A CUSUM BASED FAULT DETECTION TECHNIQUE FOR COMPENSATED LINE DURING POWER SWING

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Abstract—Distance relays perform a key role in the protection of transmission lines, however it is susceptible to power swings if a fault occurs relay is supposed to its defined work. The detection of fault in series compensated line during power swing is further complex due to the transients produced by series capacitor and the Metal Oxide Varistor (MOV) protecting it. This paper proposes negative sequence current based technique for detection of all types of faults. Algorithm is tested for Two source test system, series and shunt compensated IEEE 14 bus test system. Faults: Unsymmetrical grounded, unsymmetrical unground, symmetrical faults and high resistance faults are simulated through MiPower/ETA software to test the algorithm in Scilab. Performances of the developed algorithm have been verified by using these simulated cases and from field data.

Keywords—Distance Protection, Power Swing, Fault Detection, Series Compensation, CUSUM.

I. INTRODUCTION

Increased Electricity consumption so as the demand, regulatory developments, and difficulties in establishing new transmission lines result in efficient, optimized operation, and enhanced transmission networks. For the efficient, optimized operation the current carrying capacity of existing transmission line has to be increased. To fulfill these requirements insertion of series capacitor in long transmission line is the basic method is usually implemented by the utilities. However, series capacitor in the transmission line leads to protection problem of the line [2-4].

Power system at steady state operation maintains a balance between the generation and load. Power swing is phenomenon of the large fluctuations of power between two areas of a power system which occurs following a system disturbance such as faults, line switching, generator disconnection, switching of large loads. Power swing causes oscillation in rotor angle between two groups of generator. As a consequence, the apparent impedance seen by a distance relay may fall within its operating zone. It can be sensed as fault and may trip the lines unnecessarily. To insure reliability and stability, the Power Swing Blocking (PSB) function is integrated with the distance relay to block it during power swing [1]. The relay must detect the fault and operate earliest.

Detection of fault during power swing in a series compensated line is further challenging. It is due to generation of different frequency component in the fault signals which depends on fault type, fault location, level of compensation, method of series capacitor bypass [5]. This results in apparent impedances seen by relay to oscillate which creates difficulty in distinguishing power swing and the fault. This paper proposes technique for detecting fault in series compensated line during power swing.

Various techniques are present to detect fault during power swing for transmission line without series compensation. A method based on monitoring the voltage phase angle at the relay location can detect high impedance ground fault during power swing [6]. The rate of change of resistance is estimated to detect fault from power swing [7]. In [8] rate related to magnitude of swing center voltage is used to distinguish fault from the swing. With relative presence of decaying dc in current waveforms, symmetrical fault detection during power swing is presented in [14]. Fault detection using superimposed component of current is presented in [9]. A method based on adaptive neuro-fuzzy inference system is proposed in [13]. [11] This paper compares different techniques of fault detection during power swing for series compensated line.

Above mentioned methods are affected by some means. Non-linear impedance variation, variation of phase angle between voltage and current phasors due to impedance variation across series capacitors and MOV. Due to Voltage inversion possibility monitoring voltage phase angle cannot be achieved.

The present work proposes a cumulative summation of change in negative sequence current based approach for detecting fault during power swing in a series compensated line. Though power swing is balanced phenomenon, a small value of negative-sequence current is observed. It happen due to system unbalance, load unbalance, unbalance fault, and most importantly the conventional phasor estimation technique does not consider the signal modulation. Thus even in case of three phase fault small amount of negative sequence component current is found. In case of unbalanced fault significant amount of negative sequence current is observed. The CUSUM test is
being used widely as a technique for detecting abrupt changes in various fields [15]. The performance of the algorithm is tested for many cases for an Test system and IEEE 14 bus test case simulated with MiPower/ETA and Scilab along with various field data. The algorithm performs fine and found to be accurate and fast.

II. SERIES COMPENSATED LINE FAULT DETECTION CHALLENGES

Series Compensated line creates problem for line protection which depends on fault type, fault location, level of compensation, and over voltage protection devices for series capacitor such as MOV and air-gap. Thus series capacitor makes unfavorable conditions for protective relays that use conventional techniques. Insertion of series capacitor in transmission line has various phenomenal effects on power system. Such as voltage inversion, current inversion, transients caused by series capacitor protective element [6-7], sub harmonic oscillations. These phenomenons affect the protective element characteristics. Overreaching and directional integrity of distance relays are the areas where problem arises. The reach measurement problem for fault detection and fault location are difficult to resolve [9].

A. Voltage Inversion Affects Directional Discrimination.

A voltage inversion is a change of 180 degrees in the voltage phase angle. For elements responding to phase quantities, voltage inversion can occur for a fault near series capacitor if the impedance from relay location to the fault is capacitive rather than inductive [12]. Voltage inversion may affect directional and distance elements.

B. Current Inversion Affects Directional and Diffrential Discrimination.

A current inversion occurs on a series compensated line when, for an internal fault, the equivalent system at one side of the fault is capacitive and the equivalent system at the other side fault is inductive [12]. The current flows out of the line at one terminal, which is referred to as current out feed. For most bolted faults the protecting spark gap, MOV will bypass series capacitor. Current inversion is a rear event for these faults. However, for high resistance faults, the low fault current prevents the capacitor bypassing and creates conditions for a current inversion.

C. Series Capacitor Affects Distance Estimation

Series compensation introduces errors in the impedance that distance elements estimate. The series capacitor modifies the line impedance that the relay measures. Furthermore, subharmonic-frequency oscillations cause the impedance estimation to oscillate. The basic problem is that the impedance estimation depends on the state of the capacitor protection. The effects of series capacitor on distance elements is more critical for capacitors located at the line ends than for mid line capacitors. Line end capacitors do not affect only distance estimation but also affects the directional discrimination. Mid line capacitors do not affect directional discrimination unless the level of compensation is too high [12]. Signal inversions during low current faults may lead to wrong fault identification. On the other hand presence of series capacitors in the network results in sub synchronous oscillation with the line inductance which creates difficulty to distinguish faults from power swing.

III. PROPOSED FAULT DETECTION TECHNIQUE

After the literature survey it can be concluded that due to the limitations in the performance of the available fault detection techniques applicable to uncompensated line during power swing cannot be extended to a series compensated line. Though power swing is a balanced phenomenon, a percentage of negative sequence components of current with respect to the positive sequence current cannot be avoided because of the modulation in phasors and related phasor estimation technique during power swing. For unsymmetrical fault negative sequence component of current is bound to be present in the system. Even in case of three phase fault significant amount of negative sequence component of current is observed at the initial period of the fault due to the transient in the current signal and in the subsequent period due to the presence of modulated frequency component by the power swing. The change in the magnitude of current cannot serve the purpose as during power swing current is going to vary/oscillate. Even in case of temporary over loading current may go high so considering simply current for the detection is not preferable. Instead already discussed negative sequence component of current can serve the purpose. Present paper proposes a simple and effective fault detection principle based on a change in negative sequence current (Δ |I₂|) approach to detect faults during power swing in a series compensated line. Cumulative sum based approach is applied for transmission line fault detection using sampled values of current signal. With the suitable threshold value Δ |I₂| based technique is used in the paper. CUSUM is a vast technique used in many fields for abrupt change detection [15]. CUSUM is applied to obtain good index for fault detection from the sampled values of current.

\[ \dot{I}_n = I_a + \alpha^2 I_b + \alpha I_c \]

\[ \frac{3}{2} I_n \]

\[ \text{Where } I_n \text{ is Negative sequence component of current, } \alpha = e^{j2\pi/3}, \ I_a, \ I_b \text{ and } I_c \text{ are the phase currents [10].} \]
\[ |\Delta \bar{I}_{n_k}| = |\bar{I}_{n_k}| - |\bar{I}_{n_k-1}| \] (2)

As signals in power networks alternate, the two-sided CUSUM algorithm has been suitably designed for power system relaying applications [16]. As a fault detector, the CUSUM method takes the current samples of any phase and delivers two input signals as

\[ s_{1_k} = y_k \] (3)
\[ s_{2_k} = -y_k \] (4)

Where \( y_k \) represents the \( k \)th sample of the current signal. Then, the two-sided CUSUM indices are expressed as [combined]

\[ p_{1_k} = \max \left( p_{1_k-1} + s_{1_k} - \beta l_{\text{dyn},k}, 0 \right) \] (5)
\[ p_{2_k} = \max \left( p_{2_k-1} + s_{2_k} - \beta l_{\text{dyn},k}, 0 \right) \] (6)

Where \( p_{1_k} \) and \( p_{2_k} \) represent the fault occurrence at positive and negative half cycles, respectively. The max-operation produces a positive or zero value for either \( p_{1_k} \) or \( p_{2_k} \) with an increase in the level of signal (i.e., whenever either \( s_1 \) or \( s_2 \) becomes greater. Where \( l_{\text{dyn},k} \) is not fixed and is adjusted by the rms value of the corresponding line current from the previous cycles, and \( \beta \) is a setting parameter that raises or lowers \( l_{\text{dyn},k} \) when it takes values greater or less than one, respectively.

Trigger Signal =

\[ \begin{cases} 1, & \text{if } p_{1_k} > h \text{ or } p_{2_k} > h \\ 0, & \text{else} \end{cases} \] (7)

The value of \( h \) is set such that the algorithm can maintain the balance between reliability versus security and speed versus accuracy requirements of the relaying scheme. The value of \( h \) can be generalized for the particular system. With the consideration of no fault condition such as temporary over loading, capacitor switching or disturbance like high resistance fault, fault with very high fault inception angle close to 180 degree. With this proposed algorithm much higher index values are obtained.

The presented CUSUM algorithm for fault detection is a two sided algorithm. The nature and fault inception instant is not certain. In two sided algorithm two separate indices will look for respective changes in the negative sequence component of current in positive and negative half cycles separately [16]. For the one sided CUSUM algorithm if fault occurs at instant in any half of cycle and the index is designed for the other half cycle then delay of 0.5 to 1 cycle is expected. This is the major disadvantage and will not give the reliability in detection. Hence the two sided CUSUM algorithm is preferred over one sided algorithm.

IV. RESULTS

The algorithm for fault detection is tested for different conditions including balanced and unbalanced faults, high resistance faults, close in faults. With MiPower/ETA the line model data was generated. The instantaneous data was then converted and applied as input to algorithm. Data sampling rate was 1 KHz. The algorithm output conventions are taken as 1 for fault and 0 for no fault conditions. For CUSUM one cycle window data is considered. The data generated is processed in Scilab software. For high resistance fault the fault inception angle is taken not exactly 180 degree but closer to it.

Figure 1 shows single line diagram of tow source test system. Mainly all types of fault are categorized as symmetrical faults, unsymmetrical grounded faults, unsymmetrical ungrounded faults, with special consideration of high resistance fault, far end faults, faults with high inception angle.For testing the algorithm along with simulated data field data also used.

Figure 2 shows single line diagram of IEEE 14 bus test system.

A. Unsymmetrical Grounded Fault

The algorithm for fault detection is tested for different conditions including balanced and unbalanced faults, high resistance faults, close in faults. With MiPower/ETA the line model data was generated. The instantanous data was then converted and applied as input to algorithm. Data sampling rate was 1 KHz. The algorithm output conventions are taken as 1 for fault and 0 for no fault conditions. For CUSUM one cycle window data is considered. The data generated is processed in Scilab software. For high resistance fault the fault inception angle is taken not exactly 180 degree but closer to it.

Figure 2 shows single line diagram of IEEE 14 bus test system.
The algorithm is tested for single line to ground fault (ag type) with fault resistance 25 ohm and the results are as shown in fig.3. As the fault is unbalanced the $I_n$ observed is significant. The index value is relatively very lesser. The algorithm output shows the detection at particular sample. Fault is also tested for higher resistance and high FIA. Algorithm is detecting the fault at 4 ms.

**B. Unsymmetrical Ungrounded Faults**

To test the technique line to line fault (AB type) with Fault Inception Angle (FIA) equal to 40 degree and fault resistance of 5 ohm is considered. Fig. 4 shows the fault current, the sequence component of current, the algorithm index and the output of the algorithm. As we can see in the sequence component plot zero sequence component of current is absent as it is unsymmetrical ungrounded fault.

**C. Symmetrical Fault**

Fig. 5 shows results related to symmetrical fault; data generated from simulation. For the Symmetrical fault in simulation the zero sequence component of current is almost zero. As per the theory the negative sequence component of current is not present. But with the transient caused due to fault, switching of capacitors, and switching of protective elements of series capacitors negative sequence of component is observed. Also due to the signal modulation in phasor estimation technique the significant negative sequence current is observed even in case of symmetrical fault.

**C. Unsymmetrical Grounded Fault (Field Data)**

Here the practical faulted data from relay is taken to test the algorithm. It can be seen the FIA is roughly around 130 degree in given faulted system currents. Zero sequence component of current is significantly high as shown in Fig. 6.

**D. Unsymmetrical Ungrounded Fault (Field Data)**

Fig. 7 elaborates trip signal by CUSUM algorithm for line to line fault. It can be observed from the figure that negative sequence component of current is greater than the positive one and zero sequence currents are negligible [10].
E. Symmetrical Fault (Field Data)

The bolted faults are very rare in power system operation. They are hardly 5 percent but the severity is highest. The performance of algorithm for the severest fault is the main focus and detection of fault earliest is essential.

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In Fig. 8 we can observe nearly negligible zero sequence current and very little negative sequence current which will serve the purpose of detection. Signal modulation and the phasor estimation techniques are the things which are results in a small negative sequence current at the start of transient.

It is observed that for remote location fault from the relay location the algorithm detects the fault in 5-7 ms.

<table>
<thead>
<tr>
<th>Fault Resistance (ohm)</th>
<th>Fault Inception angle (degree)</th>
<th>Fault type</th>
<th>Detection time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>Asymmetrical Grounded</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>Asymmetrical Grounded</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>Asymmetrical Grounded</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>Asymmetrical Grounded</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>Unsymmetrical Grounded</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>Unsymmetrical Grounded</td>
<td>3.4</td>
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<tr>
<td></td>
<td>120</td>
<td>Unsymmetrical Grounded</td>
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<tr>
<td></td>
<td>160</td>
<td>Unsymmetrical Grounded</td>
<td>3.4</td>
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<tr>
<td>25</td>
<td>40</td>
<td>Symmetrical</td>
<td>4-5</td>
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<tr>
<td></td>
<td>80</td>
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</table>

It is observed that for remote location fault from the relay location the algorithm detects the fault in 5-7 ms. As the currents sensed by the relay is very less than swing currents. So the index building for detection of fault by CUSUM algorithm is bit sluggish by 1-2 ms than detection time for other fault.

CONCLUSIONS

This Paper presents a fault detection technique during power swing for series compensated line. The principle of abrupt change detection is used. Here particularly cumulative summation of the change in the magnitude of negative sequence component of current is utilized. Balanced faults, unbalanced fault, high resistant fault, close in fault, fault at different FIA are considered to test the algorithm. The algorithm tested as reliable, fast and accurate.

REFERENCES


A Cusum Based Fault Detection Technique For Compensated Line During Power Swing