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A Review on Protection of Compensated Power Transmission Line

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Abstract-— **This paper presents a survey of present and past developments in the field of protection of transmission lines having FACTS devices and also suggests the best suitable solutions for the problems. In present time extra high voltage transmission lines are used to transmit large amount of power over a wide interconnected power network. Transmission lines are capable of transmitting electric power up-to its thermal limit. To utilize the full capacity of transmission line for transmission of electric power over a power network, flexible alternating current transmission systems (FACTS) are installed in the transmission line at different locations. Presence of FACTS systems changes the transmission parameters and hence adversely affects the transmission line protection system by creating problems viz. reaching problem, zone setting, inversion (voltage and current) and resonance issues. Therefore, there is a great need to identify the wider impact of different FACTS devices on the existing protection system and simultaneously the remedies of the problems.**

Index Terms— Adaptive relaying, artificial neural network, flexible alternating current transmission system, impedance relay, over voltage, over-reaching, under-reaching, transmission line protection, support vector machine, wavelet transform, zone setting.

1. INTRODUCTION:

Day-by-day demand for electric power is continuously increasing. To meet ever increasing power demand, more electricity generating stations are needed to be installed and simultaneously upgraded transmission system is required to transmit the generated power. Transmission lines of the existing power systems are supplying power close to their stability and thermal limits, which may lead to an unstable power system. Increases wire density and requirement of extra costly towers is the main drawback of extending the existing power transmission system by constructing parallel lines. The extra construction may also best impeded by environmental issues. In the recent years, FACTS devices have been popular worldwide for increasing the power transfer by providing the optimum utilization of the system capability by pushing power system to their stability and thermal limits.

FACTS devices may be installed in the existing transmission line in series, shunt and composite manner according to application. All the FACTS devices affect steady state and transient response of voltage and current during healthy and fault condition. Distance protection is the most common protection scheme of long transmission line which measures the positive sequence impedance of transmission line and compares with a set value, if it is less than the set value the relay operates. In distance protected transmission line, generally, three protection zones are assigned, zone one protects line up-to 80-90 %, zone two covers 100 % of line one and above 20 % of adjacent line while zone three protects up-to the complete adjacent line .Insecurity is the common issue in distance protection which occurs due to uncertain fault resistance and variable compensation in transmission line. The FACTS devices affect the distance protection scheme during faulty or transient conditions because it is based on the voltage and current response at the relay point.

Controllable or fixed series capacitors are widely used in transmission line to obtain maximum transmission capability. Series compensation introduces several problems like voltage and current inversion, over voltage, phase estimation, sub-synchronous frequencies and reaching problems (distance measurements). Mho distance relay is widely used for the protection of compensated and uncompensated EHV (Extra High Voltage) transmission lines due to its directional discrimination capability. Presence of Thyristor controlled Series Capacitor (TCSC) in transmission line badly affect the operation of Mho distance relay specially the reaching characteristic of the relay. In case of capacitive

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compensation Mho relay shows over-reaching effect and in case of inductive compensation it shows under-reaching effect . TCSC is commonly installed at the end of transmission line with generating stations and relays. If any fault occurs near the relays, the apparent impedance become capacitive and current or voltage phase changes by 180 degree which is sensed by the relay as a reverse fault. Another important series device is Static Synchronous Series Compensator (SSSC) which affects reaching as well as directionality of Mho relay. M. Khederzadeh et al. in 2009 proposed the analytical study of error introduced by SSSC in impedance measurement and the study conclude that SSSC in the fault loop increases resistance and reactance of apparent impedance and its impact is worsen in capacitive mode of operation.

Shunt FACTS devices are widely used in transmission line. They maintain constant line voltage at the point of connection in transmission line by injecting current at this point. It is preferably connected in the middle of the line because voltage sag is high at that point. Shunt FACTS devices supply or absorb current into the connecting bus. The distance relay shows under reaching or overreaching affects relative to the direction of current injection into the transmission line. Composite device like Unified Power Flow Controller (UPFC) is a combination of both series and shunt device and can affect the transmission line parameters in both the way, which create serious protection issues. UPFC has the unique ability to exchange reactive as well active power with the power system at the point of coupling so it equally affects the resistive and inductive portion of apparent impedance .

So, there is a need to make a flexible transmission line protection system which can adapt all the changes pop in transmission line by the FACTS devices. Protection engineers and researchers have done pleasing effort to analyze the effect of entire FACTS devices on protection system and suggested a lot of techniques to sort out the issues. Next section of this article gives the idea of the impact of entire compensation devices on transmission line protection. Third section discusses the all-inclusive techniques which are suggested about the protection of compensated transmission line. Finally conclusive remarks are given in section IV. The orientation of this work is towards the study which analyses the impact of entire FACTS devices on the protection system and all the articles which provides the protection techniques.

2. IMPACT OF DIFFERENT FACTS DEVICES ON TRANSMISSION LINE PROTECTION

In power transmission system there are mainly two types of compensation devices: (i) series devices e.g. fixed capacitor, TCSC and SSSC; (ii) shunt devices e.g. SVC and STATCOM. Impacts of both types of devices are summarized as follows:

2.1 Impact of Series Devices

2.1.1 Impact of TCSC

Series compensation devices are connected in series with the transmission line which affects the line parameters directly. The most important series device is TCSC, which is a parallel combination of a capacitor and thyristor controlled reactor (TCR). During fault conditions, series capacitor suffers from the overvoltage that occurs across the TCSC. The overvoltage protection to TCSC is provided by connecting a MOV (Metal Oxide Varistor) across TCSC which is again protected by spark gap. A circuit breaker is also installed across the TCSC module to bypass it if a severe fault occurs. Initially it was protected by a non-linear resistor which was unable to damp transients below protective level[18]. Non-linear resistors were replaced by varistors which provide instantaneous reinsertion of capacitors during external faults[19]–[21]. An elementary single phase thyristor controlled series capacitor (TCSC) is shown in fig. 1 (a).It consists of a fixed capacitor (CS), shunted through a reactor of inductance LS in series with a bidirectional thyristor switch. Current in the reactor can be controlled from maximum value to zero by the method of firing angle delay control. Complete range of α for

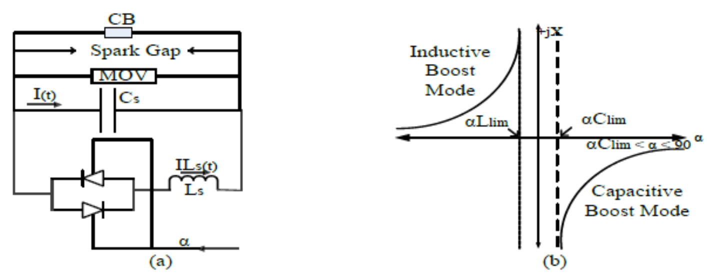

Fig. 1. Complete firing angle range of single phase TCSC.

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capacitive and inductive compensation is shown in figure 1(b). In normal operating condition, TCSC operates in four different modes and depending on MOV conduction it shows reaching problems:

(i) Capacitive Boost Mode ($\alpha_{Clim} < \alpha < \pi / 2$)
(ii) Inductive Boost Mode ($0 < \alpha < \alpha_{Llim}$)
(iii) Blocking Mode ($\alpha = \pi/2$)
(iv) Bypass Mode ($\alpha = 0$)

2.1.1.1 Reaching Problems

In TCSC transmission line, reach measurement by distance relay depends upon the status of the TCSC impedance which is varying in nature. The varying nature of impedance inserted by TCSC in the line creates under-reaching and over-reaching at the relay point in inductive and capacitive compensation respectively and that is a challenge to the protection engineer. Due to this variable impedance, there is no clear boundary between zone 1 and zone 2 hence overlapping area exists at the boundary as shown in fig. 2. Due to this overlapping area, fault in zone 1 can extend up to zone 2 while zone 2 faults may fall within zone 1 according to the mode of operation of TCSC. This creates severe problem of zone identification in case of fault in transmission line having TCSC.

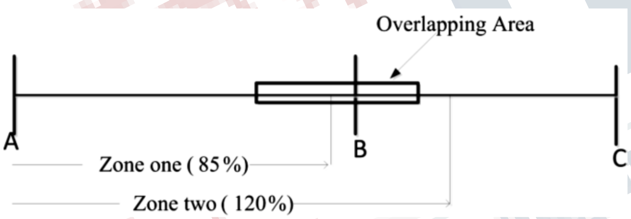

Fig. 2. Overlapping area between zone one and zone two.

2.1.1.2 Inversion Problems

(i) Voltage Inversion

In distance protection voltage inversion is a change of 180 degrees in the voltage phase angle at relay bus from the actual fault voltage. For elements responding to phase quantities, voltage inversion can occur for a fault near a series capacitor if the impedance from the relay to the fault is capacitive rather than inductive. If a fault occur in transmission line on right side of series device as shown in fig. 3 and inductive reactance of fault point to relay point in XLf, if capacitive reactance of series capacitor XC is greater than the XLf then voltage inversion take place at relay bus. Voltage inversion may affect directional and distance elements.

(ii) Current Inversion

A current inversion occurs on a series-compensated line when, for any fault in zone one, the equivalent system at one side of the fault is capacitive and the equivalent system at the other side of the fault is inductive. In this case from fig.3 if equivalent impedance left to the fault point is capacitive i.e. $X_C > X_S + X_{Lf;}$ then the current inversion takes place.

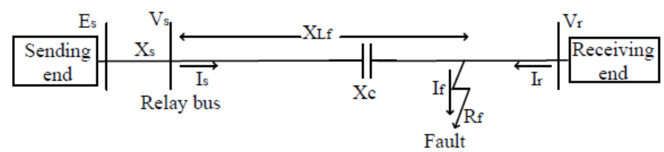

Fig. 3. Circuit for voltage and current inversion.

2.1.1.3 Causes of over-voltage across series compensator

(i)- Series capacitors voltage on heavy load or fault conditions has significant impact on closing and opening of transmission lines.
(ii)- When series compensation is employed, the upper limit of compensation level is set, beyond which self-excited oscillations may be induced in the system resulting in load rejection for the particular system. Severe temporary over-voltages occur during load rejection at the remote end of a long transmission line which initially carries substantial power.
(iii) If the fault is beyond the remote series capacitor, severe circuit breaker voltages may occur although voltages across the capacitors are not high.
(iv)- During fault the transient recovery voltage (TRV) of the circuit breakers increases due to series capacitor.

2.1.2 Impact of SSSC

SSSC also affects the reaching characteristics of distance protection and shows voltage inversion problem in the line which is similar to TCSC. A few publications have been shortsighted in literature which analyzes the impact of SSSC on protection system. The impact of SSSC on transmission line protection system can be summarized as follows:
(i) SSSC can be installed at the substation or at the middle of the line as midpoint compensator. SSSC affects the

protection system depending upon its location. SSSC does not affect the line protection system if not present in the fault loop.
(ii) SSSC is connected in series with the transmission line and works in capacitive and inductive mode of operation so it shows both over-reaching and under-reaching effects at relay end.
(iii) SSSC share both the active and reactive power in transmission line so it affects resistance as well as reactance of apparent impedance in transmission line.
(iv) Capacitive mode of SSSC mainly affects the apparent resistance while inductive mode largely affects the apparent reactance of transmission line.
(v) A. Kazemi et al. in 2008 presents the impact of voltage transformer (VT) location w.r.t. SSSC and it is concluded that for least impact of SSSC on distance protection, VT in front of SSSC is the preferred location.
(vi) A. Kazemi et al. in 2009 gives the comparison of the impact of SSSC and STATCOM on distance trip characteristics and showed that for line end installation, the impact of SSSC is more while for mid-point installation STATCOM impact is more.

2.2 Impact of shunt devices

Presence of shunt FACTS device significantly affects the performance of protection system and may create security and reliability issues. It maintains constant line voltage at the point of connection in transmission line by injecting current at that point. It is preferably connected in the middle of the line because voltage sag is high at that point. Shunt FACTS devices supply or absorb current into the connecting bus. The distance relay shows under reaching or overreaching effects relative to the direction of current injection into the transmission line. It was found that mid-point FACTS compensation could affect the distance relays concerning impedance measurement, phase selection and operating times leading to under-reaching and over-reaching of Mho relay.

2.2.1 Reaching Problems

Basic principle of distance protection is to measure impedance between relay point and the fault point; if it is less than the set value then the relay trips. In the normal loading conditions with STATCOM, resistance values are more and reactance values are less when compared to the resistance and reactance values without STATCOM. If the shunt device is connected in the middle of the transmission line and fault occurs on right half of the line, relay operating parameters changes and accordingly mal-operates. Equivalent circuit of shunt facts device in a transmission line in case of any line fault is shown in fig. 4.

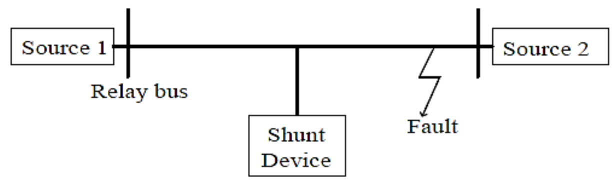

Fig. 4. Single line diagram of shunt device in transmission line.

Due to presence of shunt device in the path between relay bus and fault point, the measured impedance by Mho relay changes significantly depending upon the action of the shunt device explained below for different action.

(i) Over-reaching

Shunt device works in two modes of operation, (i) Capacitive mode and (ii) Inductive mode. SVC in normal operating mode does not show over-reaching problems. In case of light loads, line voltage increases due to Ferranti effect and the STATCOM works in inductive mode of operation to reduce overvoltage. It takes current from the connecting bus and hence absorbs reactive power from the system. In inductive mode the relay shows over-reaching effects due to reduction in net line impedance. The change in transmission line impedance by the STATCOM in both operating modes is a function of current injected by the device.

(ii) Under-reaching

In case of heavy loads, line voltage drops below the reference value and the shunt device SVC/STATCOM works in capacitive mode of operation. It supplies current into the connecting bus and hence injects reactive power into the system thus increasing the resistance and the reactance value of fault impedance. In this case net impedance of transmission line increases and distance relay shows under reaching effects.

(iii) Operating Time

Mho relay responds within the time after the fault occurs until steady state value of the line impedance is found and for Mho relay usually the operating time is less than 1 cycle. In case of fault, shunt device takes 5 to 7 cycles to settle down in steady state condition. So the operating time of Mho relay increases significantly high.

(iv) Phase selection

In case of mid-point shunt compensation if any unsymmetrical fault occurs in the transmission line, the faulty phase experiences severe under voltage effect as compared to healthy phase. Shunt FACTS device supplies even equal compensation for all the phases and healthy phase voltage increases due to this overcompensation. Due to this overcompensation healthy phase may experience high line current and the overcurrent relay may result it as a fault.

2.3 Impact of Composite device: UPFC

UPFC is the combination of SSSC (a series device) and STATCOM (a shunt device), so it affects the protection system in more complex manner. UPFC can consume both active power and reactive power. UPFC has more influence on apparent resistance because of the active power consumed by SSSC and STATCOM. The effect of UPFC on apparent impedance measurement can be summarized as follows:

(i) UPFC has greater influence on the apparent resistance; this is due to the active power injection and consumption by both SSSC and STATCOM.

(ii) When SSSC consumes active power, the apparent resistance will increase and when SSSC inject active power, the apparent resistance will decrease.

(iii) When the SSSC injects reactive power into the system, it is operated like a series capacitor and the apparent impedance decreases, in this case Mho relay overreaches. When it consumes reactive power from the system, it is operated like a series inductance and the apparent impedance increases and Mho relay overreaches.

(iv) Apparent fault impedance is influenced by the reactive power injected/absorbed by the STATCOM, which will result in the under reaching or over reaching of distance relay respectively.

3. PROTECTION TECHNIQUES

3.1 Protection of Series Compensated Line

3.1.1 Artificial Neural Network based Method

ANN has the ability to classify highly nonlinear input patterns by adjusting the weight and biases of the neurons. Multilayer neural networks are suggested to improve the accuracy of classification of various input data patterns. Back propagation (BP) algorithms and radial basis network are widely used in the differentiation of abnormal conditions from healthy condition in series compensated line. Different parameters of a system like instantaneous voltage or current or both, firing angle or various frequency signals presents in fault current filtered by WT/ FFT are selected as the feature of input vector in neural network. ANN based relay are used for fault detection, direction, classification and location in series compensated transmission line. A complete summarized algorithm for ANN and ANN/WT based relay is shown in fig.5.

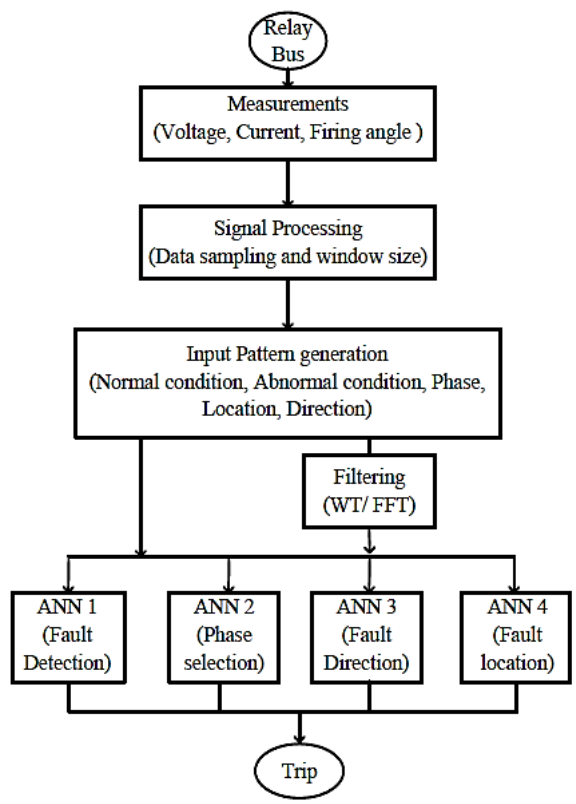

Fig.5. ANN based Protection algorithm for series compensated transmission line.

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Table I (Given in Appendix) shows the year wise development in neural network based
techniques for protection of series compensated transmission line.
It is concluded that BPNN (Back-propagation neural networks) is easy to implement and frequently used for fault detection with classification accuracy achieved up to 100%. Although, it suffers from local conversion and gives false results. RBFNN (Radial basis feed-forward neural networks) are
generally faster and less number of parameters are required to train. In most of the algorithms, rated system voltage is chosen to be 400kV or 500kV. Whereas in newly UHV transmission system has been installed above 1000kV in which transients are severe and needed to be analyzed with respect to ANN. A versatile ANN structure can be achieved through training it by a large number of patterns and it can be observed that for less numbers of testing samples can show dummy increase in percentage accuracy.

3.1.2 Support Vector Machine Based Algorithms
The SVM is a machine learning technique used for statistical classification and regression analysis. SVM constructs a number of hyper planes in a high dimensional space to separate data points which belongs to different classes. ANN based relaying technique need lot of training and testing before implementation, so it takes more time on training and can suffer from multiple local minima too. Due to better classification, features selection capability and fast convergence rate of SVM, it is used as a pattern classifier for obtaining healthy and faulty, phase selection and fault location in series compensated line. SVM are trained to detect, classify and zone identification in compensated/uncompensated transmission line and tested on various activation functions like polynomial, Radial Gaussian, linear and sigmoidal to optimize the classification. Optimization algorithm like Genetic algorithm is also used to optimize the parameter of SVM to fault classification. Input feature for SVM classifier can be current and voltage coming from CT and PT respectively or any filtered frequency component through WT/FFT as shown in fig.6.

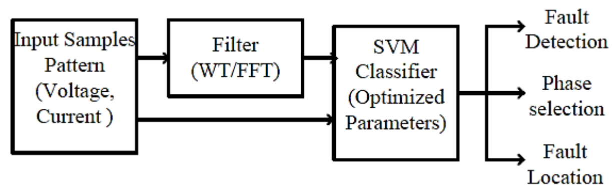

Fig.6. SVM based Protection algorithm for series compensated transmission line.

Table II(Given in Appendix) shows the yearly development in SVM based methods for protection of series compensated transmission line. From the table II, it is found that Gaussian radial basis kernel function is extensively used for fault detection and classification and accuracy is achieved up to 100% with lesser average time (1/2 cycle) than ANN based relays.

3.1.3 Wavelet Transform (WT) Based Algorithms
WT-MRA (Multi resolution analysis) decomposes the fault current into bands of various frequencies. Detailed coefficient (Dn) contains the information of particular frequency signal present in the current. Dn has been calculated at various levels from 1 to 9 for different wavelet series like db, haar etc. Pattern of Dn is analyzed to detect the type of fault and fault zone as shown in fig7. In fault clearing

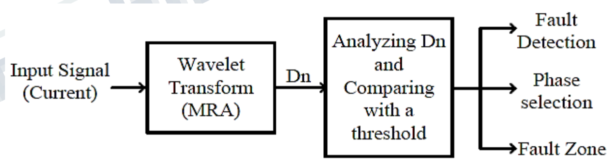

Fig.7. WT based Protection algorithm for series compensated transmission line.

process it is required to extract actuating frequency component from voltage and current as quickly as possible. WT has an advantage of less discrimination time so it is widely used in protection of compensated/uncompensated line. In series compensated line WT detects faults by comparing transient fault current signal with a predefined threshold value and the WT-MRA methods are successful in differential protection scheme for discriminating internal and external faults.

Table III (Given in Appendix) shows the year wise growth in wavelet transform based techniques for protection of series compensated transmission line and it is concluded that Daubechies wavelets (db) and Haar wavelets are widely used for the resolution of fault current and voltage signals.

3.1.4 Adaptive Distance Algorithms

(i) Voltage Compensation Based Relay

Series compensation device adds a voltage in the line during healthy and faulty conditions. In case of fault, this voltage does not allow the line voltage to fall much and creates error at the relay end which uses line voltage to calculate fault impedance. It is needed to calculate the voltage across series device during fault to sort out the error and can be calculated in terms of line current and the impedance parameters of the series device. Finally, the calculated voltage is to be compensated at the relay end to calculate actual fault impedance. A generalized voltage compensation based protection algorithm is shown in fig. 8.

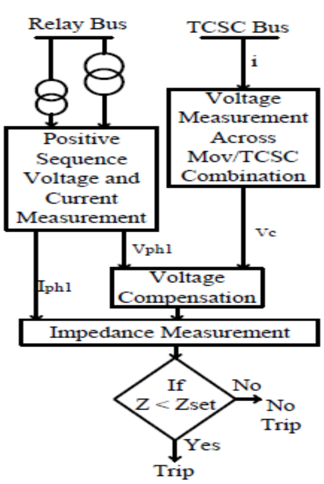

Fig.8. Voltage Compensation Algorithm.

(ii) Impedance Computation Based Relay

Series device is protected by MOV which acts as a nonlinear resistor. In case of fault, device with its protection system adds dynamic impedance in the transmission line and changes the impedance measured by distance relay resulting in reaching mal-operation. In case of fault, the dynamic impedance of protected series device is calculated in terms of line current and voltage across the device and compensated at the relay end to short-out the error introduced by the device. Combined impedance compensation algorithm is shown in fig. 9.

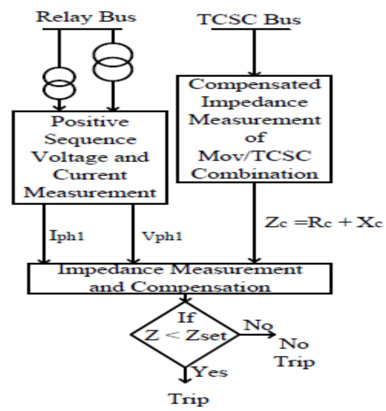

Fig.9. Impedance Compensation Algorithm.

3.1.5 Directional Relaying

In inversion problems voltage and current signals are inverted by 180 degree and relay misclassifies fault direction. Phase measurement of pre fault and post fault voltage and current techniques has been proposed in literature which solves inversion problems. Phase difference between current and voltage indicates the correct fault direction, if it is positive than direction is upstream otherwise downstream. In voltage inversion, phase angle difference of pre and post fault current gives the correct direction of fault while in current inversion, phase difference of pre and post fault voltage provides correct fault direction. Single classifier does not provides the actual fault direction and hence a voting classifier is proposed which gives the resultant output and successfully classifies the fault direction in all the cases.

3.1.6 Fault Location Estimation by Two End Measurement Method

For uncompensated line (no series device), any fault in between sending and receiving end the per unit fault length from sending end is given by (1).

$$d = \frac{1}{\gamma L}\, tanh^{-1}\left[\frac{\cosh(\gamma L)Vr - Zc\sinh(\gamma L)Ir - Vs}{\sinh(\gamma L)Vr - Zc\cosh(\gamma L) - Zc\, Is}\right]$$

Where Zc is surge impedance and L is the total length. A. Y. Abdalaziz et al. in 2013 [116] presented a

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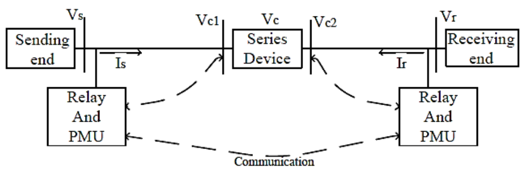
synchronized measurement technique to find the exact fault location in uncompensated and series compensated transmission line. The proposed algorithm uses distributed parameters of the transmission line and utilizes the synchronized measurements of voltages and currents at both ends of the line as shown in fig. 10.

In case of series compensation, the transmission line is divided into two sections, section between „s‟ to „c1‟ and section „c2‟ to „r‟. Voltage across series device Vc1 and Vc2 is calculated by synchronizing measurement of current through the device and fault location can be calculated in two different sections from (1).



B. Vyas et al. [117] presented a comparative study of all fault location techniques for series compensated line. Parallel computation based adaptive neuro-fuzzy inference system (ANFIS) for fault location in transmission line having SSSC has been suggested by E Mohagheghi et al. in 2012 [84], in this scheme, apparent impedance is calculated for various faults created at several locations and simultaneously SSSC equivalent impedance is calculated to train the neuro-fuzzy system to find out the optimized fault location.

3.1.7 Overvoltage Protection of Series Compensators

Based upon the experimental studies following actions have been suggested to protect series compensator from overvoltage (TRV).

(i) Installation of fast protective device across the series device for bypassing.

(ii) Force triggering of protective gap or by lowering the breakdown voltage of gap.

(iii) Impedance has to be inserting in series or an arrester in parallel with the circuit breaker to reduce the peak of TRV.

(iv) Maximum compensation has to be set up-to permissible limit. Lower value of compensation generates lower overvoltage.

3.1.8 Adaptive Distance Protection of Line having SSSC

SSSC is a voltage source invertor (VSI) based controllable device which inserts variable impedance in series with the transmission line as shown in fig.11. Therefore tripping boundary of distance relay is not constant and conventional relay fails to detect fault in different controlling modes of SSSC. Apparent equivalent impedance of transmission line has been calculated to acquire adaptive tripping characteristics for protection. SSSC injects a variable voltage Es in the transmission line according to the control strategy which depends on loading conditions of power system. Inactive SSSC inserts a constant inductance of coupling transformer as shown in the fig. 11 and shifts the tripping characteristic upward by a constant margin. In active mode of SSSC, adaptive tripping characteristics have been drawn for per unit injected voltage from 0 to 0.15pu in leading and lagging mode of operations. It is concluded that in leading mode the quadrature trip characteristics shift downward in clockwise manner and in lagging mode the characteristic shifts towards upward direction.

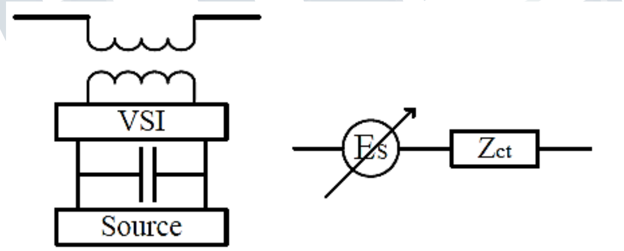


Fig.11. Equivalent Circuit of SSSC.

Additionally an ANN based zone 1 protection for transmission line having SSSC as series compensator device has been suggested by H. Rastegar et al. in 2006, In this technique resistance and reactance of up to 85 % of transmission line with large variations in power system operating parameters are taken as training parameters. ANN makes the relay adaptive for trapezoidal trip boundaries of distance relay.

3.2 Various Methods to Protect Composite/Shunt Devices and Trends

3.2.1 Suggested Protection Schemes for UPFC

(i) Adaptive Distance Algorithms Several apparent impedance calculation schemes for UPFC, when subjected to fault in transmission line have been proposed. Equivalent circuit of UPFC on transmission line is shown in fig. 12. Shunt part of it injects current Ish into the line and series part inserts a variable voltage Ese in the line. UPFC works in two modes of operations viz.; power flow control mode and bypass mode.

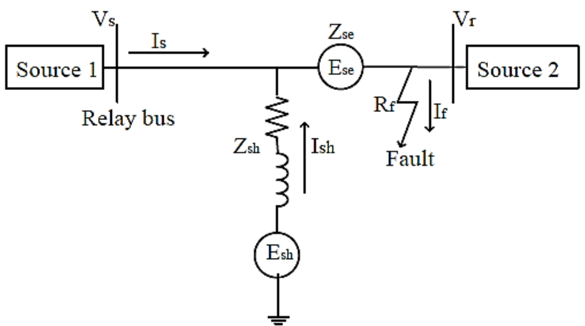


Fig. 12. Single line diagram of UPFC.

When UPFC is not present in the fault loop, its structural and controlling parameters does not affect the tripping characteristics of distance relay. If a LG fault occurs on the right side of UPFC at n per unit distance as shown in fig. 12, the apparent impedance seen by the relay at relay bus can be calculated for different modes as: For mode one sending end voltage Vs can be given as:

$$V_s = nI_sZ_1 + nI_{0s}(Z_0 - Z_1) + I_{sh}Z_1 + E_{se} + R_f I_f, \quad (2)$$

In mode two series voltage inserted by the UPFC becomes zero i.e. Ese = 0, so correspondingly voltage equation changes as:

$$V_s = nI_sZ_1 + nI_{0s}(Z_0 - Z_1) + I_{sh}Z_1 + R_f I_f, \quad (3)$$

Measured impedance

$$Z = \frac{V_s}{I_{relay}} = \frac{V_s}{I_s + \frac{Z_0 - Z_1}{Z_1} I_{0s}}, \quad (4)$$

where

L_{relay} is relaying current Measured impedance Z calculates the fault impedance in all possible operating conditions of UPFC in power system and sets the tripping boundary for an adaptive relay. The addictiveness of the relay can be achieved by using any learning algorithm like ANN.

(ii)ANN based Technique for UPFC Protection

ANN automatically adjusts the variation in power system and UPFC controlling parameters. A radial basis neural network (RBFNN) is learned by the trip characteristics of quadrature Mho relay shown in fig 13. These boundaries are achieved by varying fault resistance from 0 to 100 ohm and creating fault at distance 0 km to 90 % of line. Proposed RBFNN is able to predict the boundaries quite accurately.

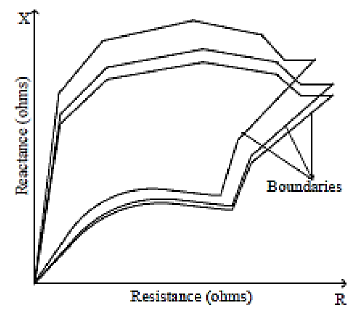


Fig.13. Adaptive quadrilateral trip characteristics.

(iii) Decision Tree (DT)

Decision tree based data mining algorithm is proposed to protect transmission line having FACTS device. DT based relay is trained by input current and voltage signal for various power system operating conditions. The proposed technique is a generalized relay which is trained for mixed data for TCSC and UPFC. DT technique is compared with SVM and it is found that it is faster and more accurate than SVM.

3.2.2 Protection Schemes for Shunt Devices (SVC/STATCOM)

In case of system faults, voltage source convertor (VSC) based shunt device like STATCOM rapidly supplies dynamic VARs for voltage support, resulting in overcurrent and mal-functioning of STATCOM after system fault when VARs are required. Emergency pulse width modulation technique has been suggested by Subhashish Bhattacharya et al. in 2006 to prevent above mentioned problem. In this technique, VSC uses self-implemented PWM (Pulse width modulation) switching to control its phase current within limit and enable STATCOM to remain online during and after fault when it is required. Following are the various suggested techniques to overcome the problem associated with protection of shunt compensated line.

(i) Adaptive Relay Setting

For any fault in transmission line, if fault resistance is zero and shunt device does not fall into the fault loop, the calculated apparent impedance shows the actual value of fault impedance and no modification is needed in protection algorithm. If shunt device falls in fault loop, it affects the trip boundaries according to controlling parameters of the device. In this case distance protection should be adaptive according to operation of shunt device. In literature apparent impedance calculation in case of fault in shunt compensated transmission line has been suggested as follows: As shown in fig. 14 for any LG fault at n per unit length of line, the sending end voltage Vs can be given as:

$$V_s = nI_sZ_1 + nI_{0s}(Z_0 - Z_1) + I_{sh}Z_1 + R_f I_f, \quad (5)$$

Measured impedance

$$Z = \frac{V_s}{I_{relay}} = \frac{V_s}{I_s + \frac{Z_0 - Z_1}{Z_1} I_{0s}}, \text{ so}$$

$$Z = nZ_1 + (n- 0.5)\, Z_1 \left(\frac{I_{sh}}{I_s}\right) + R_f \left(\frac{I_f}{I_s}\right)$$

Actual fault impedance is nZ1 and error „e" due to shunt device in impedance measurement is $e = (n- 0.5)\, Z_1 \left(\frac{I_{sh}}{I_s}\right) + R_f \left(\frac{I_f}{I_s}\right)$ which is removed out at relay end for adaptive protection.

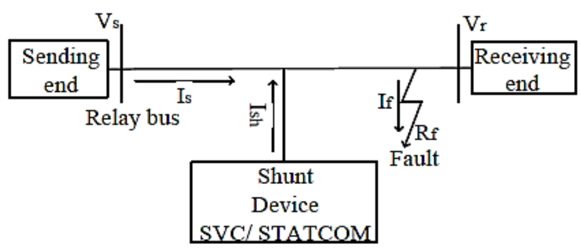


Fig.14. Equivalent line diagram of shunt compensated line.

(ii) ANN based Techniques for Protection of Shunt FACTS Devices

In literature, ANN based approach using TLS-ESPRIT (Total Least Square- Estimation of Signal Parameters via the Rotational Invariance Technique) algorithm has been used to detect and classify fault in transmission line having STATCOM. Proposed technique has two hidden layers and back propagation algorithm used for network training. Half cycle pre fault and full cycle post fault data of three phase voltage and currents for various power system operating conditions are taken as input to ANN and testing and validation accuracy is found to be 100 %.

(iii) Mitigation Trends for Reaching Effects

Literature suggests that, SVC does not show any considerable over-reaching effects as severe as shown by STATCOM. Following are the major remedial steps to reduce the over-reaching effects shown by STATCOM.

(a) By reducing the reach setting of zone one phase element.
(b) By allowing the adjacent line protection system to react for external faults.
(c) A blocking signal can be sent from remote end relay to zone one relay if remote end relay senses a reverse fault.
Following conclusive remedial steps has been taken to reduce the under-reaching effects shown by shunt FACTS device.
(a) Relays are operated with different channel added schemes to secure no under-reaching during fault in shunt compensated line.
(b) Direct under-reaching transfer trip (DUTT)
(c) Permissive under-reaching transfer trip (PUTT) DUTT scheme performs well for any internal fault except its limitations on high fault resistance.

3.2.3 Optimum Location of Shunt FACTS devices: Modern Trend

M. Ghazizadeh-Ahsaee et al. in 2011[137] proposed a novel optimization technique to locate fault in shunt compensated transmission line without using the shunt device parameters. Distributed transmission line with synchronized measurement of voltage and current at both ends is used for algorithm. This technique converts fault location calculation into an optimization problem under some constraints of line fault. The algorithm was tested for several fault location and calculated error was of the order of 10^{-2}.
Table IV(Given in Appendix) gives year wise summarized idea about the protection trends in the transmission line having composite and shunt devices. Adaptive distance protection has certain advantages over the other protection techniques suggested for the purpose.

Apparent impedance of transmission line in the presence of compensating device is calculated in terms of current or voltage injected by the device in the line and distance relay trip characteristic has been strategized for a large variation in fault resistance and power factor (leading to lagging). Learning algorithms viz. ANN, DT and ELM are required to adapt variable quadrature trip characteristics of distance relay.

4. CONCLUSIONS

A review of the protection of compensated power transmission line has been done in this work. Various papers are mentioned which discussed the impact of entire FACTS devices on transmission line protection. Series compensation affects the reaching and directional characteristics of relay. Series device installed at the substation shows severe inversion issues. Mid-point series compensation affects the impedance measurement and fault location estimation by distance relay. In literature, a lot of efforts have been done to protect series compensated transmission line. ANN and fuzzy based techniques can classify faulty and healthy conditions with the accuracy of more than 99 percent. Due to better classification feature of SVM, can classify fault in faster and efficient way. Composite techniques like ANN-WT, neuro-fuzzy, SVM-WT and TW-ANN etc. have better feature extraction ability and show good accuracy. However, these techniques have some limitations in zonal coordination in a large power transmission network and needed for further consideration. A universal technique is required to protect transmission line having TCSC. Technique should be adaptable with all the operating modes of TCSC in healthy and faulty conditions and capable of classifying precise fault location in all types of faults.

Shunt and composite FACTS devices also affect the reaching characteristics of distance relay. A few learning algorithm like decision tree and ANN, are suggested in literature which classify the fault in shunt compensated line. Apparent impedance calculation of transmission line, having STATCOM / UPFC in case of fault is calculated successfully which makes the protection system adaptive. Adaptive distance protection technique has advantages in this trend. To introduce intelligence in distance protection, adaptive quadrature trip boundaries are used to train ANN and results are highly satisfactory in case of UPFC protection. Protection scheme can be faster and efficient by using more intelligence techniques to analyze the patterns viz. various types of neural networks, neuro-fuzzy techniques; wavelet techniques are useful in frequency and time localization of signal; and machine learning techniques like SVM, ELM can be used to protect transmission line having shunt and Composite FACTS devices.

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Appendix

Tables

Table I. Comparative study of ANN based algorithm for protection of series compensated line.

Publishing Year	Methods /Types	System Specification (voltage/length)	Sampling rate/time	Sample Window length	Patterns	Accuracy (max) %	Output
1993	MLP- BPNN	500kV/240miles	1.4 msec	8	27	100	Fault Detection
1996	MLBPNN	500kV/380km	960s/sec	4	5000	100	Fault detection/ classification/ location
1998	Neuro- Fuzzy			½ cycle			Fault detection/ classification
2005	Traveling Wave/BPNN	500kV/100miles	16s/cycle	¼ cycle	70	100	Fault classification/ phase selection
2007	RBFNN	500kV/380km	720s/sec	4	2000	95.99	Detection/classification/location/ direction
2009	MLPNN-BPNN	500kV/160miles	960 s/sec	¼ cycle	7650	95.6	Fault classification/ Location
2011	Total Least Square/BPNN	230kV	512s/cycle	½ cycle	54	100	Detection/ Classification
2012	TDNN	500kV/400km	16s/cycle		768	100	Fault Classification
2012	ANFIS	400kV/300km			500	99.90	Fault Location in SSSC line
2014	ChNN/ WT/SVM	400kV/300km	4 KHz	½ cycle	32400	99.39	Fault Classification

Table II. Comparative study of SVM based algorithm for protection of series compensated line.

Publish Year	Method Used	Kernel Function	Sampling Frequency	Window Length	Training Pattern	%Testing Accuracy	Output
2007	SVM	Polynomial Gaussian	1 KHz	½ cycle	500	95.09	Fault Classification/ Section Identification
2008	SVM/WT	Gaussian	4 KHz	-	25200	93.917	Fault Detection
2010	SVM	Gaussian	-	1 cycle	25200	98	Fault Classification
2011	SVM	Polynomial	-	½ cycle	672	100	Detection/ Classification
2012	SVM /GA	Gaussian	1-4 KHz	4-80 samples	4400	99.93	Fault Classification
2012	SVM/S-Transform	Gaussian	2.5 KHz	-	1870	100	Fault detection/ classification/

2012	SVM/WT	Gaussian	4 KHz	½ cycle	2400	99.81	Fault Detection
2014	SVM/ANN	Gaussian	4 kHz	½ cycle	32400	99.39	Fault classification

Table III. Comparative study of WT based algorithm for protection of series compensated line.

Publish year	Authors	System Specification (voltage/freq/length)	Wavelet/series used	Level	Frequency/ Sampling rate	Output
2004	Z Chen et al.	500kV/50Hz/480km	Wavelet Packer transform	2	-	Fault Zone detection
2006	A I Megahad et al.	500kV/50Hz/400km	Haar/ db4	1-6	1-3 KHz	Fault zone/classification
2007	V J Panda et al.	400kV/50Hz/300km	Db4/db6	6	20KHz	Fault zone/classification
2009	E S T Eldin et al.	500kV/50Hz/150km	Db4/Clark Transform	1	200 KHz	High Impedance fault detection
2011	H C Dubey et al.	230kV/50Hz/300km	Db4/haar/ICA	2	-	Fault detection
2014	B Vyas et al.	400kV/50Hz/300km	Wavelet Packet transform	2	4 KHz	Fault classification

Table IV. Yearly advancement in protection of transmission line having UPFC and shunt devices.

Year	Authors	Device	System Descriptions (Ratings/ Length)	Techniques Used	Outcome/ Remediation of
2000	P K Dash et al.	UPFC	400 kV, /200km	Adaptive distance protection (Apparent impedance calculation)	Ideal trip boundaries
2000	P K Dash et al.	UPFC	-	Adaptive distance protection / ANN	Under-reach/ Over-reach
2006	S Bhattacharya et al.	STATCOM	138kV, 150 MVAR	Emergency PWM	Overcurrent protection of VSC
2007	F A Albasri et al.	SVC/ STATCOM	230kV,110MVAR /300km	Channel aided Distance protection	Under-reach/ Over-reach
2008	S R Samantaray	UPFC/ TCSC	230kV /300km	Decision Tree	Fault zone identification and classification
2008	J U Lim et al.	STATCOM /UPFC	154kV, 100 MVA	Differential current protection	Secure protection
2009	S Jamali et al.	STATCOM	400kV/ 300km	Adaptive distance protection	Adaptive trip boundaries
2009	Seethalakshmi et al.	UPFC	345 kV	Adaptive distance protection (ADP)/	Under-reach/ Over-reach
2010	W H Zhang et al.	STATCOM	500kV, 100MVA /200km	Apparent impedance calculation (Adaptive distance protection)	Zone protection

2010	S Jamali et al.	UPFC	400kV/300km	Apparent impedance calculation	Zone protection
2011	Z Xi et al.	STATCOM	500kV, 100 MVAR	Instantaneous phase lock loop	Overcurrent protection of
2011	A M Abrahim et al.	STATCOM/ TCSC	230kV	ANN/TLS- ESPRIT	Fault Detection, classification
2012	A R Singh et al.	SVC/ STATCOM	-	Adaptive distance protection	Robust Distance protection