exceeds the preset values.
The majority of TRV simulations were performed with the API closing after at least one phase fault current through the corresponding MOV reaches the preset current value. In case the current does not reach the preset value during a fault on the compensated line, the FPD bypass operation will be triggered by signals from this transmission line terminal relays. In this case the series capacitors are bypassed in about 40.5 ms assuming that only backup communication is in service. For each compensated line and every fault type twenty two event scenarios were simulated. Each scenario includes 20 faults applied over a 60 Hz cycle. It should be also mentioned that for the comparison purposes a number of base cases without the series capacitors are also analyzed.
The series capacitor protection system parameters are presented in Table 1 for all three lines. The inductance and resistance values in this table are the optimized parameters with respect to the capacitor discharge process and TRV waveform characteristics.

Table 1. Capacitor Protection System Parameters

Transmission line	B-C	A-D	D-C
Protective Level, kV_{peak}	309.1	106.4	81.1
Reactor Inductance, mH	0.58	0.28	0.28
Reactor X/R	150	150	150
Damping Resistor Resistance, Ohm	11	4.3	4.3
Capacitor Discharge Frequency, Hz	711	592	516

The maximum TRV with corresponding time values for each series compensated line are summarized in Table 2. It should be mentioned that each maximum TRV value in this table is extracted from 440 fault application cases. The TRV during these simulations were also monitored, when appropriate, for all adjacent to the compensated line (external) circuit breakers as represented in Figure 6. The highest TRV values occur at the terminal circuit breakers of the series compensated lines. The rate of rise of the maximum TRV for each fault type can be determined by using the corresponding time to TRVmax given in Table 2

Table 2. Maximum TRV and corresponding time for the series compensated lines with FPD

Transmission Line	**B - C**		**D – C**		**D - A**	
Fault Type	**TRV_{max} p.u.**	**t_{max} ms**	**TRV_{max} p.u.**	**T_{max} ms**	**TRV_{max} p.u.**	**T_{max} ms**
3 Ph-G	2.87	9.2	2.49	1.9	2.67	8.3
Ph-G	2.78	9.6	2.85	13.2	2.79	14.0
2PH-G	2.83	10.3	3.02	10.4	2.77	8.2
Ph-Ph	2.75	8.5	2.78	16.3	2.70	8.0

For comparison, similar TRVmax and time values for the same line circuit breakers but with the series capacitors bypassed are presented in Table 3.

Table 3. Maximum TRV and corresponding time for the lines with series capacitors system bypassed.

Transmission Line	**B - C**		**D – C**		**D - A**	
Fault Type	**TRV**max **p.u.**	**t**max **ms**	**TRV**max **p.u.**	**t**max **ms**	**TRV**max **p.u.**	**t**max **ms**
3 Ph-G	2.88	9.5	2.48	1.9	2.62	0.82
Ph-G	2.80	10.0	2.85	13.2	2.80	14.3
2PH-G	2.81	11.0	3.02	10.5	2.81	8.3
Ph-Ph	2.73	7.0	2.83	16.3	2.75	8.0

Figures 7, 8 and 9 for the line terminal circuit breaker voltages allow comparisons of the TRV waveforms with and without the series capacitor banks in service. These figures show that the corresponding waveforms closely match. Also, Table 2 and Table 3 show that the voltage differences do not exceed 2% between the maximum values of the terminal circuit breaker TRV with and without the series capacitor banks in service. These comparisons confirm the

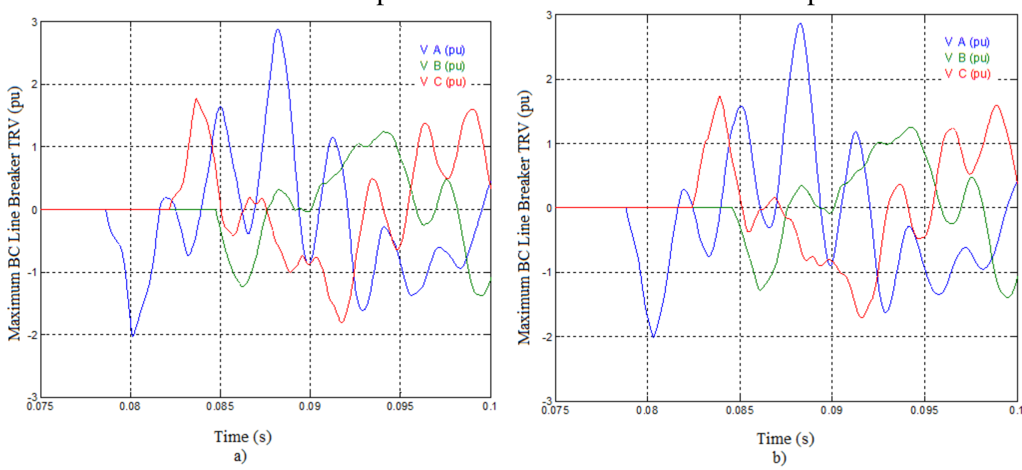


Figure 7. Maximum TRV on the B-C line circuit breakers with (a) and without (b) series capacitors for a three phase fault clearing.

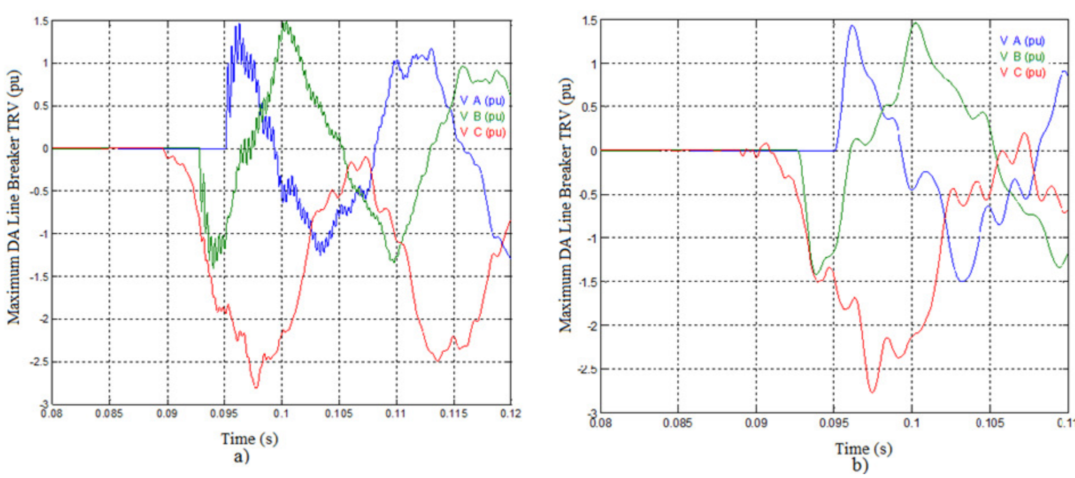


Figure 8. Maximum TRV on the D-A line circuit breakers with (a) and without (b) series capacitors for a two line-to-ground fault clearing.

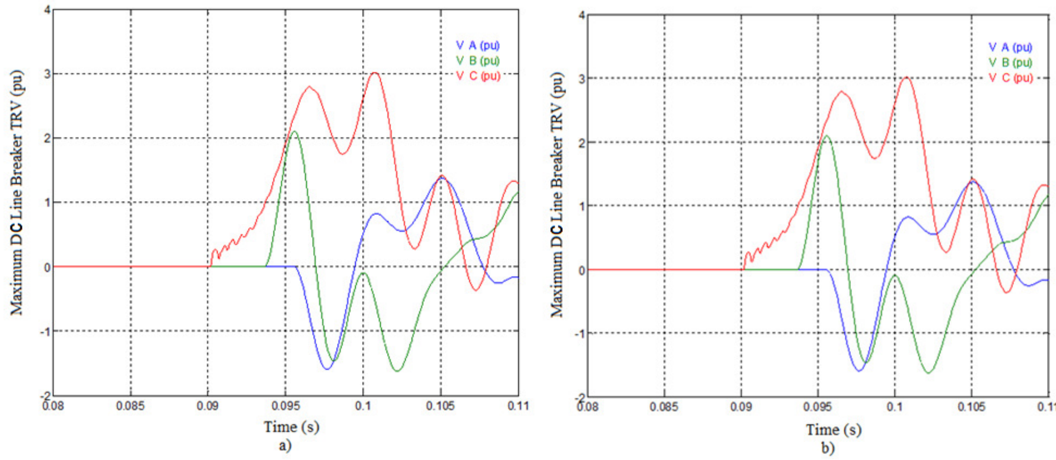


Figure 9. Maximum TRV on the D-C line circuit breakers with (a) and without (b) series capacitors for a two line-to-ground fault clearing.

importance of the FPD system for the TRV reduction of the transmission line circuit breakers and illustrate the effectiveness of the CLDE parameters for this purpose.

Triggering all three poles of the FPD reduces the healthy phase TRV peak values, which are caused by the series capacitor charging voltage in addition to the switching overvoltages.

It should be mentioned that the application of the FPD also provides SSR mitigation, when it is required. Under such conditions, fast bypassing of the series capacitors by the FPD, will mitigate development of damaging SSR forces in the generators.

In summary, benefits of the application of the Fast Protective Devices and Current Limiting Damping Equipment for the series compensated EHV lines are analyzed and defined. The maximum TRV for the circuit breakers on the series compensated lines, with the optimal capacitor protection system parameters, practically do not differ from the maximum TRV for the same circuit breakers but with the series capacitors bypassed. It is noted that the FPD also can provide sufficient mitigation for potential sub-synchronous resonance conditions.

IV. INDUCED VOLTAGES AND CURRENTS

An energized circuit induces voltage and current in de-energized transmission lines in the vicinity. These voltages and currents may present serious equipment and / or work hazard for line crew personnel.

The Occupational Safety and Health Administration (OSHA) requires temporary protective grounds (TPG) whenever work is performed on de-energized transmission lines where induction hazard could exist. However, during connecting or disconnecting the TPGs, if the induced currents and/or voltages are large, very long arcs may occur which could be lethal [6-8].

Segments of the series compensated lines are on double circuit towers. One of these circuits could be open. In this case, voltage and current can be induced in the open circuit from the energized circuit. The induced voltage and current levels for the series compensated 345 kV lines are provided.

SAFETY ISSUES FOR LINE WORKERS

There are three voltage types that may exist on an open line. **First** is trapped charge: when breakers open to de-energize a line about 1.0 pu voltage due to trapped charge remains on the line. This voltage decays with a time constant in the order of seconds to tens of seconds depending on the line insulator condition (wet or dry, clean or contaminated, etc.) and the connected equipment to the line (transformer, reactors, etc.). **Second** is the voltage due the electrostatic coupling. **Third** is the voltage due to the electromagnetic coupling.

The major hazard to a line worker is if the person is placed in series from ground to a conductor of a “de-energized” or opened line, soon after the breakers operation or any time later if the opened line is in the proximity of an energized line[8]. It should be noted that current that is fatal to humans ranges from 0.06 A to 0.2 A, depending on the person and the type of current (AC current being worse than DC).
Generally, the majority of the current through single temporary protective grounds (TPG) on the line is due to the electrostatic coupling. And, the current through two TPG’s is due to electromagnetic field. Many of the worker accidents occur during connection or removal of the TPG, when very long arcs may appear. The workers should be cautious during this process and must adhere to the OSHA 1910.269 rules of “order of connection” and “order of removal.”

INDUCED VOLTAGE AND CUDRRENT STUDIES

The representative 345 kV transmission tower configurations and conductor types are used for calculating the line parameters. Particularly, single and double circuit segments of the series compensated lines are properly represented (Figure 1).
A large number of cases are run and the results are tabulated. Voltage and currents are calculated with and without power flow through the energized lines and for with and without faults at the terminal busses of the energized line. The maximum opened circuit induced voltages (kV rms) at major nodes are calculated with and without a short at one terminal. The voltages are also calculated for opened only one phase conditions (stuck pole, for example). The open circuit induced currents (A rms) are calculated for one or both shorted terminals. Cases are also run with one of the opened circuit terminals shorted and the other terminal shorted through a 5000 Ohms resistor, representing a human body resistance.

Table 4 presents a brief summary of the maximum induced voltages and currents. The induced voltages range from 1.8 to 45.2 kV and currents 35 to 336 A without and 0.1 to 8.2 A with the 5000 Ohms resistors. It should be noted that majority of the currents exceed the

Table 4. Induced Voltages and Currents (rms) in Opened Phases

	Opened		**Induced Current**	
Opened Line	**3 Phases** (kV)	**One Phase** (kV)	**R=0.0** (A)	**R=5000** (A)
B - C	16	35	247	8.2
A - D	24	45.2	336	6.2
D - C	1.8	31.1	35	0.1

0.06 A to 0.2 A range which could be fatal to the human being. Also, it should be noted that the induced currents are higher due to the series compensated opened line.

It is recommended that the suggestions below to be followed if line maintenance is to be conducted while one circuit is energized.

- Install and close grounding switches at the line terminals.
- Series capacitors on the open line should be bypassed.
- Install temporary protective grounds (TPG) at the work area.
- Adhere to the OSHA 1910.269 rules of "order of connection" and "order of removal" of the TPG.
- The provided induced voltage and current levels should be referred to in order to determine the TPG requirements.

V. CONCLUSIONS

Results of selected studies for the application of three series capacitor banks on existing 345 kV lines are presented. The selected studies are a) current waveform analysis for detection of subsynchronous resonance (SSR) conditions, b) line terminal breaker transient recovery voltages (TRV) and c) induced voltages and currents in the opened phases located in the vicinity of energized lines.

The current waveform analysis identifies the fault events that may be of SSR concern and suggest frequencies and magnitude setting for relaying at the generator site.

The extensive line breaker TRV studies show that, the application of the Fast Protective Device (FPD), prevents the breaker transient recovery voltage increase.

The induced voltages and currents for series compensated lines may be of safety concern. Recommendations, including shorting of the series capacitors, during line maintenance are provided.

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