Transient Performance for a Series-Compensation in a High Voltage Transmission System

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***Abstract*-- This paper intends to analyze the transient performance of a high voltage transmission system in presence of series compensation. For this purpose numerous simulations of out-of-phase tripping and short-circuit were performed using ATP/EMTP, in which the fault location was varied along the series compensated line. For these cases, the transient recovery voltage (TRV) and rate of rise of recovery voltage (RRRV) levels were analyzed and compared with the standard values for existing circuits breakers. The test bed system for the analysis was the IEEE 14-bus test system, modified to include series compensation on two transmission lines.**

***Index Terms* — ATP, ATPDraw, capacitor banks, series compensation, rate of rise of recovery voltage (RRRV), special protection schemes, surge impedance loading (SIL), temporary overvoltages (TOV), transmission system, transient performance, transient recovery voltage (TRV).**

I. INTRODUCTION

WHEN exist the need to transmit large amount of electric power over transmission lines, it is necessary to consider a group of factors that limit the electrical energy transmission capacity. Some of these factors are but not limited to: the voltage drop, the stability problem, the thermal effect on the conductors, etc. The constraints imposed by these factors may be overcome by means the construction of new transmission lines or by a transmission upgrade. These alternatives are commonly very expensive, especially in the case of long transmission lines. A more economic alternative in these cases is the series compensation.

Transmission line compensation implies a modification in the electric characteristic of the transmission line with the objective of increase power transfer capability. In the case of series compensation, the objective is to cancel part of the reactance of the line by means of series capacitors. This result is an enhanced system stability, which is evidenced with an increased power transfer capability of the line, a reduction in the transmission angle at a given level of power transfer and an increased virtual natural load [1].

Series compensation has been in use since the early part of the 20th century. The first series capacitor for EHV power transmission application was installed in a 245 kV line back in 195 1 in Sweden [2]. It was followed by a similar project in the USA in 1951. The first 400 kV series compensation project was energized in 1954 in Sweden. In 1960s the first 500 kV series compensation project was introduced in the USA. As a result of the success of these projects, series compensation has become a common practice to enhance the power transfer over long AC transmission lines.

Despite the benefits of the series compensation, one of the concerns in the implementation of this type of compensation in practical systems is their influence on line breakers, due to high level of transient recovery voltage (TRV) and rate of rise of recovery voltage (RRRV) that result when opening these breakers in case the abnormal conditions, i. e., short-circuit fault, tie-line between grids of opposite phase, etc [3].

This paper intends to analyze the transient performance of a high voltage transmission system in presence of series compensation. For this purpose numerous simulations of out-of-phase tripping and short-circuit were performed using ATP/EMTP, in which the fault location was varied along the series compensated line. For these cases, the transient recovery voltage (TRV) and rate of rise of recovery voltage (RRRV) levels were analyzed and compared with the standard values for existing circuits breakers. The test bed system for the analysis was the IEEE 14-bus test system, modified to include series compensation on two transmission lines.

II. LITERATURE REVIEW

A. Series compensation basis

There are many different methods used to improve the stability of power systems. Some of these methods include reducing generator and transformer reactance, increasing the number of parallel lines used, using shunt compensation, or using series compensation.

Series compensation is the use of capacitance in series on a transmission line. The addition of capacitance serves multiple purposes, the most important being the improvement in stability along the entire line. Another compensation method

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is shunt compensation which is used to support voltage at a certain point on the line as opposed to the entire line.

Series and Shunt compensation have been in use since the early part of the 20th century. The first application of shunt compensation was in 1914 and has been used ever since becoming the most common method of capacitive compensation. Series compensation was first used in the United States for NY Power & Light in 1928, but didn't become popular until the 1950's when the voltage levels that could be handled began increasing. By 1968, a 550kV application had been implemented and today there are applications approaching 800kV.

Series compensation is used in numerous applications and locations around the world. There are currently approximately 500 series compensation installations worldwide. The principal applications of series compensations are [4]:

1. Improves voltage regulation

Series compensation is frequently found on long transmission lines used to improve voltage regulation. Due to the long transmission lines, voltage begins to decay as the line moves further from the source. Series compensation devices placed strategically on the line increase the voltage profile of the line to levels near 1.0 p.u.

2. Improves power transfer capability of the transmission line

Another application where series compensation is commonly used includes situations where improved power transfer capability is required. Series compensation is a valid solution to increasing power transfer capabilities mainly because it is a more cost effective method compared to other methods currently available. One less common method to increasing power transfer capabilities is to install additional lines to an existing system. Adding new lines presents many disadvantages when compared to using the alternative of series compensation. The main disadvantages posed when installing additional lines to a system include astronomical equipment and installation costs, long-term planning and approval periods that can exceed 3 years, as well as long-term installation periods. Series compensation does not pose any of the disadvantages previously mentioned.

3. Improves system stability

Series compensation is most well known for its use in improving system stability. Added stability greatly improves how the grid can handle a fault. When stability is questionable in certain areas, series compensation is a viable method used today to improve its stability.

The applications previously mentioned are merely a select few of the uses that series compensation devices provide. These applications and others are used throughout the world to improve the system as a whole. One common location where series compensation devices are used heavily is on long transmission lines fed from hydroelectric generating plants. Many of the lines use the series compensation devices to improve voltage regulation because the main load area is commonly several hundred kilometers from the generating station, allowing for large voltage decay.

B. Percentage of series compensation

The degree of series compensation is defined as the relation between the capacitive reactance of the series capacitor and the inductive reactance of the transmission line.

$$\text{Degree of Compensation} = \frac{X_C}{X_L} \times 100\% \tag{1}$$

Theoretically, the degree of compensation could be 100%, however this degree of compensation may produce large currents flows in the presence of small disturbances or faults. The circuit would also series resonant at the fundamental frequency, and it would be difficult to control transient voltages and currents during the disturbance [5]. In the other hand a high level of compensation highlight the problems in protective relays and in the voltage profile during fault conditions. A practical limitation of compensation is 80%, but common values in current installations are in the order of 50%.

C. Series compensation and surge impedance load of a transmission line

The Surge Impedance Load (SIL) is the power delivered by a lossless line to a load resistance equal to the impedance characteristic of the line Z_c [6], which is defined as follows:

$$Z_c = \sqrt{\frac{L}{C}} = \sqrt{\frac{X_L}{B_C}} \tag{2}$$

Where L and C are the series inductance and shunt capacitance of the transmission line per unit length, and X_L y B_C are their corresponding impedance and susceptance. The "*Surge Impedance Loading (SIL)*", P_{n0} is defined as:

$$P_{n0} = SIL = \frac{V^2}{Z_c} \text{ (MW)} \tag{3}$$

where V is the voltage in kV and Z_c is the characteristic impedance of the line in ohms.

When a line is terminated with a load of equivalent impedance equal to Z_c, then the line is operating at is *SIL* level and the voltage profile across the line is flat. However, when the load impedance is greater than Z_c, the line is lightly loaded and the receiving end voltage is greater than the sending end voltage, and viceversa. It is not practical to hold the load at the *SIL* level; especially with the objective to increase the power transfer among interconnected areas. The *SIL* can be increased by decreasing the line reactance, i.e., inserting series capacitors [2].

$$Z_{comp} = \sqrt{\frac{X_L - X_{Cs}}{B_C}} = \sqrt{\frac{X_L(1-k)}{B_C}} = Z_c\sqrt{1-k} \tag{4}$$

$$P_n = \frac{P_{n0}}{\sqrt{1-k}} \tag{5}$$

where k is the degree of series compensation and X_{cs} is the reactance of the series capacitor. Thus, the increasing of the degree of compensation results in lower characteristic impedance and higher *SIL*.

D. Series compensation and the improvement of the of the power transfer capability of the transmission line

Dynamically, the power transfer between two interconnected systems, as shown in Figure 1, is defined by:

$$P = \frac{V_s V_R}{X_L} \sin\delta, \quad \delta = \delta_1 - \delta_2 \qquad (6)$$

Where:

V_s : Voltage at the sending end of the transmission line

V_R : Voltage at the receiving end of the transmission line

X_L : Reactance of the line

δ : Angular difference between the sending and the receiving end

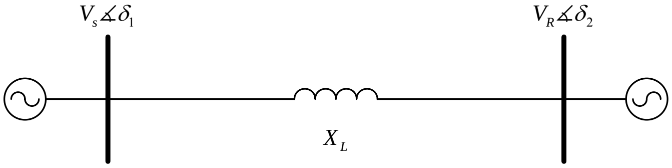

Fig. 1. Equivalent network configuration for two interconnected systems

In Figure 2, the tie line reactance change from X_L to $X_L - X_C$ due to series capacitor compensation, and hence power transferred across the transmission line is increased to:

$$P = \frac{V_s V_R}{X_L - X_C} \sin\delta \qquad (7)$$

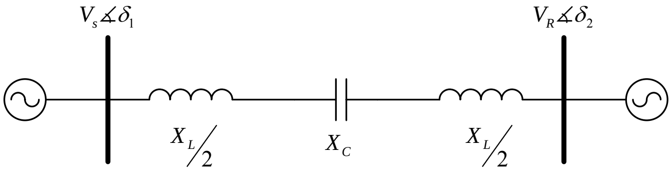

Fig. 2. Equivalent system with series compensation

E. Series compensation and the improvement of the of the transient stability limit

The series compensation affects the transient stability limit of a power system. This limit is necessary to maintain all the generating units in synchronism when a disturbance occurs.

Transient stability, as described in [7], is the ability of the power system to maintain synchronism when subjected to severe transient disturbance such as fault in transmission facilities, loss of generation, or loss of large load. The system response of these disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables. If the resulting angular separation between the machines in the system remains within certain bounds, the system maintains synchronism. Loss of synchronism, if it occurs, will usually be evident 2 to 3 seconds of the initial disturbance.

Although the transient stability must be evaluated through detailed simulations, the equal area criterion could be used to evaluate the dynamic performance of a power system in response to fault conditions. Figure 3 shows the power – angle curve for the system with and without compensation (assuming 50% of degree of compensation). The area between the load power (P – load) and the power – angle curve is a measure of the transient stability. As shown in the figure, the area with compensation is greater than the area without compensation, which indicates an enhancement in the transient stability performance of the system.

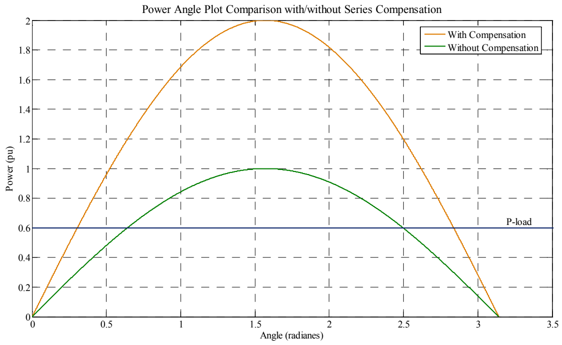

Fig. 3. Power – angle curve for the interconnected two systems

F. Transient Recovery Voltage in series compensated transmission lines.

When the circuit breaker contacts open they draw an arc between the poles. In the current zero crossings of AC current, the arc extinguishes. Whether or not the arc reoccurs is determined by the breakers' capability to quickly de-ionize the gap between the poles. This, in part is influenced by breaker properties such as the speed of the departing contacts, SF6 gas pressure, the way the arc is mended within the chamber, but it also depends on the way voltage builds up as this has an effect on the dielectric strength of the gap. The objective of TRV analysis therefore is to determine the fastest initial build-up of the voltage after current interruption. Figure 4 illustrates useful terms to describe TRV [8].

The presence of series capacitor banks on transmission lines substantially increases TRV stresses across line circuit breakers due to the presence of trapped charges on series capacitor banks. Furthermore, temporary over voltages can appear on long radial transmission lines in case of total load rejection. In these conditions, out of phase and unloaded line interruption will result in severe TRV stresses on line circuit breakers. To reduce stresses, line surge arresters are installed commonly at both ends of each compensated line [9].

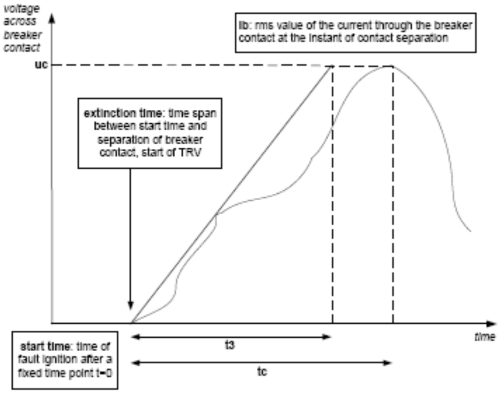

Fig. 4. TRV definition of terms

G. Protection aspects in series compensated transmission lines [10]

Inside the line, three protection schemes must work together, the series capacitor protections and the line protections at both ends. The operation of any of these relays changes the system configuration and the transient behavior detected by the other relays.

Additionally, the placement of capacitors at the center of the line reduces installation costs but introduces particular difficulties under fault states. Depending on fault location, resonant conditions are frequently obtained. Capacitors fully compensate inductances and only the losses of the system reduce fault currents. Resonant currents are dangerous not only for its magnitude but also for reducing the feeding of the non-resonant extreme. They create difficulties in the detection of the fault from this extreme and transform reclosing in a risky operation.

Traditional impedance relays are not very well suited to protect series compensated lines. Due to fault location and overcompensation of line reactance by the capacitor, the relay frequently misleads the fault position.

Three principles had been used for series compensated lines:

1. Traveling wave relays were very popular and many systems are still using them. It is based on comparisons of current and voltage traveling waves generated in the fault location.
2. Digital impedance relays, usually with its measurement points connected between the capacitor and the line, became usual. The flexibility of digital relays allows considering many functions necessary to make it work correctly.
3. Phase comparison principle, is also used for series compensated lines. The phase of voltage signal at each end of the line is matched to detect abnormal changes introduced by line faults. This principle requires an elaborated communication system between line extremes and cannot be used in long lines.

In order to preserve capacitors and their internal insulation, a complex protection scheme is frequently used. Shown in Figure 5, arresters (usually of ZnO) are mounted in parallel arrangement with the capacitor bank. They reduce overvoltages due to the system faults. A fast-operated gap is frequently included in bypass capacitors and arresters [10].

Finally a switch bypasses capacitor, arrester and gap. These equipments are controlled by a microprocessor fed with internal signals from the arrangement. In most faults, only the arrester acts, but for critical faults (under risk of damage) gap and switch are triggered. Some functions of this relay have been successfully settled using a simulator.

When any of these protections operates, the wave forms detected by the others relays are changed. To find their proper settings, time domain simulations, including the logic of the relays, are necessary.

Another less common but equally effective method is to inserting resistors with the circuit breakers to reduce the transient overvoltage [11].

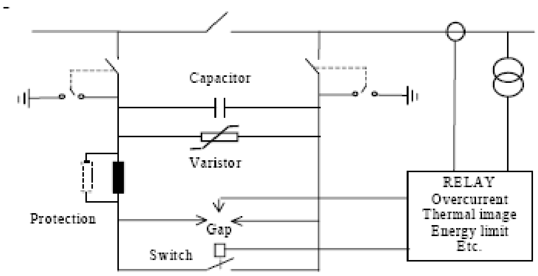

Fig. 5. Series capacitor protection scheme

III. STEADY STATE ANALYSIS

To assess the impact of series compensation on the normal operation of electric power systems, a test system was developed in ATP. The test used in the analysis is the IEEE 14 bus test system modified for that purpose, which is shown in Figure 6. System data used in the analysis are provided in Tables [A.I – A.III] of the Appendix [12]. The system has 14 buses, 20 branches and 5 generating units. The system operating voltage is 132 kV. Two shunt capacitors banks were installed in buses 5 and 9 for reactive power and voltage control. The lines 1-5 and 4-5 were modified to add series capacitors which compensate 50% of the original reactance of these lines.

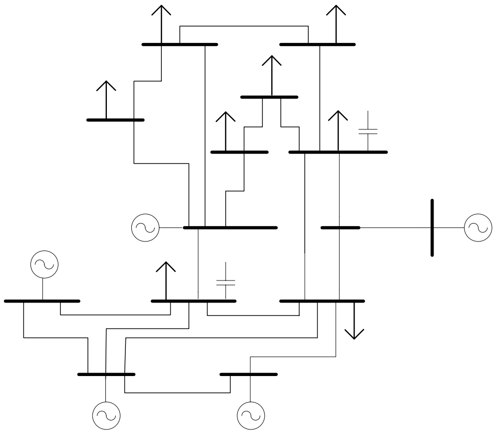

Fig. 6. Modified IEEE-14 bus test system

All load values were simulated as constant impedance loads instead of the load model specified in the IEEE test system specification. These loads were integrated into the system as lumped passive RLC elements with the adequate R, L and C values for the real and reactive power requirements. Three phase loads were implemented using the RLC-Y or RLC-Δ ATP models. This was done for simulation efficiency and ease of convergence.

All lines were simulated as line/cable equivalent (LCC) provided in ATP, instead the PI equivalent. This modification was done to adapt the model implemented to more realistic scenarios. The conductors used were selected according with the power transfer capability of the lines specified in the original data. Various tower configurations were used in the line model according with the Standard of Transmission Lines Construction of the Electric Power Authority of Puerto Rico for this voltage level [14]. Finally, the transmission lines length were calculated in order to obtain similar values of resistance, reactance and shunt susceptance than the original data of the IEEE 14-bus test system.

The feeder configuration as implemented in ATPDraw is shown in Figure 7.

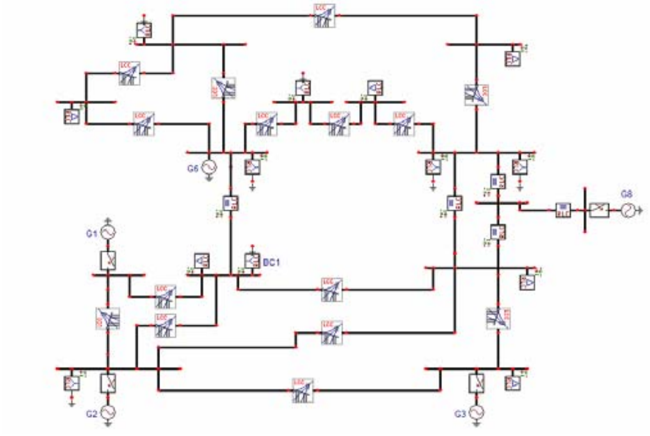

Fig. 7. ATP model for the modified IEEE-14 bus test system

A. Steady state analysis

In order to demonstrate the ability of series compensation increasing the power transfer capability of transmission lines, some steady state analyses were performed using MatPower 3.0 [13]. Table 1 shows the results of these simulations.

TABLE I
LINE FLOW COMPARISON FOR THE CASE STUDY WITH/WITHOUT SERIES COMPENSATION

From Bus	*To Bus*	S_{ij} *Orig. (MVA)*	S_{ij} *Comp. (MVA)*	*Rating (MVA)*
1	2	120.81	94.59	100
1	5	59.81	86.17	100
2	3	73.86	68.63	100
2	4	46.56	35.34	100
2	5	34.06	25.84	50
3	4	33.45	38.93	50
4	5	53.48	71.70	100
4	7	30.77	30.24	50
4	9	4.96	4.70	50
5	6	14.26	15.03	50
6	11	19.90	19.57	50
6	12	17.17	17.12	50
6	13	41.01	40.82	50
7	8	88.40	88.46	100
7	9	58.32	58.76	100
9	10	10.45	10.66	50
9	14	18.60	18.82	50
10	11	11.23	10.91	50
12	13	4.10	4.07	50
13	14	14.05	13.82	50

As shown in the table, in the original case line 1-2 is operating beyond it steady state limit. For alleviating the congestion on this line, a compensation of the 50% of the series reactance in lines 1-5 and 4-5 are proposed. The result is a considerable reduction in the apparent power that flows on line 1-2 as well as a considerable improvement in the power transfer of line 1-5 and 4-5, as shown in Table 1. All other lines are also affected by the installation of series compensation, especially those lines that are in the neighborhood of the compensated lines. However, with the installation of this type of compensation, the voltage profile across the system is practically unaffected. The effectiveness of the series compensation improving the power transfer capability of the transmission line is demonstrated with this simple case.

IV. TRANSIENT ANALYSIS

Despite the great potential of series capacitors improving the steady state and the dynamic performance of the system, in presence of line faults, severe overvoltages and large transient recovery voltages are produced due to the trapped charge in series capacitors after the switching operations.

To assess the transient performance of the series compensated transmission lines of the modified IEEE 14-bus test system, several simulations have been performed, mainly to determine the worst-case stresses by transient recovery voltage in one of the series compensated lines.

Simulations of breaker operation during out-of-phase conditions have also been performed. Specifically, the most severe cases of phase opposition have been studied. Phase opposition occurs during severe dynamic swings of the power system shortly before parts of the system are out of synchronism. Isolation of these asynchronous parts may lead to breaker opening situations in which the phase-to-ground voltages at both breaker contacts are 180° out of phase, causing voltages of 2 pu or more across the breaker contacts.

A. Base case - fault placed on line 1-5

For the base case, a three phase fault is placed in the vicinity of the series capacitor bank, as shown in Figure 8. The fault location is varied from 10% to 90% of the longitude of the line. The fault is cleared locally by opening the breakers S1 (series compensation bank breaker) 4.17 ms after the fault occurs, and remotely 9.17 ms by opening the breaker SL-1.

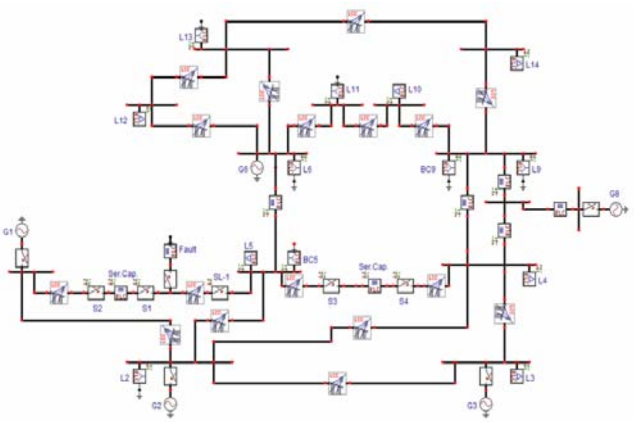

Fig. 8. Fault location for the base case

With this operation, a trapped charge of approximately 3 p.u. is stored in the series capacitor placed on line 1-5, as shown in Figure 9.

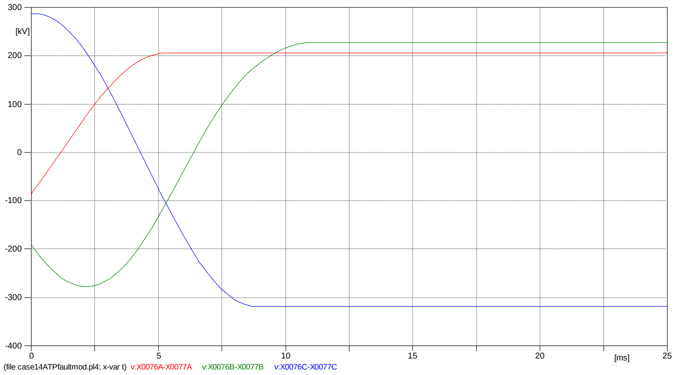

Fig. 9. Voltage at series capacitor bank placed on line 1 – 5

The worst transient recovery voltage is produced on the breaker S1, as shown in Figure 10. The peak voltage levels at this point exceed 840 kV, which is approximately 7.8 times the nominal value. These values are clearly over the insulation flashover of the equipment connected to the series capacitor bank.

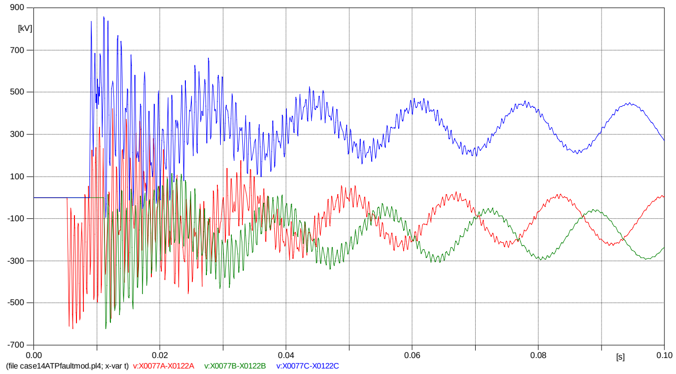

Fig. 10. Transient recovery voltage on breaker S1 at the series compensation bank

Temporary overvoltages are also produced in loads placed in the vicinity of the series capacitor bank (bus 5), as shown in Figure 11. The peak value obtained during the transient operation approaches to 1.4 p.u. It is interesting to note that a severe distortion in the voltage waveform is produced in this node of the system.

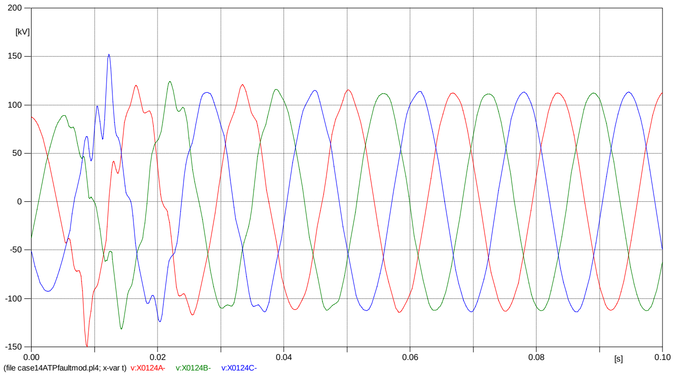

Fig. 11. Temporary overvoltages on bus 5 during the transient operation

B. *Capacitor reinsertion*

The second case analyzed is a modification of the original case to consider the capacitor reinsertion with a trapped charge after the fault on line 1 – 5 is cleared locally in 4.16 ms by opening the breaker S1-1, and remotely by opening the breakers S2-1 9.16 ms. The one – line schematic for this case is shown in Figure 12.

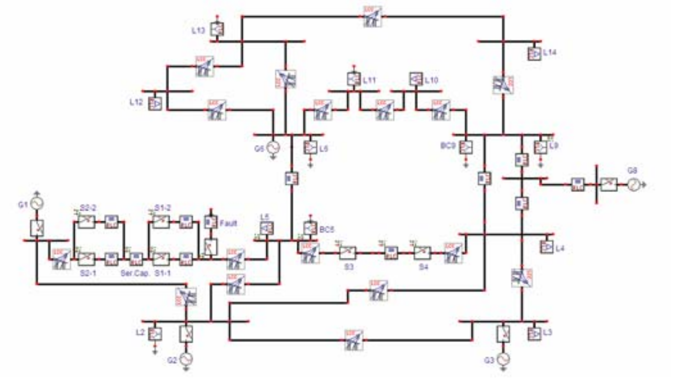

Fig. 12. Line schematic considering capacitor reinsertion

The worst transient recovery voltage occurs on the breaker S1, as shown in Figure 13. The peak voltage reaches 684.17 kV, which is equivalent to 6.34 the nominal voltage value of the system.

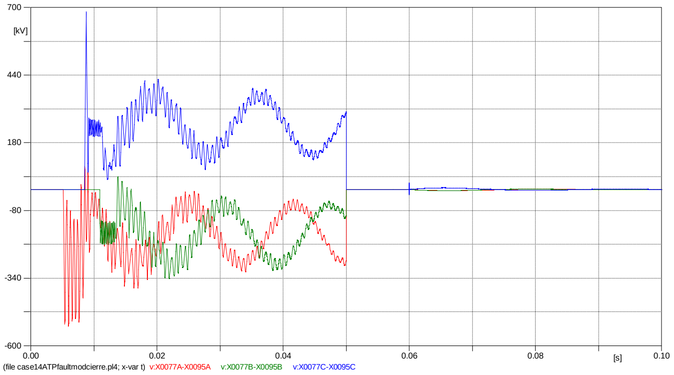

Fig. 12. Transient recovery voltage on breaker S1 at the series compensation bank

The trapped charge in the series capacitor bank is dissipated slowly after it reinsertion, as shown in Figure 13. A very fast transient with peak value of 424.96 kV occurs in the series capacitor at 0.6 ms, when the second breaker is switched in. This fast transient is shown in figure 14.

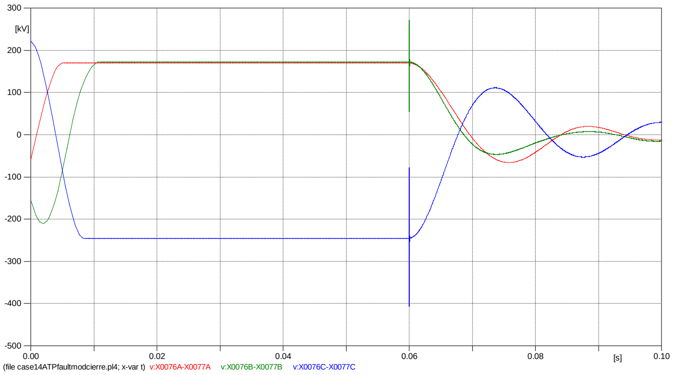

Fig. 13. Voltage at series capacitor bank placed on line 1 – 5

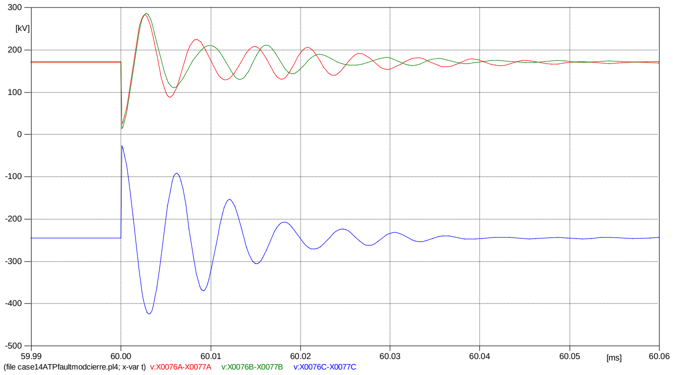

Fig. 14. Fast transient at series capacitor bank placed on line 1 – 5

Figure 15 shows the voltage profile in the vicinity of the series capacitor bank during the switching operations. It should be noted that the voltage at bus 5 reaches approximately 200.2 kV (1.86 p.u.) after the capacitor reinsertion.

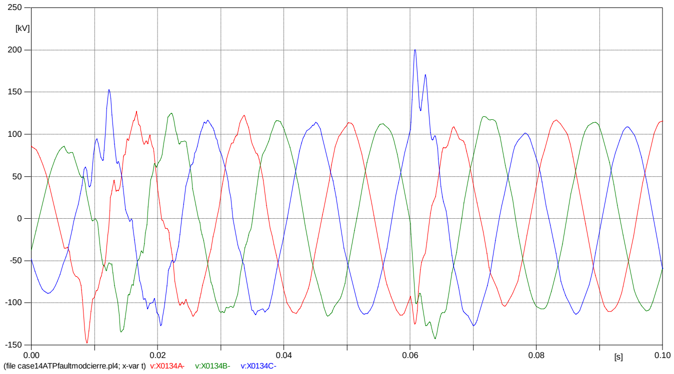

Fig. 15. Temporary overvoltages on bus 5 during the transient operation

In order to reduce the peak transient recovery two solutions were evaluated. The first one is to insert resistors when the breakers at the series capacitor bank are switched out. The other solution is to insert an arrester in parallel with the series capacitor bank in order to dissipate the trapped charge on capacitors when the switches of the bank are opened.

C. Solution 1: inserting resistor.

In this case a fixed shunt resistor of 20 Ω is inserted in all circuit breakers placed on line 1 – 5, when these breakers are switched out. It is interesting to note that all circuit breakers on line 1 – 5 must be opened during the operation to effectively reduce the TRV. The schematic of this case is shown in Figure 16.

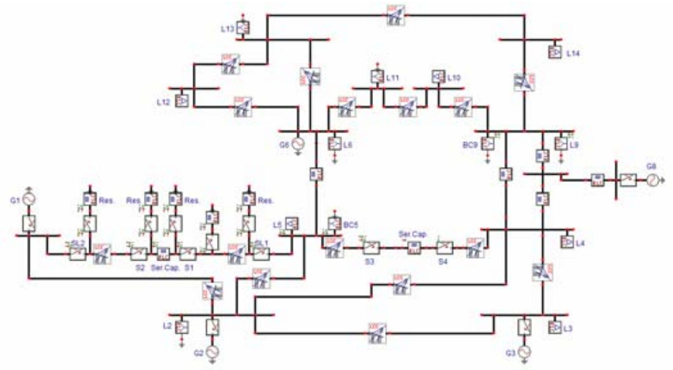

Fig. 16. Schematic for the solution 1: inserting resistors

Figure 17 shows the voltage profile at the series capacitor bank placed on line 1 – 5. As shown in the figure, the resistors inserted during the switching operation dissipate the energy stored in the capacitor bank. The transient recovery voltage on switch S1 is effectively reduced by means this operation, as shown in Figure 18. The peak transient recovery voltage obtained in this case is 212.25 kV, which is approximately 1.97 the nominal voltage. When compared with the base case, a considerable reduction in the transient recovery voltage is achieved in this case.

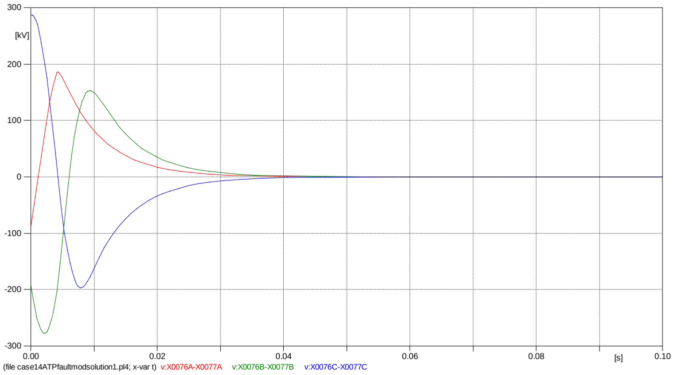

Fig. 17. Voltage at series capacitor bank placed on line 1 – 5

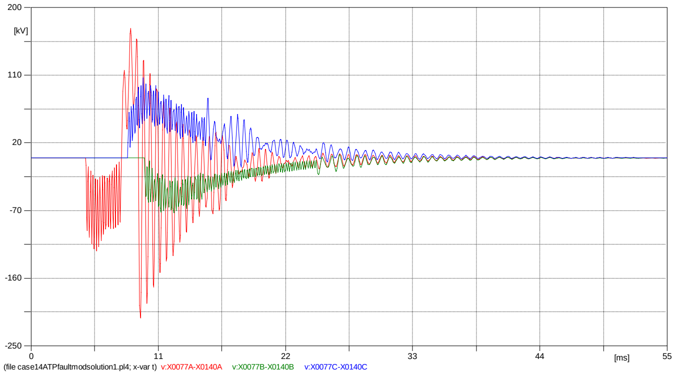

Fig. 18. Transient recovery voltage on breaker S1 at the series compensation bank

However, as a result of this operation, the peak voltage in the load at bus 5 is increased to 176.11 kV, as shown in Figure 19. The distortion is the voltage waveform is accentuated by means this operation.

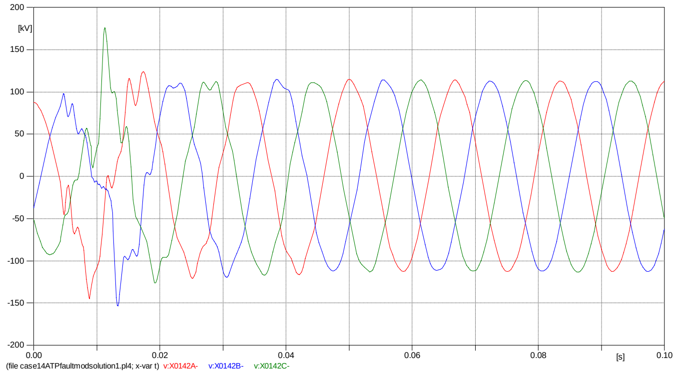

Fig. 19. Temporary overvoltages on bus 5 during the transient operation

D. Solution 2: inserting arresters in parallel with the capacitor bank.

In this case a non – linear resistor (arrester) is placed in parallel with the series capacitor bank. The Figure 20 shows the schematic for this case in ATPDraw. The arresters were simulated using the non – linear resistor model of ATP, with nominal operating voltage of 69 kV. The non – linear characteristic for these arresters is shown in Figure 21[9]. The breakers S1 and S2 are switched out 4.17 ms after the occurrence of the line fault. The line switch SL1 is opened 5 ms after this operation.

Figure 22 shows the voltage profile in the series capacitor bank placed on line 1 – 5, after the switching operation. Part of the initial energy is dissipated by means the arresters, but high voltages values are maintained in this capacitor bank after the transient operation. As a result, a considerable reduction in the transient recovery voltage on the switch S1 is achieved, when compared with the base case. The peak transient recovery voltage approaches to 200 kV (1.86 p.u.), as shown in Figure 23.

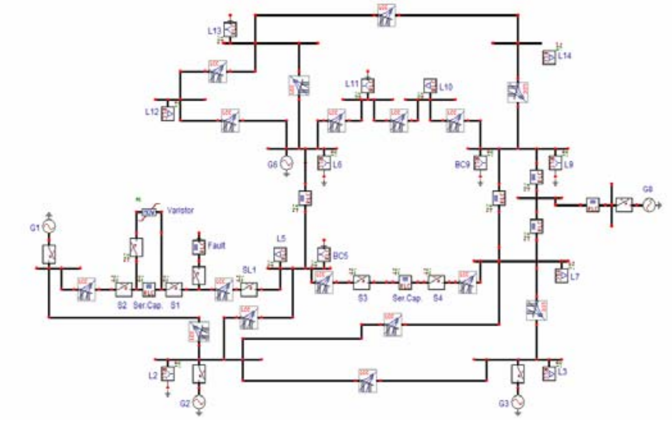

Fig. 20. Schematic for the solution 2: arresters in parallel

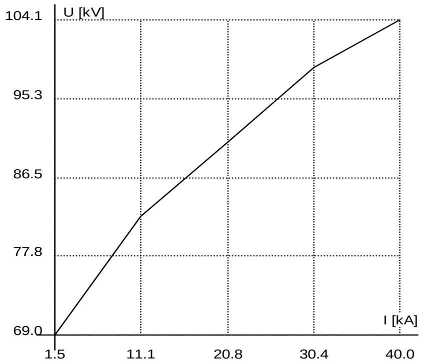

Fig. 21. Non – linear characteristic of the arresters installed in parallel of the series capacitor banks

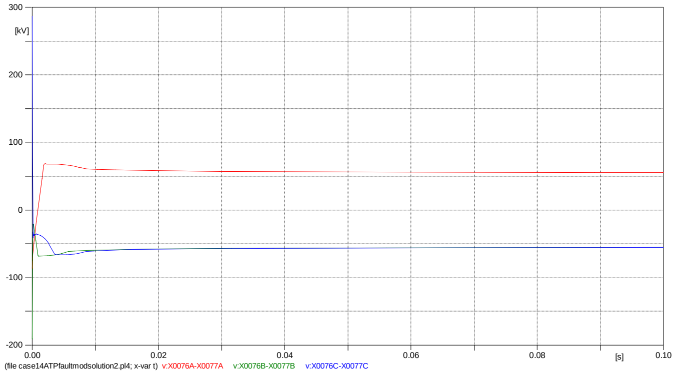

Fig. 22. Voltage at series capacitor bank placed on line 1 – 5

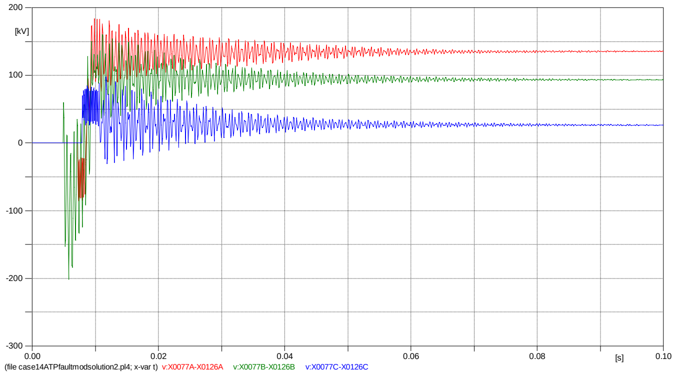

Fig. 23. Transient recovery voltage on breaker S1 at the series compensation bank

The energy plot for the arresters used in simulations is shown in Figure 24. Arresters used for this type of application should be designed for ultra high energy capability [8]. In this case, the maximum energy dissipation was 4.688 MJ. This value is well within the maximum allowable energy dissipation for the high energy arresters usually installed in this type of application. Nominal energy dissipation capability for this type of arresters is 78 – 165 MJ [15].

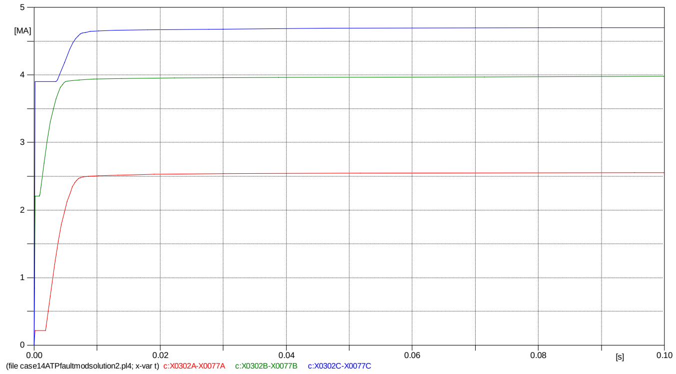

Fig. 24. Energy dissipation for arresters installed in parallel with the series capacitors

The peak load voltages in the vicinity of the series compensation bank (node 5) are 144.4 kV, which is 1.33 greater than the nominal value.

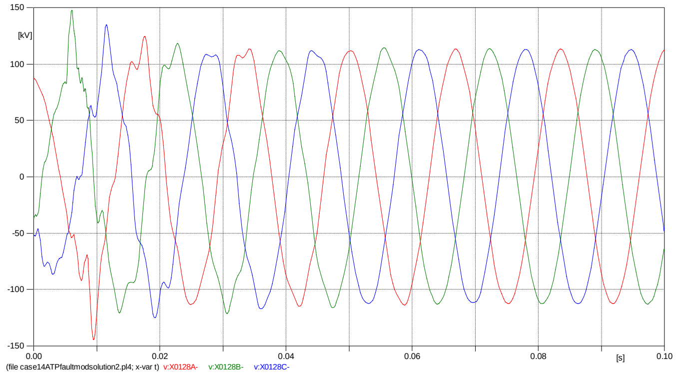

Fig. 25. Temporary overvoltages on bus 5 during the transient operation

E. Summary of results

Table 2 presents a summary of the results obtained with the case studies. The results are compared with rated values provided in the standard of preferred ratings and related required capabilities of AC High-Voltage breakers [16].

TABLE II
COMPARISON OF RESULTS

Case	TRV	RRRV		Load
	Peak Value	Peak Value	Standard	Peak Value
	(kV)	(kV/µs)	(kV/µs)	(kV)
A	840.68	3.220	2.0	150.9
B	684.17	2.469	2.0	200.2
C	212.25	1.656	2.0	176.1
D	203.05	0.848	2.0	144.4

It is interesting to note the improvement in the performance of the system in response to the transients. The original and modified case study, fault in the vicinity of the series capacitor bank – case A and reinsertion of series capacitor after the fault is cleared – case B, may produce high values in the transient recovery voltage on the breakers of the series capacitor bank. These high voltages could produce insulation failure on substation structures and damage to the connected equipment.

Both solutions proposed, inserting resistors – case C and installing varistors in parallel – case D, are very effective reducing the peak transient recovery voltage and improving the overall system performance. However, the varistors installed in parallel with the series capacitor bank seems the solution more cost-effective, because of only minimal modifications to the original capacitor bank configuration is required to fulfill with this improvement of the system.

V. CONCLUSIONS

Series compensation is a reliable solution to the problem of transient stability in power systems. It is used to increase power transfer, raise the lines transfer capability limit, improve the reactive power balance, improve voltage regulation, and is less costly than adding additional lines to the system. The benefits of the method make it suitable for numerous applications.

Despite the benefits of the series compensation, one of the concerns in the implementation of this type of compensation in practical systems is their influence on line breakers, due to high level of transient recovery voltage (TRV) and rate of rise of recovery voltage (RRRV) that result when opening these breakers in case the abnormal conditions. However, minimal modifications to the original capacitor bank configuration is required to improve the overall system performance, reducing the peak transient recovery voltage and maintaining the voltage profile of the system within acceptable values.

Since technological advancements in recent years have contributed to the development of more efficient capacitors, varistors and fuses, an evident improvement in the system reliability would reached by means the series capacitors. As initial implementation costs come down, more transmission lines worldwide will begin using series compensation as a primary method of increasing transient power system stability.

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VII. APPENDIX: IEEE 14-BUS TEST SYSTEM DATA

TABLE A.I
LINE DATA

Line	From	To	R	X	1/2 B	MVA Limits
1	1	2	0.0194	0.0592	0.0264	100
2	1	5	0.0540	0.2230	0.0246	100
3	2	3	0.0470	0.1980	0.0219	100
4	2	4	0.0581	0.1763	0.0187	100
5	2	5	0.0570	0.1739	0.0170	50
6	3	4	0.0670	0.1710	0.0173	50
7	4	5	0.0134	0.0421	0.0064	100
8	4	7	0.0000	0.2091	0.9780	50
9	4	9	0.0000	0.5562	0.9690	50
10	5	6	0.0000	0.2520	0.9320	50
11	6	11	0.0950	0.1989	0.0000	50
12	6	12	0.1229	0.2558	0.0000	50
13	6	13	0.0662	0.1303	0.0000	50
14	7	8	0.0000	0.1762	0.0000	100
15	7	9	0.0000	0.1100	0.0000	100
16	9	10	0.0318	0.0845	0.0000	50
17	9	14	0.1271	0.2704	0.0000	50
18	10	11	0.0821	0.1921	0.0000	50
19	12	13	0.2209	0.1999	0.0000	50
20	13	14	0.1709	0.3480	0.0000	50

TABLE A.II
BUS DATA

Bus	P (MW)	Q (MVAr)	Q_c (MVAr)
1	0	0	0
2	43.4	25.4	0
3	188.4	38.0	0
4	95.6	-7.8	0
5	44.7	19.8	20
6	22.4	15.0	0
7	0	0	0
8	0	0	0
9	29.5	16.6	10
10	18.0	11.6	0
11	7.0	3.6	0
12	12.2	3.2	0
13	27.0	11.6	0
14	29.8	10.0	0

TABLE A.III
GENERATOR DATA

Bus	Voltage V	P MW	Qmax MVAr	Qmin MVAr
1	1.06	100	1000	-1000
2	1.045	80	1000	-1000
3	1.01	84	1000	-1000
6	1.07	100	1000	-1000
8	1.09	86	1000	-1000