Correlation Factor-based Fault-Phase Detection for Series Compensated Transmission Line

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***Abstract*— Distance relays are designed to perform correctly on a resistive/inductive power system. If series capacitors are introduced, the voltage and current relationships deviate from their normal way especially when the fault levels are not sufficient to flash-over the gaps or to produce significant conduction in the Metal Oxide Varistors (MOV). A compensated line imposes problems to directional relaying schemes due to voltage and current inversion situations, operation of MOV which protects series capacitor and reactance modulation issues. In this paper, a novel methodology is proposed to identify faulty phases based on correlation factor computation. The presented method is tested on series capacitor compensated transmission lines (SCCTLs) for the IEEE-14 and IEEE-57 test systems. Simulation results show that the proposed method has identified the correct fault zone. Simulations are done using PSCAD/EMTDC platform.**

Keywords*— Distance Relay, Series Capacitor, Series compensated transmission line, MOV, PMU, wide-area monitoring system(WAMS), supervise zone of protection, adaptive out-of-step relaying.

INTRODUCTION

The series capacitor protection unit may affect the accuracy of fault location in transmission line. Its location in the middle or end of the line can affect the accuracy of the result [1]. Without phase of the fault detection, the fault detection problem is incomplete. If any communication link fails in the network, then information required to obtain fault detection will be incomplete. Fault direction estimation is also an important part in a fault detection algorithm. The Estimated fault direction may be either upstream or downstream should be investigated.

A phasor-based technique for fault location is described in [1]. Paper [2] has described a fault location technique on double-circuit series-compensated lines using two-end unsynchronized measurements. Here MOV is considered in its natural environment without having any modeling inaccuracies. A nutshell about introduction to a phasor-based fault location algorithm is presented in [3]. In Ref. [4] MOV is considered in the natural environment and it is avoiding any modeling inaccuracies.

The presence of a series capacitor and its overvoltage protective devices (metal–oxide varistor (MOV) and/or air gap) create problems to distance relaying based transmission-line protection. Different problems associated with relays have been discussed in [5, 6] that include phenomena like voltage/current inversion, sub-harmonic oscillations, transients etc.

But, the above literature has failed in considering the impact of the series capacitor protection unit, detection of Phase of the fault, considering the communication link failure and, in fault direction estimation.

In this paper, the behavior of series compensated EHV transmission lines during faults is simulated. The importance is given on the impact of capacitor protection on modern techniques (MOV protection). A novel methodology is proposed to identify faulty phases based on correlation factor computation. Under various fault conditions, the proposed method is tested for its validation. The presented method is tested on series capacitor compensated transmission lines (SCCTLs), IEEE 14 bus and IEEE 57 bus test system with their various configurations and contingency combinations and performance is observed with transmission line both end voltage profiles. Distance characteristics are also drawn for various zones of protection. This faulty phase identification algorithm gives better results compared to the detection of faulty phase by imposing the tolerance limit method and the polar plot analysis gives more insight about the zone of the fault and chance of mal-operation.

I. SINGLE AND MULTI-PHASE FAULT PHASE DETECTION

In the proposed work, a novel methodology is proposed to identify faulty phases based on correlation factor computation. Linear correlation coefficient r is a measure of how similar the two signals or variables are. The mathematical expression for computing $\boldsymbol{r}$ is as follows:

$$r = \frac{n\sum AB - (\sum A)(\sum B)}{\sqrt{n(\sum A^2 - (\sum A^2)}\sqrt{n(B^2) - (\sum B^2))}} \quad (1)$$

Here, n indicates the number of pairs of data. The value of r varies between -1 to +1. The positive and negative signs indicate positive linear correlations and negative linear correlations, respectively.

Positive Correlation: A and B vectors are said to have a strong positive linear correlation if r value is near to +1. If r value is exactly +1, then it indicates a perfect positive fit. A Positive

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value indicates that an increase in values for A vector will also increase B vector values.

Negative Correlation: A and B vectors are said to have a strong negative linear correlation if r value is near to -1. If r value is exactly -1, then it indicates a perfect negative fit. A negative value indicates that if the values of A vector increases, values for B vector will *decrease*.

No-Correlation: No-correlation or weak correlation means r value is near to 0. r value near zero means that there is a random, nonlinear relationship between the two variables.

A Perfect Correlation of ± 1 occurs only if all the data points lie exactly on a straight line. If $r = +1$, the slope of this line has positive value. If $r = -1$, the slope of this line is negative.

A correlation greater than 0.8 is generally considered as *strong*; a correlation less than 0.5 is generally considered as *weak* [7-8]. These values can vary depending on the type of data that is being examined. These statistical concepts will be used for detection of the phases involved in fault. The algorithm proposed is as follows:

Algorithm for Proposed method:

Step1: Start

Step2: Sample the faulted voltage or current waveform during Fault duration.

Step3: From the samples find out the greatest change of current or least change in a voltage.

The phase containing the greatest change of current or least change in voltage must contain a fault. The change is considered to eliminate ZCD (Zero Crossing Detector) Problem.

Now, the algorithm will run for checking whether two or more phases are involved in fault or not. The computational steps continued to be are:

Step 4: Take I_a, I_b, I_c or V_a, V_b, V_c sample data during fault time and store it in three different variables A, B, C.

Step 5: Now compute correlation between $A\&B(r_{ab})$, $B\&C(r_{bc})$ and $C\&A(r_{ca})$.

Step6: Stop

If at least two values come between -0.5 to -1 then all the phases involve fault (LLL or LLLG fault), or if any value comes between -0.5 to -1 then that two phases involve fault. Figure 2 shows the flow chart of the proposed algorithm. The reason behind selecting the range to be in between -0.5 to -1 is as explained below.

The value -0.5 to -1 is chosen based on studying properties of a 3-phase waveform. E.g. Phase-A and Phase-B are intercepting at +0.5 or -0.5. At +0.5, Phase-C value is -1 and in -0.5, C value is +1. Therefore, fault involving phases A and B is assumed to happen when more than 50% sampled wave is following down for a voltage-based analysis or 50% of the sampled wave is rising up during current-based analysis. Similarly, Phase-B and Phase-C are intercepting at +0.5 or -0.5, if Phase-A value is -1 or +1. Likewise Phase C and Phase A are intercepting at + 0.5 or -0.5, while Phase-B value is -1 or +1. Thus for Phase B and C or Phase C and A involved fault is assumed to happen when more than 50% sampled wave are following down for voltage based analysis or 50% of the sampled wave are rising up during current based analysis.

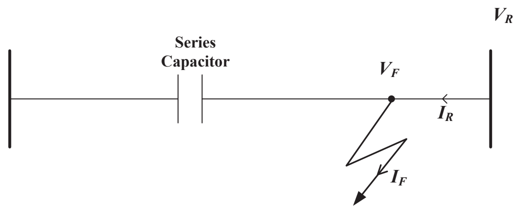

Fig. 1. A two-terminal transmission line.

II. Results and Discussions

During fault, from the available voltage and current samples, data corresponding resistance and reactance parameters are estimated to plot the impedance characteristics, and to confirm the zone where the fault has located. R and X values are estimated as follows:

1) First fault data is simulated and extracted using PSCAD software.

2) Then, the fault impedance is calculated as, $Z=E_b/I_b$.

3) From the above impedance value, calculate the resistance and reactance using the instantaneous value obtained from FFT.

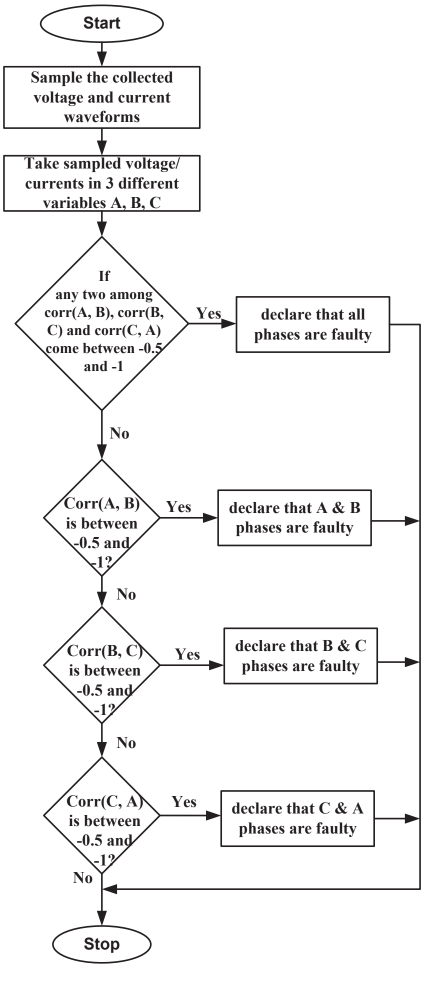

Fig. 2. Flowchart for the proposed faulty-phase detection algorithm.

A. Fault detection

From faulted voltage and current samples, fault impedance (Z) is estimated, and instantaneous phase angles are obtained through FFT block. From Z and instantaneous angle values, R

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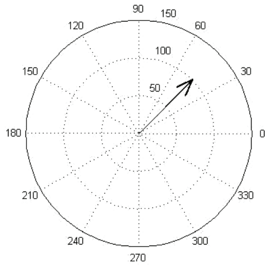
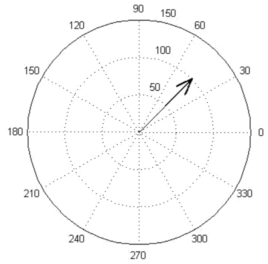
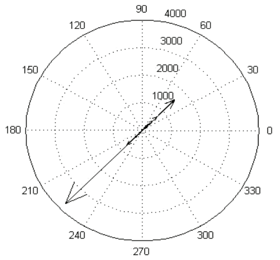
and X values are calculated. Then values of R, X are plotted in a polar-plot. From this plot, the zone of fault can be predicted.



(a)



(b)



(c)

Fig. 3. Fault Impedance locus during (a) LG fault, (b) LLG fault, (c) LL fault.

The fault impedance characteristics for different types of faults are plotted on the *R-X* plane. Here it is considered up to magnitude 50Ω circle as Zone1, up to 100Ω circle as zone 2 and beyond this magnitude as zone 3. From the above characteristics, it is clear that the LG fault and LLG fault both located at Zone 2. But, Fig 3(c) is located at Zone 3. Therefore, in Fig. 3(c) case, there may be a possibility for the involvement of load encroachment problem and distance relay may give a trip signal to the circuit breaker. From the angle values, fault direction estimation is also possible in case of plot-based analysis of fault impedance locus.

Fig 1 is implemented in PSCAD simulation. The test system data are obtained from Ref. [3]. Test results obtained from the algorithm are enlisted in Tables 1-3. An LLLG fault is created on a two-terminal transmission line (between bus 1 and 2) at 75 km distance from sending end at 0.34 sec for 0.01 sec. The sampled values of the faulted current waveform are extracted. The analysis of faulty phase detection is shown in Table 2. The simulation and data extraction is done by using PSCAD software.

TABLE 1. CORRELATION-BASED ANALYSIS FOR FAULT PHASE DETECTION

$\|I_a\|$	$\|I_b\|$	$\|I_c\|$	r_{ab}	r_{bc}	r_{ca}	Phases
0.001179	0.002222	-0.0034	0.90 336	-0.922 74	-0.99 887	A,B,C
0.000869	0.002461	-0.00333				
-0.00345	0.001829	0.001625				
0.000638	-0.00326	0.001622				

TABLE 2: RESULTS OF VARIOUS FAULTS SIMULATED AT 60% ON LINE 1-5 OF IEEE-14 SYSTEM. LINE 1-5 IS PROVIDED WITH 40% SERIES COMPENSATION.

Type of fault	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
LLLG	-0.921476	0.998517	-0.999996	A,B,C
ABG	-0.938641	0.99349	0.798948	A,B
BCG	0.97958	-0.99875	0.955486	B,C
AB	-0.999543	0.987523	0.894315	A,B
BC	0.939216	-0.732856	0.885487	B,C
CA	-0.432313	0.820156	-0.933956	C,A
CAG	-0.423978	0.721316	-0.982317	A,C
AG	0.972836	0.932577	0.982536	Not fault
LLL	-0.923876	0.892772	-0.913624	A,B,C
BG	0.942831	0.823456	0.923815	Not fault
CG	0.932588	0.953197	0.917328	Not fault

TABLE 3: RESULTS OF VARIOUS FAULTS SIMULATED AT 70% ON LINE 1-2, OF IEEE-57 SYSTEM. LINE 1-2 IS PROVIDED WITH 40% SERIES COMPENSATION.

Type of fault created	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
LLLG	-0.998673	0.998517	-0.999996	A,B,C
AG	0.997647	0.99349	0.998948	Not fault
BCG	0.99953	-0.99964	0.999956	B,C
AB	-0.99963	0.997677	0.9975618	A,B
BC	0.913672	-0.782116	0.821637	B,C
CA	-0.381692	0.573621	-0.882779	C,A
CAG	-0.441738	0.672993	-0.955136	C,A
LLL	-0.942972	-0.872631	-0.983217	A,B,C
BG	0.962531	0.972315	0.992358	Not fault
CG	0.983156	0.967123	0.983276	Not fault
ABG	-0.943859	0.973429	0.823526	A,B

B. Overreach of Distance Relays

If the distance relay operates at impedances larger than its pre-set value or reach, then it is known as overreach condition [9]. The main cause of overreach is the presence of DC offset in the fault current signal. Suppose current signal is denoted by *i* and the voltage signal is denoted by U. Then RMS value of fault current will be as follows:

$$i = \sqrt{i_{ac}^2 + i_{dc}^2} \quad (2)$$

Where, i_{ac} is ac harmonics of the fault current and i_{dc} DC offset present in the fault current. Since, the RMS value of fault current with DC offset is greater than RMS value of a pure alternating current having symmetrical wave, the impedance seen by the relay appears to be less than the actual value, and the relay will overreach.

$$Z_{withoffset} = \frac{U}{i} = \frac{U}{\sqrt{i_{ac}^2 + i_{dc}^2}} = Z_1^a \quad (3)$$

$$Z_{withoutoffset} = \frac{U}{i} = \frac{U}{i_{ac}} = Z_2^b \quad (4)$$

$$Z_{withdcoffset} < Z_{withoutdcoffset}$$

$$\%Overreach = \frac{Z_1^a - Z_2^b}{Z_2^b} \times 100 \quad (5)$$

C. Effect of fault impedances

From [3], the fault loop equations can be written as,

$$V_F(d) - R_F I_F(d) = 0$$

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$$V_F(d) = R_F I_F(d)$$

$I_F(d)=R_F^{-1}\, V_F(d)$ (6)

$I_{abc}=[A]I_F(d)$ (7)

Where,

$$[A]=\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix}$$

Here, V_F is the fault voltage and I_F is fault currents. I_{abc} denotes phase currents and R_F is fault resistance (or impedance). From the above equations (6) and (7), we get,

$I_{abc}= R_F^{-1}\,[A]I_F(d)$ (8)

From the equation (8), it can be said that the proposed algorithm is affected by the value of the fault resistances as phase values of currents are affected by the fault resistances. If the fault resistance value is high, the chance of getting affected is less, and if the fault resistance value is low, the chance of getting affected is more. This is due to the fact that the phase current matrix is inversely proportional to fault resistance (or impedance) matrix.

In the case of balanced faults, there will be no negative or zero sequence components. In case of fault alike condition (power swing), this model is also valid.

D. Validity of the above Method During Transient conditions of PMUs:

The method will work fine during transient conditions. e.g., power swing or electromagnetic transients, etc... As the method depends on correlation factor calculation, which is a measure of how two signals are changing together. Therefore, there is no problem with cycle to cycle or sample to sample comparison which happens in case of power swing due to frequency variation of power other than voltage or current signal [9-10]. To test this methodology a series compensated transmission line (Fig. 1) was taken and LG fault was created at 0.3 sec with a duration of 0.04 sec. It will induce a power swing. Immediately after that, below mentioned faults are created from 0.34-0.38 sec. The data obtained are processed through the proposed methodology. The correlation factors obtained with sampled voltage waveforms for different cases are listed below in Table 4.

TABLE 4. THE RESULTS DURING TRANSIENT CONDITIONS OF PMUS

Type of fault created	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
LLL	-0.5382	0.4845	-0.9349	All
AB-G	-0.965	0.509	-0.387	A,B
LLLG	-0.8325	-0.9476	-0.8892	A,B,C
CA	0.5133	-0.3827	-0.9286	A,C
BC	0.7326	-0.6352	0.8715	B,C
BC-G	0.3834	-0.6956	0.84327	B,C
CA-G	0.36298	-0.47136	-0.8951	A,C

TABLE 5. CASE-STUDY DURING FAULT LIKE CONDITION

Fault like condition	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
Power Swing	0.94054	0.84922	0.956523	No phase identified

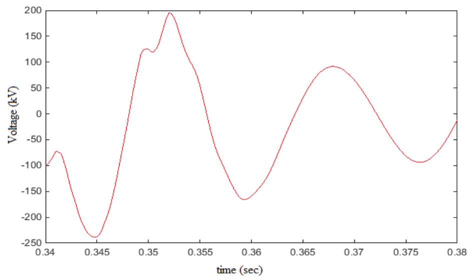

Fig. 4.Swinging Phase-A voltage waveform during LLL fault.

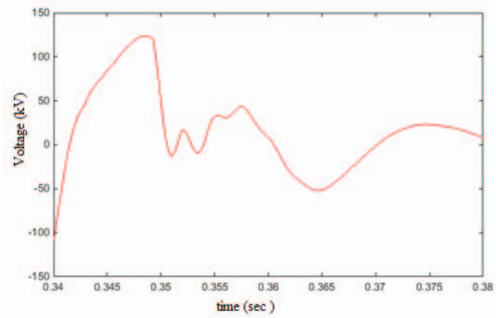

Fig. 5. Swinging Phase-B voltage waveform during LLL fault.

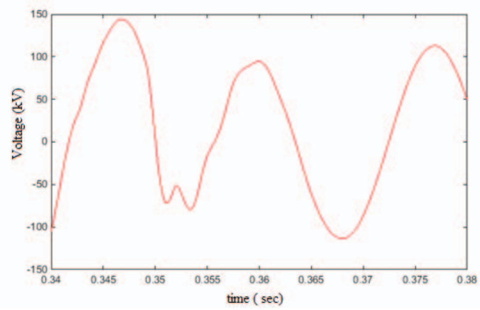

Fig. 6. Swinging Phase-C voltage waveform during LLL fault.

Fig 4, 5 and 6 shows the swinging Phase voltage waveforms during LLL fault in the power swing introduced condition.

E. Stability of the proposed Method:

The method is based on the correlation coefficient calculation between two signals. It depends on the sampling process of the signal. It is not having a direct relation with fault levels or phase angles. Entirely the method depends on the features of the samples extracted from the voltage or current signals. It can work on the transient condition of PMUs and as well as fault like conditions (power swings). Therefore, the method is stable. To prove its function in fault like condition, a series compensated transmission line (Fig. 1) was taken and created LG fault at 0.34 sec for 0.01 sec. It will induce a swing in the voltage and current waveforms and oscillations are available up to small amount of time duration even after fault period. In that case, we have taken the correlation factor of the remaining sampled waveforms. The results are as given in Table 5.

During fault like condition, the impedance trajectory may enter into the working zone of the distance relay, but it will not sustain there, as shown in Fig. 7. It will immediately go out of the working zone. Thus relay detects it as a fault like condition, but not as fault. For Fig 7, a power swing condition is created by using PSCAD simulation and impedance values are calculated with voltage and current signal samples. Then the impedance trajectory is plotted in R-

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X plane, and it is observed that the impedance trajectory is entering in the working zone in the distance relay but immediately going out maintaining the system state stable.

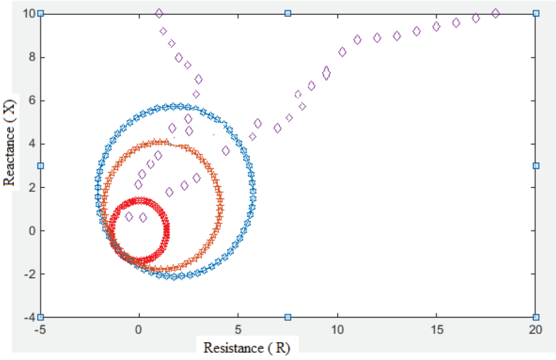

Fig. 7. Impedance trajectory during power swing.

F. Effect of Varying Fault Impedances:

The effect of varying fault impedances is observed on the proposed method. The test system used is Series capacitor compensated transmission line (Fig. 1). The results are listed below using Tables 6-8.

TABLE 6. EFFECT OF FAULT IMPEDANCE DURING LG-FAULT

Fault impedance (Ω)	r_{ab}	r_{bc}	r_{ca}	Multi-phase fault identified
0.1	0.952736	0.918888	0.963251	No
1	0.998137	0.943261	0.992231	No
10	0.782351	0.883271	0.912513	No
100	0.482511	0.743216	0.887543	No
1000	0.911854	0.746235	0.895267	No

TABLE 7. EFFECT OF FAULT IMPEDANCE DURING LLG-FAULT

Fault impedance (Ω)	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
0.1	0.45697	-0.432317	-0.9923	A,C
1	0.92745	-0.72867	0.86538	B,C
10	0.9774	-0.9981	0.9791	B,C
100	-0.586723	0.98744	0.74321	A,B
1000	0.765217	0.971345	-0.8234	A,C

TABLE 8. EFFECT OF FAULT IMPEDANCE DURING LLLG-FAULT

Fault impedance(Ω)	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
0.1	-0.77893	-0.99379	-0.9943	A,B,C
1	-0.779953	0.723765	-0.9937	A,B,C
10	-0.921468	0.998675	-0.9992	A,B,C
100	-0.996523	-0.998643	0.9213	A,B,C
1000	0.992345	-0.721725	-0.6285	A,B,C

It is observed that with varying fault impedances also, this method is identifying the faulted phases correctly.

III. CONCLUSION

This work is having vivid contributions concerning distance protection of series compensated transmission line. First of all, a novel methodology is proposed for phase detection of fault based on correlation factor computation, which is very simple and effective in correctly predicting the phase of the fault and is further extended to the analysis of polar plot which is helpful in the assessment of system internal state. It can judge the state of the fault with fault direction estimation as well as any chance of mal-operation of the system. Eventually, this methodology is helpful not only for predicting of fault but also for the condition monitoring of the system which improve security and reliability. Comparing with results of Ref.[3], the proposed methods gives better results in several aspects. Ref. [3] has not achieved fault phase detection and limited upto 6 Ω fault impedance. But proposed method has achieved fault phase detection part and tested successfully upto 1000 Ω fault impedance.

The proposed method is implemented in case of fault-like conditions in the system and the transient performance issues of the PMUs etc. The stability of the proposed method concerned to the system stability is also addressed.

This faulty phase identification algorithm gives accurate results irrespective of the value of the fault impedances. The polar plot analysis gives more insight about the zone of the fault, the chances of mal-operation and also capable to estimate the direction of fault (upstream or downstream). Thus this work is commendable with respect to the distance protection of series compensated transmission line.

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