Power Swing Protection of Series Compensated Transmission Line

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ABSTRACT- Fault detection during power swing condition is a challenge for stable operation of power system due to several reasons like protection problems, Voltage/current inversion, sub-harmonic oscillations and transients especially if it is series compensated modulation of voltage and current waveforms with swing frequency etc. This paper proposes a negative-sequence current–based technique for detecting presence of fault, classification of fault occurred, estimated zone and location of the fault occurred and the fault inception time with respect to system reference clock during the power swing condition in a series compensated line. In proposed work negative sequence current was analysed as it keeps the other parameters in the system in healthy state. The technique is tested for different series-compensated power systems including a SMIB system and a WSCC-9bus-3machine power system with their different configurations and contingency combinations. Power swing caused by various faults are simulated with PSCAD / EMTDC and MATLAB/SIMULINK and compared with available techniques to prove the effectiveness of the proposed technique algorithm.

INDEX TERMS : fault detection, power swing, series compensation, negative sequence current, fault classification & location.

INTRODUCTION:
Fast and accurate determination of a fault in electrical power system is a vital part in power restoration. Power Swing is caused by large disturbances in power system, which if not blocked caused mal-operation of distance relays and undesired tripping of breakers, change in load impedance, unwanted relay operations at different locations of the network, major power-outages or even power blackout. If a fault occurs during the power swing, the relay must detect the fault and operate quickly. The detection of faults in a series-compensated line during power swings is more challenging due to different frequency components in the fault signals which depend on the fault location, type, level of compensation etc cause the apparent impedance seen by the relay to oscillate and imposes difficulty to distinguish faults from the power swing. This paper proposes a technique for detecting faults in a series-compensated line during the power swing. During unbalanced faults, the negative-sequence components become significant and due to transients in current signals in the initial period, a negative sequence component is present even in three-phase faults. To detect the faults during swing in a series-compensated line, a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence current-based approach is proposed in this paper[5]. The performance is tested for numerous cases for an SMIB system and a 9-bus system simulated with SIMULINK/PSCAD.
Further we detected the classification of the fault using fine tuning method and detected the location of the fault.

**FAULT DETECTION CHALLENGES DURING POWER SWING IN SERIES-COMPENSATED LINES:**

Series compensation imposes protection problems. The use of series capacitors in transmission lines results voltage/current inversion, sub-harmonic oscillations, transients, sub-synchronous oscillations\[10\].

A test system shown in Fig. 1 is considered\[2\]. Both Line-1 and Line-2 are 40% compensated and the capacitors are placed \[10\]. The system details are provided in Appendix A. The system with the distributed line model is simulated using SIMULINK/PSCAD. The traditional fault detection techniques, like the sample-to-sample or cycle-to-cycle comparison of current (or voltage) signals cannot be reliable during the power swing\[9\].

The computation steps for the method are provided

\[
I_2 = \frac{(I_a + \alpha^2 I_b + \alpha I_c)}{3} \tag{1}
\]

\[I_2=\text{negative sequence current}; \alpha=\exp(j2\pi/3) \text{ and } I_a, I_b \text{ and } I_c \text{ are phase currents.} \]

\[S_k=\text{del}(I_{2k})=I_{2k}-I_{2k-1}. \tag{2}\]

For \(S_k > \epsilon\),

\[g_k = \max (g_{k-1} + S_{k-1} - \epsilon, 0) \tag{3}\]

\(g_k = \text{fault index and } \epsilon = \text{the drift parameter in it.}\)

A fault is registered if \(g_k > h\) \(\tag{4}\)

\(h\) is a constant and ideally zero. Epsilon provides the low-pass filtering effect and influences the performance of the detector. When \(S_k > \epsilon\), the \(g_k\) value increases by a factor of difference between \(S_k\) and \(\epsilon\). After each fault detection index \(g\) is reset to zero. The selection of \(\epsilon\) and \(h\) is important for determining the performance of the algorithm. Epsilon is a very small quantity which having a value greater than zero. The value of \(h\) is set such that the algorithm can maintain the balance between dependability versus security and speed versus accuracy requirements of the relaying scheme. Considering all extreme fault situations during the power swing we worked with \((h)_{\text{max}}=0.48\) and \((\epsilon)_{\text{max}}=0.05\) value. The proposed method is based on the CUSUM approach and, therefore, a distinctly much higher index value is obtained during the fault.

**CASE-1: SMIB SYSTEM:**

**TEST AND RESULTS**
The algorithm is tested for different conditions including balanced and unbalanced faults etc. Using SIMULINK/PSCAD with distributed parameter line model data was generated. The data-sampling rate was maintained at 4 kHz for the 50-Hz power system.

**Line-to-Ground Fault in the Series Compensated Line**

The fault is detected after 4.75 ms of fault initiation. At the time of fault inception the fault index \( g \) glows enormously high. Output shows 1 after inception of the fault and 0 before inception.

![Fig5 : Implementation of SMIB Test System Using PSCAD](image)

![Fig6 : a)g - t plot b) output-t plot](image)

Algorithm is tested for a line to ground fault of ag-type with a fault resistance of 0.1 ohm initiated at 0.34 sec for 0.04 sec duration at a distance 240KM from bus1.

![Fig7 : SIMULINK Implementation of SMIB system](image)

![Fig8(a,b,c)Performance Analysis of a healthy signal and a signal containing LG fault](image)

**Fault Detection During Single-Pole Tripping**

Initially phase-a of Line-1 is out of service following an ag-fault occurring during normal operation. It introduced swing into the system. A line-to-ground fault of bg-type with a fault resistance 100 Ohm is created at 0.2s at a distance of 160 km from the relay location toward bus N during swing. For this case, and the fault detection is possible after 0.6-ms fault inception.

![a) g - t plot during single pole tripping](image)
Fault Detection During Double-Pole Tripping

CLASSIFICATION OF THE DETECTED FAULT:

Classification or type of detected fault can be detected by tracking the absolute variation of fault index g and the variation of variation of fault index g (fine tuning of g).
CLASSIFICATION OF LG AND NON-LG FAULTS:

The variation of g in case of a LG fault is very less with compared to other case. The maximum variation of fault index g in case of LG fault 0.16 unit here, for other fault the value of (gmax)var goes beyond 0.3 and above unit.

CLASSIFICATION OF NON-LG FAULTS:

The trick of the detection is the nature of the g-variation curve. The variation of g gradually diminishes to zero towards the end of fault duration and this tendency of variation declining towards zero rapidly increases with respect to if any additional line or ground involved in the fault. See the similarities between the plot of g-variation in case of LL and LLL & LLG and LLLG. In case of LL and LLL there is a set of local maxima other than the global maxima variation (local maxima approx. 60% of global max.). This is missing in case of LLG or LLLLG. So, by seeing the local maxima in the plot we can segregate LL, LLL from LLG, LLLLG fault.

CLASSIFICATION OF PHASE FAULTS:

The variation of (Variation of) g gradually diminishes to zero towards the end of fault duration and this tendency of variation declining towards zero rapidly increases w.r.t if any additional line or ground involved in the fault.

CLASSIFICATION OF GROUND FAULTS:

The variation of (Variation of) g gradually diminishes to zero towards the end of fault duration and this tendency of variation declining towards zero rapidly increases, if any additional line or ground involved in the fault.
PREDICTION OF ZONE AND LOCATION OF THE DETECTED FAULT:

Zone is a function of fault distance. By analyzing the time delay to sense the fault after actual time of inception of the fault, we can predict the Zone of the fault.

\[ Z_f = \frac{V_f}{I_f} \text{ Ohm} \]

\[ \text{Fault Location} = \left( \frac{Z_f}{Z_{1\text{ohm/Km}}} \right) \text{ KM} \]

As it is a 3-Zone Protection scheme, impedances and time Constants of the relays varies zone to zone, so, sometimes it becomes problematic to detect the exact location of the fault but of course, zone of the fault we can predict. More the length increases the algorithm for fault location identification gives more accurate value. In case of fault impedance, during healthy state positive sequence impedance (Z1) present in the system and the value is given in the paper. \( V_f \) and \( I_f \) can be obtained from the sampling of the waveforms we got.

CASE-II-WSCC-9BUS SYSTEM:

TEST AND RESULTS

A WSCC-3-machine-9-bus configuration is considered for the study where a modification has been incorporated by providing 40% compensation at the beginning of line 7–8. The system details are given in Appendix B. A three-phase fault is created in line 5–7 at 0.1 s. The fault is cleared at 0.3 s by opening breaker B3 and B4. The removal of line caused swing condition. Different faults are simulated on line 7-8 to test the algorithm.
Case-1: Line-to-Ground Fault:

An ag- fault with a fault resistance of 0.1ohm is created during the power swing on line 7–8 at a distance of 160 km from the relay location at 0.3 s. The index increases to a higher value at the inception of the fault. The technique is able to detect the fault within half-a-cycle of its inception.

Case-2: Double Line-to-Ground Fault:

The performance of the algorithm for a double-line-to-ground fault of abg-type with a ground fault resistance of 0.1 is created at 0.3 s on line 7–8 during the power swing at a distance of 160 km from the relay location.
CONCLUSIONS

In this paper we have developed a novel fault detection technique for detecting the classification and location of the fault. LLG fault is created at 240 KM distance during power swing condition. After analysing it we got below waveform.

By analysing the Delg & Del (Delg) - t plot we got this is a non-LG ground fault and less inclined to zero. i.e from Delg vs t plot it is clear that it is either LLG or LLLG fault and from Del(Delg) vs t, it is coming as LLG fault. By sampling the fault voltages and performing calculations, the fault location was obtained at 241.07 km with actual fault location of 240 Km.

Accuracy:
Error in measurement of fault distance from the proposed algorithm is computed as follows.

\[
\text{Accuracy} = (100\% - \frac{(241.07 - 240) \times 100\%}{240}) = 99.554\%
\]

Proposed novel fault detection technique for the series compensated line during the power swing is presented in this paper to detect the location and classification of the fault. It uses fine tuning or the nature of variation of fault index to detect the classification of the fault and the fault impedance calculation for the location of the fault. The performance of the proposed algorithm is tested for balanced and unbalanced faults for different series compensated systems.

APPENDIX A

System data for SMIB

Generator:
600MVA, 22KV, 50HZ, H=4.4MW/MVA
Xd=1.81p.u, Xd’=0.3p.u, Xd”=0.23p.u,
Td0’=8s, Td0”=0.03s, X0=1.76p.u,
Xq”=0.25p.u, Tq0”=0.03s, Ra=0.003p.u,
Xp(Potier reactance)=0.15p.u.
Transformer:
600MVA,22/400KV,50Hz,D/Y,X=0.163p.u,
Xcore=0.33p.u,Rcore=0.0p.u,Pcopper=0.0
0177p.u
Transmission lines:
Length=320Km
Positive-sequence impedance=0.12+j0.88
Ohm/Km
Zero-Sequence Impedance=0.309+j1.297
Ohm/Km
Positive-sequence capacitive
reactance=487.723x1000 Ohm-Km
Zero-sequence capacitive
reactance=419.34x1000 Ohm-Km.

APPENDIX B
System data for 3-machine 9-bus configuration:
Generators
Gen-1: 600 MVA,22KV,50Hz
Gen-2: 465 MVA,22KV,50Hz
Gen-3: 310 MVA,22KV,50Hz
Transformers
T1: 600 MVA,22/400KV,50Hz,D/Y;
T2: 465 MVA,22/400KV,50Hz,D/Y;
T3: 310 MVA,22/400KV,50Hz,D/Y;
Transmission line:
Length of line 7-8=320Km,line 8-
9=400Km,line 7-5=310Km,line 5-
4=350Km,line 6-4=350Km,line 6-
9=300km.
Loads
Load A=300MW+j100MVAr.
Load B=200MW+j75MVAr.
Load C=150MW+j75MVAr.
Other parameter used are same as
APPENDIX A

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