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Reliable and Economical Scheme to Improve Protection and Stability of Heavily Loaded Double Circuit Transmission Lines Using Series Compensation

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Abstract: Tripping of one circuit of a heavily loaded double- circuit transmission line may lead to tripping of the healthy circuit due to an out-of-step condition. Out of step is resulted by overloading of the healthy circuit. In this paper, a reliable and economical scheme of using series capacitors is proposed to avoid tripping of healthy circuit. Series Capacitors improve the power transfer capability of the remaining circuit by inserting a capacitor in series with the healthy circuit at the same instant of tripping faulted circuit. The insertion of series capacitors SCs improves system stability and prevents system blackouts, but in other hand affects the transient performance of distance relays. Then Elliptical characteristics are proposed to reduce the effects of SCs on distance relays.

Keywords: Distance Protection, Double Circuit Transmission Line DCTL, Elliptical characteristics, Series Compensation SC, SC protection.

Introduction

Double Circuit transmission lines (DCTL) have been broadly utilized in modern power systems to enhance the reliability and security for the transmission of electrical energy. Any single circuit of DCTL can carry the whole power transferred by both circuits at emergency situations. But there is a problem can occur which is loss of synchronism. This problem happened when large amount of current transferred from disconnected faulty circuit to the remaining healthy circuit. This problem can be solved by the following methods: first method, increase the transmission voltage to higher voltages, which requires to use step up and step down transformers and which needs higher voltage insulators, means higher cost; second method, install new transmission line to share the current transferred from the disconnected circuit, this method involve very high cost too; third method, which is the lowest cost, using series capacitors with healthy circuit, which increase the maximum power transmitted by healthy circuit, then makes the system stable.

Yemeni Grid, a case study, has encountered the problem of loss of synchronism when one circuit disconnected of the double circuit transmission line DCTL. The DCTL connects MAREB power plant station with the substation of BANI ALHARETH. The power transmitted through MAREB-BANI ALHARETH DCTL is large which about 350 MVA. The MAREB plant is considered as the main generation in the whole grid so this DCTL is heavy loaded. If one circuit has been tripped, power system will lose synchronism due to the large amount of current transferred to healthy circuit. In this paper, a reliable and an economical scheme is proposed in order to insert series capacitors with remaining healthy circuit.

Series Compensation Theory

A. Basic Principle of Series Compensation

Increasing the capability of transmission line to transfer larger power can be obtained by decreasing the value of inductive reactance of transmission line TL. Reducing inductive TL reactance can be done by inserting capacitors in series with transmission line. The series compensation SCs approach is the best alternative choice instead of installing new transmission lines. SCs approach can provide the benefits of increased system stability, reduced system losses, and better voltage regulation. The series compensation is widely used either for long EHV transmission line or with heavy loaded transmission lines [1, 2]. Fig. 1 shows the simplified model of a power transmission system.

The real power can be calculated as in (1)

$$P = \frac{E_S . E_R}{X_L} \sin(\delta) \qquad (1)$$

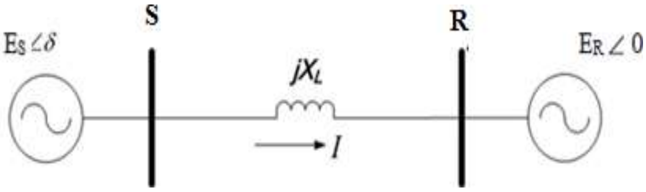

Figure 1 simplified model of power system

Where E_S and E_R are the voltage magnitudes at sending and receiving ends of Fig. 1, X_L is the inductive reactance of TL connecting two systems, and δ is the power angle between two systems.

It is clear from (1) that the flow of active power can be increased by decreasing the inductive reactance of TL, which can be obtained by insertion of capacitor sets in series with transmission line which decrease the total reactance $X_T = X_L - X_C$. A measure of the degree of series compensation k can be considered, then $X_C = k. X_L$; so $X_T = X_L (1 - k)$, so the active power equation can be written as in (2) and (3)

$$P = \frac{E_S . E_R}{X_L - X_C} \sin(\delta) \qquad (2)$$

$$P = \frac{E_S . E_R}{X_L (1-k)} \sin(\delta) \qquad (3).$$

B. Voltage Regulation

The approximated voltage drop per phase ΔV from source to load in Fig. 2 with presence of SC can be obtained from phasor diagram in Fig. 3. ΔV is the real part of voltage drop $I.X_L$ because the imaginary part is very small with presence of series capacitors. It is clear from (4) that the voltage regulation will be improved with existing of series capacitors [3].

$$\Delta V = I_L R * \cos(\theta) + I_L (X_L - X_C) * \sin(\theta) \qquad (4)$$

The receiving active and reactive power can be obtained as following (5) and (6)

$$P_R = E_R . I_L . \cos(\theta) \qquad (5)$$

$$Q_R = E_R . I_L . \sin(\theta) \qquad (6)$$

Then By substituting (5) and (6) in (4) then the voltage drop will be as the following

$$\Delta V = \frac{P_R * R + Q_R * (X_L - X_C)}{E_R} \qquad (7)$$

Equation (7) proves that the voltage regulation will be improved with existing of series capacitors.

C. Protection of Series Capacitor Set

During short-circuit; the fault current pass through the capacitor produces overvoltage across the terminals of the series capacitor, which can damage the capacitor. Each series capacitor contains one part per phase. The series capacitor protective scheme, which shown in Fig. 4, consists of a Metal Oxide Varistor (MOV), Current Limiting Damping Equipment (CLDE), the Fast Protective Device (FPD), and a By-pass Switch (B).

MOV was announced in the mid of 1970s as a means of series capacitor protection, which replaced spark gaps that previously used to protect series capacitors. The MOV is a nonlinear resistive device, which starts to conduct at specific instantaneous voltage and ends to conduct when the voltage falls below the same voltage at each half cycle of the power frequency.

The CLDE consists of a current limiting reactor, plus a resistor and a varistor in parallel with the reactor. The FPD scheme is based on a hermetically sealed and very fast high power switch, which replaces conventional spark gaps. The FPD works in combination with the MOV, and allows by-passing in a very controlled way in order to reduce the energy dissipation in the MOV [4].

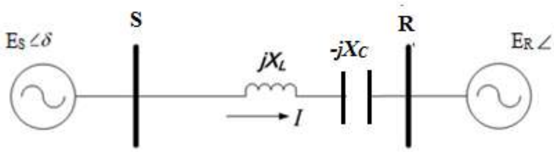

Figure 2 simplified model of power system with series capacitor

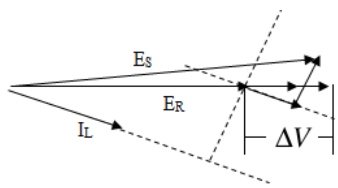

Figure 3 Phasor diagram of voltage's with presence of capacitor

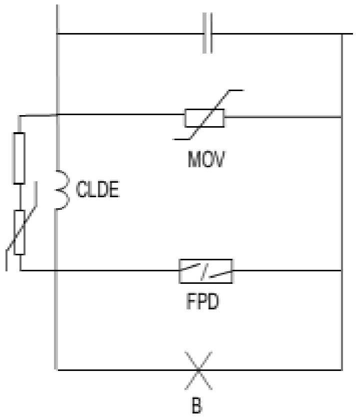

Figure 4: Protection of the series capacitor bank against over voltages [4]

Proposed Series Compensation Scheme for Double Circuit Transmission Line

Tripping one circuit of heavy loaded DCTL due to fault will lead large current to transfer to healthy circuit which can cause loss of synchronism of power system. Loss of synchronism can lead to cascaded outages of transmission lines and generation units ending to power system blackout.

In this paper, a reliable and economical scheme is proposed to use the concept of series compensation to avoid loss of synchronism by inserting capacitor banks in series with remaining healthy circuit of DCTL. Series Capacitors SCs are by-passed by normally closed circuit breaker during the normal operation of DCTL. If Fault occurred in any circuit of DCTL then this circuit will be disconnected by distance relays, which send signals to trip circuit breakers at both ends of faulted circuit, then within 0.01 s the by-pass circuit also will be opened by same signal sent from the same distance relays. Fig. 5 shows the proposed scheme to insert the SCs in series with healthy circuit of DCTL.

The by-pass circuit breaker receives trip signal from any of distance relays of both circuits of DCTL, so the main benefit of this proposed scheme is whatever circuit remains healthy, then it can operate with the same SCs. The by-pass circuit breaker will return to the normal closed state if the disconnected circuit comes back to the service, Also SCs can operate manually all the time in series with DCTL to increase the system stability and improve the voltage regulation.

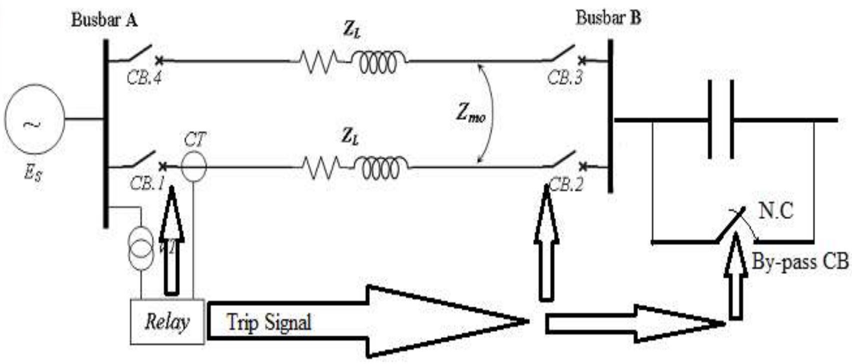

Figure 5 Proposed scheme shows how Capacitors can be inserted in series with healthy circuit

Simulation and Results

The system shown in Fig. 6 is modeled by PSCAD. The model contains of a synchronous machine model, transformer model, double circuit transmission line DCTL model, series capacitor SC model with MOV for protection, single circuit transmission line, and controlled voltage source which represents infinite bus. The parameters of models are mentioned in the appendix of this paper.

The type of fault in this simulation is three phase fault to ground and the fault resistance is 0.01 Ω. The simulation is performed with different cases with or without SCs. The measurements obtained are phase currents and voltages. These measurements are obtained from current and voltage transformers located sending end (Bus S) of healthy circuit of DCTL. The protection zones of distance relay are represented at R-X diagram. Only zone 1 is displayed in measurements of distance relay at Bus S of healthy circuit which is considered as reference.

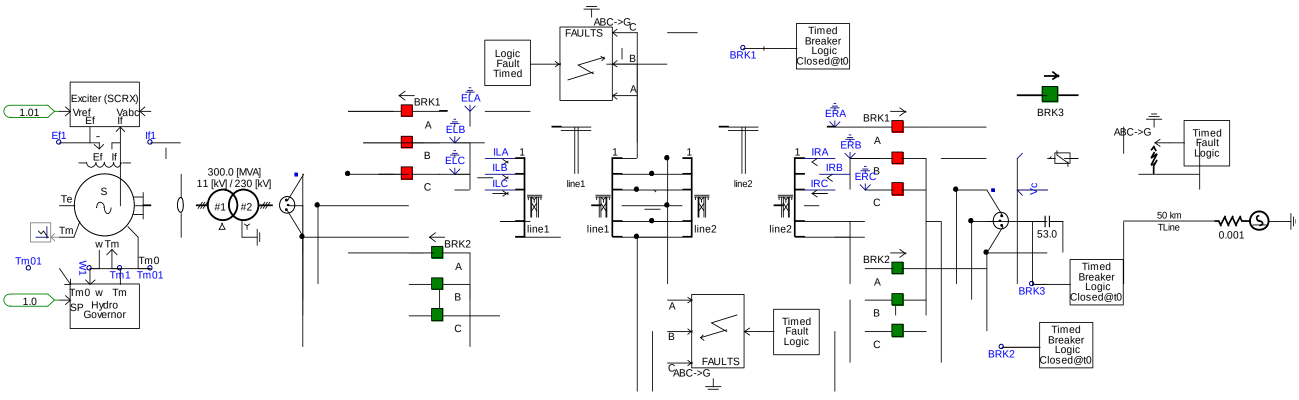

Figure 6: Simulated model of power system with double circuit transmission line using PSCAD

A. Disconnecting faulted circuit without inerting SCs

Three phase fault is incepted at time 3.00 [s] in the middle of circuit 2 of DCTL (300 km). After that the faulted circuit will be disconnected at 3.04 [s] without insertion of series capacitors. The resulted Fig. 7 and Fig. 8 show that the system loses synchronization which means out of step condition.

B. Disconnecting Faulted circuit with inserting SCs

Fig. 9 shows the system after disconnecting faulted circuit with existing of capacitor set in series with healthy circuit. Fig. 10 and Fig. 11 show that the system will be stable with inserting SCs, because the total reactance decreased then the power transfer increased as in (2), as in

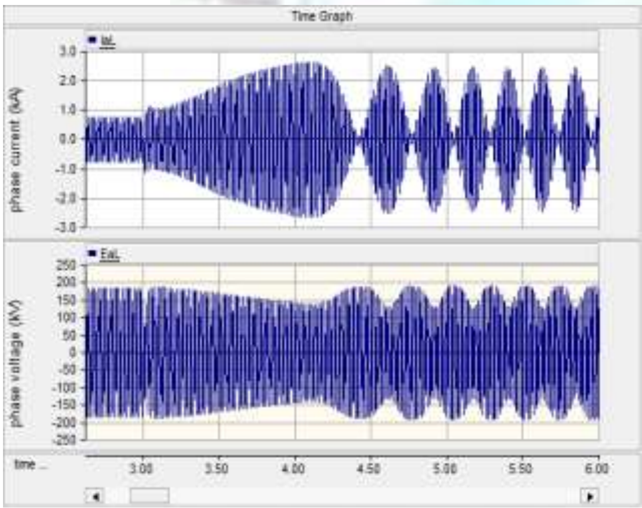

Figure 7 Phase Current and Voltage at Bus S of healthy circuit without SCs

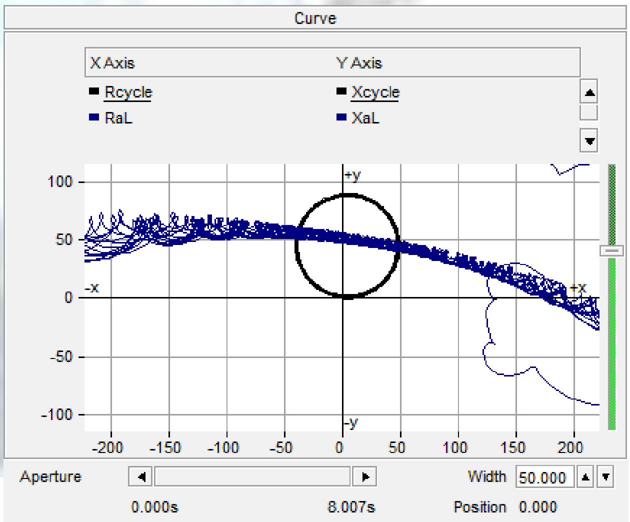

Figure 8 measured impedance at Bus S, in R-X graph without SCs

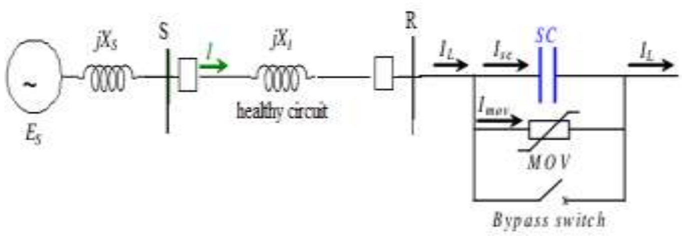

Figure 9 simplified system model with existing of series compensation

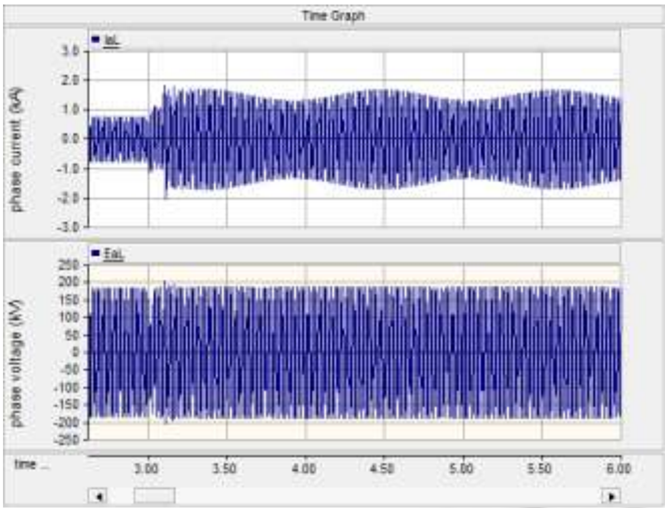

Figure 10 Bus S Phase Current and Voltage of healthy circuit with SCs

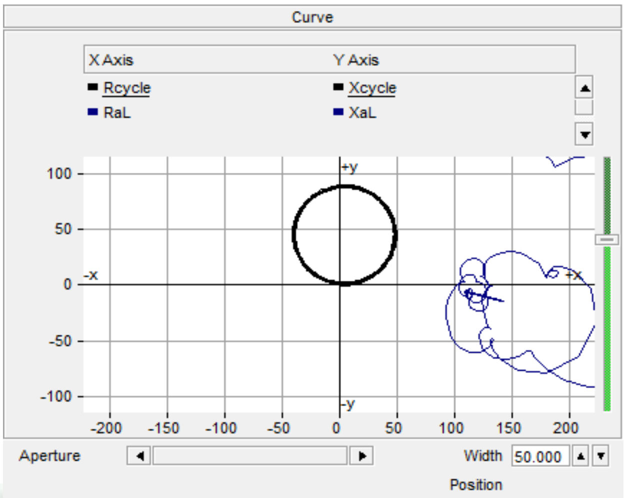

Figure 11 measured impedance at Bus S of healthy circuit at R-X graph with SCs

C. SCs are in service permanently

In this case it is considered that SCs are permanently in series with double circuit even both circuits are existed. Fig. 12 and Fig. 13 show that the system remains stable after disconnecting faulted circuit. But the measured impedance in Fig. 12 shows that nearly the trajectory of impedance will enter the zone 3.

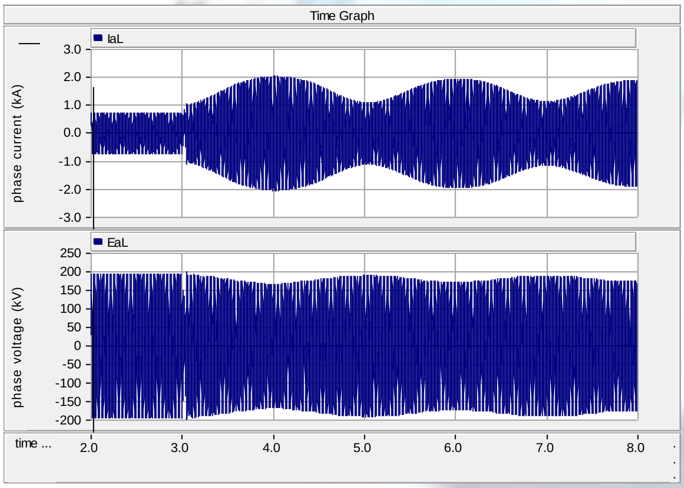

Figure 12 Bus S Phase Current and Voltage with permanent SCs

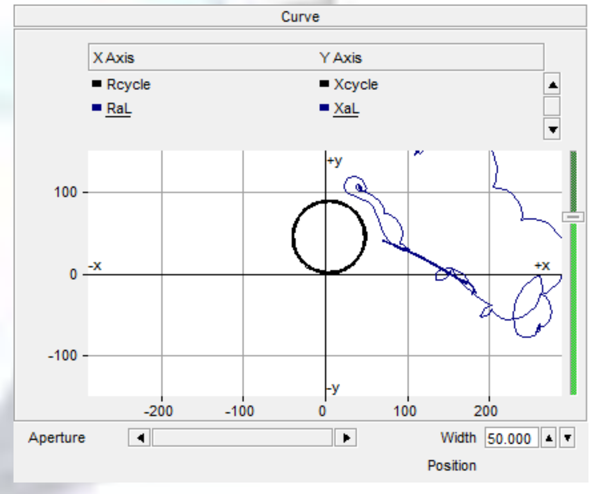

Figure 13 measured impedance at Bus S of healthy circuit with permanent SCs

Distance Relay Response Discussion

The presence of series capacitors affects the selectivity of distance protection which overreaches the protected zones. The setting of distance relay zones (1 and 2) at sending end bus S without series capacitors SCs is: Zone1 is 80%X_L; Zone 2 is 120%X_L.

But with SCs, it depends on the location of faults. Fig. 15 shows that the fault occurred at zone 1 and no effects appeared from existing of SCs.

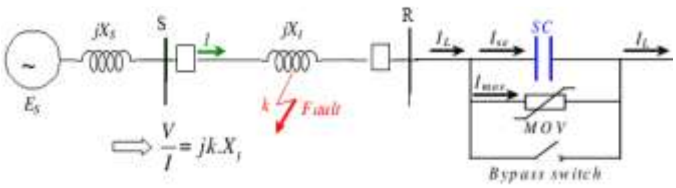

Figure 14: Fault located inside healthy circuit, zone 1

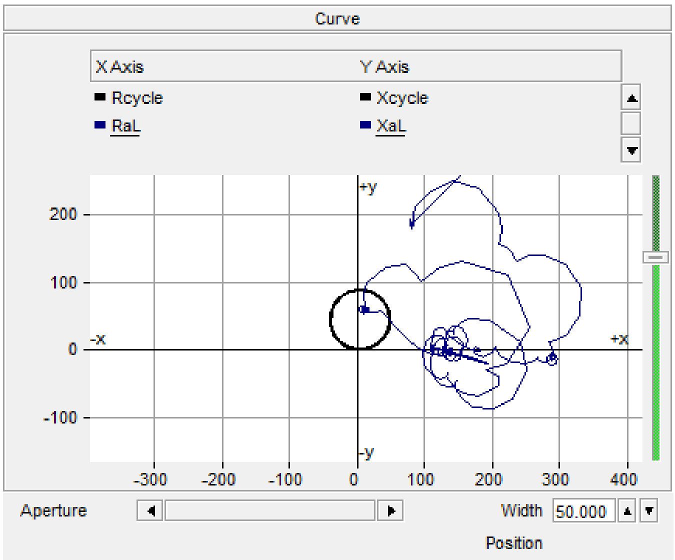

Figure 15: the measured impedance at Bus S; fault inside healthy TL with SCs

If the fault located beyond bus R as shown in Fig. 16, if the fault at bus R behind SC, the measured impedance will be $Zr=R+jX_L$ and located at zone 2 as shown in Fig. 17.

If the fault beyond SC without MOV, the measured impedance will be affected as the following: $Zr=R+j(X_L-X_C)$, where the degree of compensation is 50% then $Zr=R+j0.5X_L$, so the measured impedance will be inside zone 1 rather than zone 2 as shown in Fig. 18.

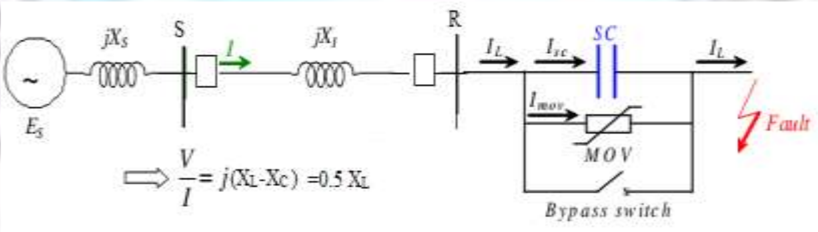

Figure 16 Fault located beyond SCs

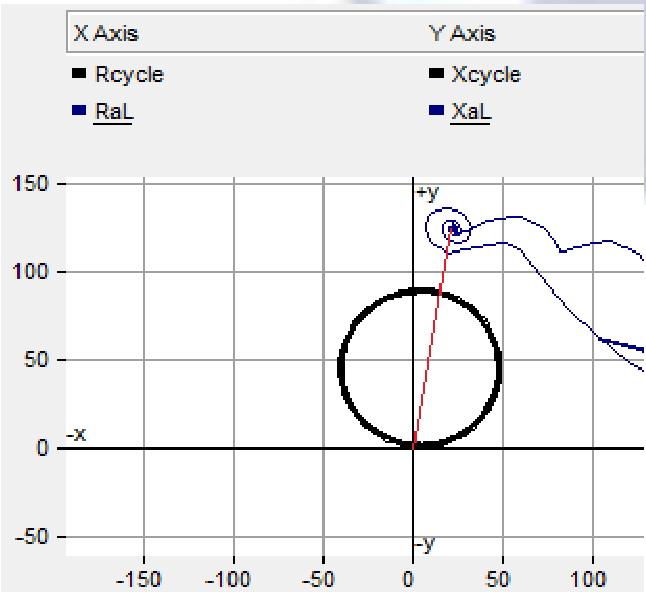

Figure 17 measured Z at Bus S where Fault is located behind SC at bus R

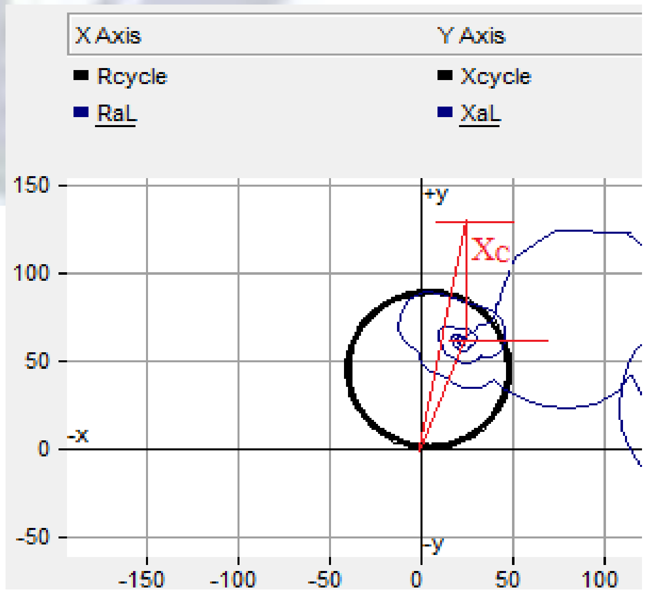

Figure 18 measured Z at Bus S where Fault Located beyond SC without MOV

Fig. 19, Fig. 20, and Fig. 21 show the effects of MOV on the voltage across SC and measured impedance at relay location. High current during fault is passing through series capacitor will cause overvoltage across it which can damage the capacitor. So Metal Oxide Variaster (MOV) are used to protect the SC from damage during the over voltages because MOV by-pass the SC during overvoltage caused by high current fault. Existing of MOV cancel the effect of SC, so the measured impedance seen by relay will be $Zr=R+jX_L$, then the effect of SC will vanished only during short circuits, and the relay will see the impedance outside the zone 1 as shown in Fig. 21.

It is clear in Fig. 21, that zone 1 of distance relay can overreach to zone 2 because the measured impedance is very close to the zone 1 characteristics. Elliptical characteristics can be used instead of mho characteristics to avoid overreaching of zone 1 to zone 2. The Elliptical characteristic is shown in Fig. 22, which reduces the zone coverage and therefore increases the amount of permissible load [5].

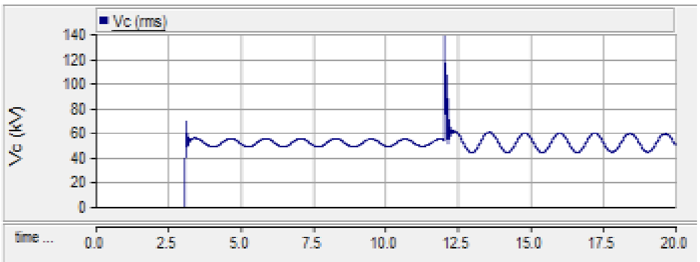

Figure 19 Voltage across SC without MOV

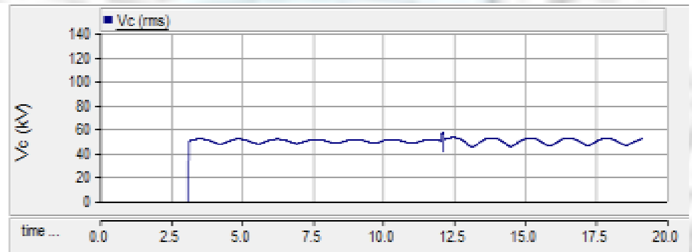

Figure 20 Voltage across SC with MOV

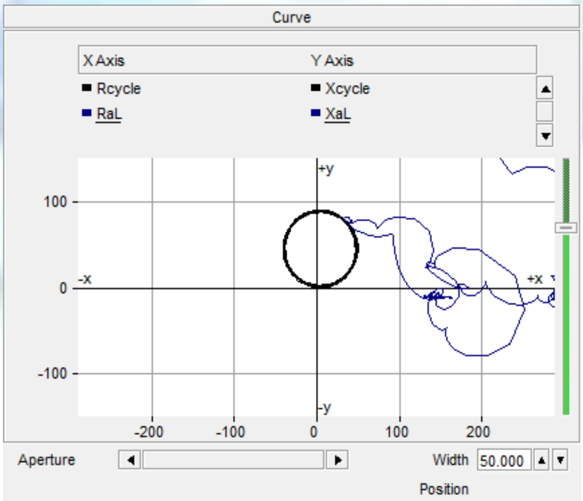

Figure 21 Measured impedance at Bus S with MOV and Fault beyond SC

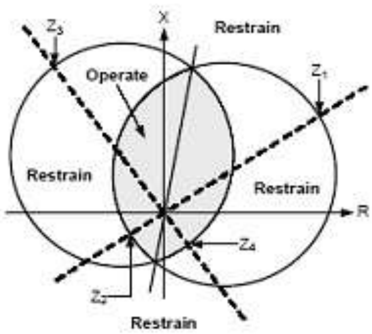

Figure 22 Elliptical Characteristic of distance relay

Conclusion

This paper introduced reliable and economical scheme to avoid loss of synchronism when one circuit of heavily loaded double circuit transmission line DCTL is disconnected. The scheme use Series Capacitors SCs to maintain system stability after tripping faulted circuit of heavily loaded DCTL. The proposed scheme inserts capacitors in series with remaining healthy circuit of DCTL when the other circuit is disconnected. The results of simulation of proposed scheme had explained how series compensation improves system stability after tripping faulted circuit of heavily loaded DCTL. Metal Oxide Varistor MOV can protect series capacitors from damage; on the other hand it decreases the effect of existing of series capacitors on the protection zones reach. Therefore, it is suggested to use the Elliptical characteristics for zone 1 of distance relay instead of the mho characteristics to avoid overreach of zone 1.

Appendix

Synchronous Machine Parameters:

11 kV, 207 MVA, 50 Hz

H=3.117 sec

Number of coherent machines: 10

Transformer Parameter:

11 kV/ 230 kV, 300 MVA, 50 Hz

Double Circuit Transmission line

230 kV, 50 Hz, 300 km

6 phase conductors, 1 ground wires

Positive Sequence impedance: 0.0689 + j 0.4 Ω / km

Zero Sequence impedance: 0.305 + j 1.25 Ω / km

Series Capacitor Set

Degree of compensation: 50 %

Capacitance: C=53 μ F / phase

Single Circuit Transmission Line:

230 kV, 50 Hz, 50 km

Positive Sequence Impedance: 0.0345 + j 0.37 4 Ω / km

Zero Sequence impedance: 0.247 + j 1.29 Ω / km

Voltage Controlled Source (Infinite Bus): 230 kV, 50 Hz

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