A Hybrid Scheme for Fault Locating for Transmission Lines with TCSC

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Abstract—presently, the use of series compensators in AC transmission systems, especially in long transmission lines, is an effective and economical measure to increase the transmission capability and improve the transient and lasting stability of the system. There are various methods for locating in series compensated lines with series equipment. This paper presents a novel A Hybrid Scheme algorithm on series compensated lines with the presence of Thyristor Controlled Capacitor Compensator (TCSC). The proposed algorithm can theoretically detect the fault location in transmission lines equipped with series compensators. This algorithm uses the TCSC time domain model and the distributed transmission line model. In addition to detecting the fault location, it can detect the type and direction of the fault regardless of the location of the series compensator in the shortest time. The proposed algorithm was presented and the simulation was modeled in MATLAB software. The results show that the proposed algorithm increases the accuracy and at the same time speeds up the detection of the fault location in the series compensated transmission lines in order to prevent the malfunction of the relay operation.

Keywords- Fault Locating; TCSC; relay operation; series compensated

I. Introduction

Despite the advantages of using series compensators in AC transmission systems to increase line transmission capability and improve transient and durable stability, problems such as series capacitor and its protection equipment also cause serious problems for line protection, cannot be ignored. Therefore, the performance of the distance relay, which is the most common protection relay in the transmission network [1-5], is usually strongly affected by the capacitor series compensation, and this can cause the remote relay to malfunction. The most important problem caused by line series compensation is that the impedance measured by the relay no longer represents the actual distance from the fault point to the relay location because the apparent resistance and reactance seen by the relay during the fault period are affected by capacitor voltage changes. Placed. Most of the problems encountered by series compensated line relays have been investigated in several papers and include phenomena such as protection zone shrinkage, voltage or current reversal, sub-synchronous fluctuations, and transistors due to capacitor protection equipment performance [6-7]. The above problems
cause the protection schemes based on the frequency signal of the system power to be affected by the variable characteristic of the system impedance and, as a result, the independent operation (without the use of communication channel) of the distance relays of the line lines is not very satisfactory. Algorithms and methods have also been proposed to improve the performance of independent distance relays in the correct detection of line faults, most of which use high frequency or voltage component analysis [8], but most of these methods are complex and only in relays. Advanced digital can be used. In addition, these protection schemes may also be affected by high-frequency noise resulting from the nonlinear nature of the capacitor protection equipment, as well as problems with very close relay faults - leading to The voltage drop is very low - they have], [9], [10], [11] and [12].

In addition to these problems, the limited bandwidth of current measuring transformers (CTs) also weakens the high frequency components used in these algorithms [13-14]. Nevertheless, the penetration of power electronics-based devices impacts the power system dynamics and performance, and thus new / modified control and protection schemes are required [15] - [16].

In this light, fault locating and isolation by an appropriate protection technique is a challenging issue [17] - [22]. A fuzzy logic-based method is used to detect the fault location [18]. Reference [19] provides a method for solving the corresponding linear differential equations that can correctly eliminate the negative effects of the fault resistance on the apparent impedance in short transmission lines. A method of compensating the fault resistance in phase adjustment is presented in [20] and studies show that this method improves the performance of the relay. In reference [21] zero sequence is used to estimate the fault impedance and the destructive effects of fault resistance on the relay performance is compensated. However, the problem is the power electronics instrument reveals resistive characteristics / impedance at fault conditions, depending on their application, when they are switched to current limiting [22].

A comprehensive review of recent developments in the protection of TCSC / UPFC compensated high voltage transmission lines is presented [23]. The merits and relative differences of each of the available methods are also presented for comparison. The power system study mostly consists of a synchronous generator that is connected to an infinite bus through a conventional transmission line with a capacitor compensator [24].

And classification of current and future research trends in this field has been done [25]. The shortcoming of the existing works is that the methods used are not able to accurately identify the location of the fault [26] -[28]. Besides, these methods are not capable of detecting the correct fault zone with any number of FACTS devices and compensating elements and use them for faster and more accurate relay performance [29-31].

**In summary, the advantages / contributions of the proposed method are listed as follows:**

- **a.** Constant measurement of voltage and current of bus power system
- **b.** Detection of fault occurrence according to the measured values of voltage and current
- **c.** Estimate the impedance equivalent to TCSC at the moment of the fault using the pre-fault angle information of the thyristors
- **d.** Determining the direction of the fault using the FSI criterion) The proposed algorithm determines the terminal voltage of the TCSC where the fault occurred
- **e.** Calculate the function F for the entire length of the fault and specify the point at which this function is at its lowest value as the location of the fault.

**The structure of the present paper is as follows:** In Section 2, the problems that occur in the protection of compensated single-circuit transmission lines are examined and possible solutions to eliminate these problems are proposed. Then, in step 3, a new algorithm is proposed to accurately identify the fault location for the lines compensated by the thyristor-controlled series capacitor (TCSC). In step 4, the distributed transmission line model and also the distributed time domain model for TCSC equipment are introduced. In step 5, the exact location is determined using a parametric change called the FSI (fault detector), and in section 6 the simulation results are reviewed and interpreted.

**II. The structure of TCSC circuits**

Similar fig.1 under normal operating conditions, the TCSC has four operating modes, which include off, bypass, capacitive compensation, and inductive compensation. In the off state, the thyristors never turn on, and as a result the TCSC will act as a capacitor. In contrast to the bypass mode, the thyristors are always
on and only a small inductor is in service. In capacitive compensation mode, the capacitive impedance of the circuit is set approximately equal to the impedance of the fixed capacitor TCSC. Finally, there is the induction compensation mode, which is less welcomed and in which the TCSC acts as an inductor. In addition to these operating modes, protective equipment will be activated during a fault to prevent damage to the equipment. The change in TCSC operation mode during the fault depends on the control structure of the thyristor fire angle and the severity of the fault. In contrast, due to the delays of the TCSC control circuit, it is considered that the firing angle of the thyristors does not change in the first cycle after the fault. The flow control is controlled by the trigger angle control of the switches. The effective TCSC impedance is:

\[ X_{\text{Tcsc}} = X_c \left| X_L(\alpha) \right| \]  

\[ X_L(\alpha) = \frac{\pi x L}{\pi - 2\alpha - \sin \alpha} \]  

So, to determine the TCSC range of capacitors or inductors, we use the following method:

\[ X_c = X_L(\alpha_r) \]  

\[ X_c = \frac{\pi x L}{\pi - 2\alpha - \sin \alpha} \rightarrow \pi - 2\alpha - \sin \alpha = \frac{x L \pi}{X_c} \]  

Assuming \( X_L \) and \( X_c \) are known, we get the following equation:

\[ \pi - 2\alpha - \sin \alpha = C \]  

Similar fig.2 the algorithm for calculating TCSC trigger angle parameters is summarized below:

We use the tone theory to calculate the fault flow as we assume for a line with length \( L \), the fault occurs at distance \( L_f \) from source \( E_1 \) and the fault impedance is \( R_f \). By considering the points as fault guess points, the flow of guessed fault points resulting from inverted time signals is calculated (Equation 6). Due to the physical nature of the time reversal technique, the inverted time signals are concentrated towards their point of propagation and the energy concentration is higher at the point where the fault occurred, so the fault location is calculated using the energy of the guessed points according to Equation 7. \( \gamma \) The wave propagation constant and the reflection coefficients at the observation point are considered as \( \rho_1 = 1 \).

\[ I_{1f} = \frac{(1+\rho_1)e^{\gamma X_f}}{(1+\rho_1)e^{-2\gamma X_f} I_{A1}^r (\omega)} \]  

\[ \Gamma(X_f') = \sum_{\alpha=1}^{\beta} \sum_{\gamma=1}^{\nu} \left[ I_{X_f}^r \right]^2 \]
III. Study network:

Single-phase model of a transmission line in Figure 3: Extensive model of the transmission line between transmitter and receiver bus-bars Figure 4 is shown. In this figure, the symbols S and R represent the points of the transmitter and the receiver of power, respectively. The point F indicates the location of the fault. The parameter x in this figure indicates the distance from the point of the power transmitter.

IV. The proposed algorithm for fault location

Figure 5 shows a transmission network in the presence of the TCSC series compensator. In this figure, the compensating element is located in the middle of the transmission line. As shown in this figure, if an fault occurs in the first half of the transmission line, TCSC from the network side A is not in the fault loop that includes bus A and the fault location, but if the fault occurs in the second half, the TCSC is in the fault loop from network A. For each of these scenarios, a sub-algorithm will run to identify the fault location. These algorithms estimate the estimated location of the fault on both sides of the TCSC using synchronous voltage and current line data. The first cycle after that, detects the location of the fault in the direction after or before the TCSC, the combination of the results of the sub-algorithms and the auxiliary algorithm, in addition to determining the type of fault, will also determine its exact location.

A. Scenario 1: Fault before TCSC

Prior to the fault, the TCSC current can be measured using bus voltage and current A and B. If this current passes through a filter and a phase-locked loop, the zero points of the current that are most important for TCSC control will be identified. The voltage of point T₁ belonging to the primary terminal of TCSC will be calculated using the voltage and current of bus A and the voltage of point T₂ belonging to the secondary terminal of TCSC will be calculated using the voltage and current of bus B. By these two voltages, the TCSC voltage will be determined. Using this information, the apparent reactance of TCSC will be calculated:

\[
x_{app} = \text{Im}\left(\frac{V_{TCSC}}{I_{TCSC}}\right)
\]
In this regard, $V_{T_C S_C}$ and $I_{T_C S_C}$ are TCSC synchronous voltage and current, respectively. It is an imaginary part. The compensation ratio is calculated using the following equation:

$$K_B = \frac{X_{app}}{X_C}$$  \hspace{1cm} (9)

Where $X_C$ is the capacitance of the TCSC capacitor. The amount of TCSC compensation in terms of thyristor firing angle and considering its effect on TCSC impedance is calculated as follows:

$$K_B = 1 + \frac{2\lambda^2}{\pi \lambda^2 - 1} \left( \frac{2\cos^2 \beta}{\lambda^2 - 1} \right)$$

$$\sin 2\beta - \frac{1}{\lambda}$$  \hspace{1cm} (10)

$$\lambda = \sqrt{\frac{X_C}{X_L}}$$  \hspace{1cm} (11)

In this equation $\beta = \pi - \alpha$, where $\alpha$ is the thyristor firing angle. During the fault, the voltage and current of 2T will be determined by the current and voltage of bus B using the equation expressed in the previous section. Similarly, the voltage of T1 will be calculated using the TCSC model. When an fault occurs at distance $x$ from bus A (between bus A and TCSC), the fault point voltage can be calculated using two types of information: bus A voltage and current information and point T1 voltage and current information. Therefore, to find the fault point, it is sufficient to minimize the following function:

$$F(x) = \sum_n (V_{xa}(x,t) - V_{xf}(x,t))^2$$  \hspace{1cm} (12)

In this equation $t = nT$ that $T$ is the sampling time. The value of the parameter $x$ indicates the exact location of the fault when the function is minimized. Using this method, if a fault occurs between the transmitter bus and the TCSC, it can be easily measured. In the fault-free scenario and shows the line model when a fault occurs with $R_f$ fault resistance. The basis of this method is based on the fact that when a network fault occurs, a reasonable value for $x$ can be calculated. But when no grid fault has occurred, the values calculated for $x$ are unreasonable and out of range. For example, the allowable range for $x$ is 5 to the length of the line. When no fault has occurred in the grid, if we calculate the values $V_{xa}(x,t)$ and $V_{xb}(x,t)$ for each point along the line, the two numbers are equal; But if an fault occurs on the line, because the current at the beginning and end of the lines are not the same and the fault current causes this inequality, using current and voltage of bus A can only current and voltage to the point where the fault occurred It was calculated carefully and after that it is not possible due to the unknown fault current and its resistance. On the other hand, using bus current and voltage B can only accurately calculate the current and voltage to the point where the fault occurs, and then it is not possible. Due to the unknown amount of fault current at fault, the voltage and current of each point of the line calculated by the information at both ends of the line are not equal and only one of $V_{xa}(x,t)$ and $V_{xb}(x,t)$ It is calculated correctly. The only point where both $V_{xa}(x,t)$ and $V_{xb}(x,t)$ are calculated correctly when the fault occurs is the fault occurrence point. This is why in case of fault. It is not clear that by changing the parameter $x$ in the calculation $V_{xa}(x,t)$ and $V_{xb}(x,t)$ we can reach a unit $x$ for which $V_{xa}(x,t)$ and $V_{xb}(x,t)$ will be equal and that $x$ represents the location of the fault. Of course, it is possible.
Randomly equal to other values of x (such as negative x or x greater than the length of the line) these two values are equal, but as it turns out, these values are not allowed. Note that this algorithm is always calculating the fault location and when a large difference between the values of voltage and current appears in several consecutive samples, it announces the location of the fault, so the delay in fault detection by protection equipment does not affect the performance of this algorithm.

B. Scenario 2: Fault after TCSC

For faults of this type, the fault location is identified as in the previous scenario. The difference is that in this scenario the voltage of point T1 is calculated using the voltage and current of bus A. The voltage and current of the T2 point are also calculated using the TCSC time model. Now, as before, it is enough to calculate the voltage of the fault point from side T2 and again from side B. By doing this process, a point along the line where two voltages are equal will be identified as the location of the fault. According to the two scenarios mentioned above, it is observed that for each fault that occurs on the line, two fault points will be identified, only one of which is correct. Use an auxiliary algorithm based on the TCSC voltage and current diagram, which will be presented in the next section.

V. Fault detection algorithm

Considering Figure (5) as the line compensated by TCSC and assuming that the power flux is from network A to network B, the voltage and phase current of TCSC can be calculated using the following equation and considering the nominal frequency of the network:

\[
\overline{V}(t) = \int_{t_1}^{t_2} v_i(t) \cos(2\pi ft) \, dt - j \int_{t_1}^{t_2} v_i(t) \sin(2\pi ft) \, dt \tag{12}
\]

\[
\overline{I}(t) = \int_{t_1}^{t_2} i_i(t) \cos(2\pi ft) \, dt - j \int_{t_1}^{t_2} i_i(t) \sin(2\pi ft) \, dt \tag{13}
\]

During the initial periods, the fault of the event is 255 km on bus A (15 km on bus B). These results were performed using fault simulation on a 355 km line with a voltage of 455 kV in MATLAB software. Including information about the transmission line and TCSC is given in Table 1.
According to the diagrams shown above (Fig. 8-11), if the power flux is from network A to network B, and an fault occurs between points A and 1T, the real part $\frac{V_i(t)}{I_i(t)}$ at the beginning of the fault with a steep slope will move to the positive. On the other hand, as shown in the figure, if the fault occurs between points 2T and B, the real part $\frac{V_i(t)}{I_i(t)}$ will slope negatively. To validate this conclusion, many simulations have been performed on different types of faults by considering different locations of the fault, and all of them confirm this conclusion, for which purpose a criterion called the Fault Section Indicator $I_{FSI}$ defined as follows:

$$I_{FSI}(t) = \text{real}\left(\frac{V_i(t)}{I_i(t)}\right)$$

In this equation, real is also an operator representing the real part. The FSI signal form for these faults is (shown in Fig. 10 and 11). During normal operation of the TCSC, only a capacitor and a thyristor-controlled reactor are in the circuit, so $I_{FSI}(t)$ is equal to the true part of the TCSC impedance, which is zero due to the absence of any resistance element. Now if a fault occurs in the network, during the initial periods after the fault, the value of $I_{FSI}(t)$ will change. If the fault occurs before TCSC between points A, T1 and $I_{FSI}(t)$ for the phase or phases involved, the fault is 1. However, if the fault occurs after TCSC (between points T2 and B) on the tenth, $I_{FSI}(t)$ for the phase or phases involved, the value is -1. In this algorithm, $I_{FSI}(t)$ is calculated for all phases and its value will be compared with a threshold value determined according to past observations and simulation results for different events. The signal subject to the fault will be sent to the end of the two lines and, as mentioned in the previous section, will be used to determine the exact location of the fault. If the grid side is A, the values given above will change their sign, in addition, no separate measuring equipment is required to implement this algorithm because TCSC control the angle of fire. They need to measure their instantaneous current and voltage. The flowchart of how to measure and detect $I_{FSI}(t)$ is shown in Fig. 12. The final algorithm for how to locate faults in TCSC-compensated lines is (shown in Fig. 13).

![Figure 12: FSI determination algorithm](image)

The proposed algorithm for single-circuit lines is able to detect the fault in the shortest possible time, which is shown in Fig. 15. In this figure, the fault location is 110 km from the transmitter bus and the fault starts in 1.971 seconds and in Time 2.09221 seconds, fault is detected at 110.1 km, the measurement fault rate is as follows:

$$\text{percentage fault} = \frac{110.1 - 110}{300} \times 100 = 0.039$$

![Figure 13: Start time and fault detection by fault location for single-line line Table 1(Test network specifications)](image)
Tables (2) and (3) also present the algorithm for the results of the various faults on the transmission line between networks A and B. Assuming that the firing angle of the thyristors is 165 and 175. As the results show, the firing angle of the thyristors has no effect on the accuracy of the proposed algorithm.

Table 2: Estimation of fault location for fire angle of 165 degrees for single-circuit line

<table>
<thead>
<tr>
<th>Fault %</th>
<th>Fault estimation</th>
<th>FSI signal</th>
<th>Exact location of the fault</th>
<th>Fault type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>9.989</td>
<td>1 1 1</td>
<td>10</td>
<td>abcg</td>
</tr>
<tr>
<td>0.7</td>
<td>50.35</td>
<td>1 1 1</td>
<td>50</td>
<td>abcg</td>
</tr>
<tr>
<td>0.71</td>
<td>75.5315</td>
<td>1 1 1</td>
<td>75</td>
<td>abcg</td>
</tr>
<tr>
<td>0.42</td>
<td>99.5775</td>
<td>1 1 1</td>
<td>100</td>
<td>abcg</td>
</tr>
</tbody>
</table>

Table 3: Estimation of fault location for fire angle of 175 degrees for single-circuit line

<table>
<thead>
<tr>
<th>Fault %</th>
<th>Fault estimation</th>
<th>FSI signal</th>
<th>Exact location of the fault</th>
<th>Fault type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>160.2</td>
<td>-1 -1 -1</td>
<td>160</td>
<td>abcg</td>
</tr>
<tr>
<td>0.03</td>
<td>200.0587</td>
<td>-1 -1 -1</td>
<td>200</td>
<td>abcg</td>
</tr>
<tr>
<td>0.04</td>
<td>225.0965</td>
<td>-1 -1 -1</td>
<td>225</td>
<td>abcg</td>
</tr>
<tr>
<td>0.11</td>
<td>250.2648</td>
<td>-1 -1 -1</td>
<td>250</td>
<td>abcg</td>
</tr>
<tr>
<td>0.15</td>
<td>290.422</td>
<td>-1 -1 -1</td>
<td>290</td>
<td>abcg</td>
</tr>
<tr>
<td>0.09</td>
<td>10.0087</td>
<td>0 0 1</td>
<td>10</td>
<td>ag</td>
</tr>
<tr>
<td>0.32</td>
<td>49.841</td>
<td>0 0 1</td>
<td>50</td>
<td>ag</td>
</tr>
<tr>
<td>0.14</td>
<td>75.102</td>
<td>0 0 1</td>
<td>75</td>
<td>ag</td>
</tr>
<tr>
<td>0.74</td>
<td>100.7392</td>
<td>0 0 1</td>
<td>100</td>
<td>ag</td>
</tr>
<tr>
<td>0.88</td>
<td>138.7635</td>
<td>0 0 1</td>
<td>140</td>
<td>ag</td>
</tr>
</tbody>
</table>
VI. Conclusion:
The proposed algorithm can theoretically detect the fault location in transmission lines equipped with series compensators. This algorithm uses the TCSC time domain model and the distributed transmission line model. In addition to detecting the fault location, it can detect the type and direction of the fault event independently of the location of the series compensator in the shortest time. However, in order for this algorithm to be operationalized and implemented in practice, considerations must be taken. This algorithm is very efficient for a series-compensated transmission line by TCSC, which is 300 km and 400 kV, and the proposed combined method for the protection of compensated lines of single-circuit series. This algorithm was used to locate the compensated lines of the series and simulated in MATLAB software; For different situations of fault occurrence (fault location, type of fault, thyristor firing angle, etc.) it is checked that the accuracy and speed of operation is very good.

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