DISTANCE RELAY PERFORMANCE EVALUATION ON SERIES COMPENSATED TRANSMISSION LINE UNDER FAULTED CONDITIONS

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Abstract- *A compensated line imposes problems to directional relaying schemes due to Voltage and current inversion situations and operation of metal oxide varistor (MOV) protecting series capacitor, reactance modulation issues .In this paper the behavior of series compensated EHV transmission lines during faults is simulated. The use of series capacitors for compensating part of the inductive reactance of long transmission lines increases the power transmission capacity. Emphasis is given on the impact of modern capacitor protection 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 proposed method is tested on series capacitor compensated transmission lines (SCCTLs) with their different 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. Simulation results show that proposed method has identified correct fault location.*

Index Terms-*Distance Protection, Distance relay Performance, Variation of R&X, Transmission Line, Series Compensation, Series Capacitor Protection Unit, correlation, faulty phase identification.*

I.INTRODUCTION

Use of series capacitors for compensating inductive reactance of long transmission lines increases the power transmission capacity [3-8]. It also increases transient stability margins, optimizes load-sharing between parallel transmission lines and reduces system losses [5-6-7]. Transmission line compensation implies a modification in the electrical characteristic of the transmission line with the objective of increase power transfer capability [4]. In the case of series compensation, the objective is to cancel part of the reactance of the line by means of series capacitors [9]. This result in an enhanced system stability, which is evidenced with an increased power transfer capability of the line, a reduction in the transmission angle at a given level of power transfer and an increased virtual natural load [10-11-12].

Fast and accurate determination of a fault in electrical power system is a vital part in power restoration [13]. In Power system majority of the faults are happened to be single line to ground fault [14]. Other important types of faults are LLG, LLL, LL, LLLG faults. The presence of the capacitor in the circuit immediately after a fault is very important, because it helps in improvement the transient stability of the system. Also in case of unbalanced faults, only the protection devices of the faulted phases operate leaving the capacitor of the other phases on line. It is indispensable to be able to model such devices in a fault analysis program and predict the level of short circuit currents as well as the energy absorbed by the conducting MOV.

Some of the advantages of series compensation of transmission line are listed below:

1) Reduces line voltage drop.
2) Limits load-dependant voltage drops.
3) Influences load flow in parallel transmission lines.
4) Increases power transfer capability

5) Highly effective in maintaining the desired voltage profile along the transmission line interconnecting two busses of the ac system and providing support to the end voltage of radial lines in the face of increasing power demand [21-25] .

This paper proposes a novel methodology to identify faulty phases of a transmission line which is tested on a series compensated transmission line through PSCAD/EMTDC simulation . This faulty phase identification algorithm gives better result compare to 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.

II. SERIES CAPACITOR EFFECT ON DISTANCE MEASUREMENT:

Distance relays are designed to perform correctly on a resistive/inductive system. When SCs are introduced, the normal voltage/current relationships are affected, especially when the fault levels are not sufficient to flash-over the gaps or to produce significant conduction in the MOV's [21] .

III.SINGLE AND MULTI-PHASE FAULT DETECTION :

Linear correlation coefficient r, measures the strength and the direction of a linear relationship between two variables. It is a measure of how similar the two signals or variables are. The mathematical formula for computing ***r*** is:

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

Where n is the number of pairs of data. The value of r is such that $-1 \leq r \leq +1$. The + and – signs are used for positive linear correlations and negative linear correlations, respectively.

Positive Correlation: If A and B have a strong positive linear correlation, *r* is close to +1.
An *r* value of exactly +1 indicates a perfect positive fit. Positive values indicate a relationship between A and B variables such that as values for A increases, values for B also increase.

Negative Correlation: If A and B have a strong negative linear correlation, *r* is close to -1.
An *r* value of exactly -1 indicates a perfect negative fit. Negative values indicate a relationship between A and B such that as values for A increase, values for B decrease.

No-Correlation: If there is no linear correlation or a weak linear correlation, *r* is close to 0. A value near zero means that there is a random, nonlinear relationship between the two variables. *r* is a dimensionless quantity; It does not depend on the units employed.
A Perfect Correlation of ± 1 occurs only when the data points all lie exactly on a straight line. If *r* = +1, the slope of this line is positive. If *r* = -1, the slope of this line is negative.

A correlation greater than 0.8 is generally described as *strong*, whereas a correlation less than 0.5 is generally described as *weak*. These values can vary based upon the type of data being examined. A study utilizing scientific data may require a stronger correlation than a study using social science data. These statistical concepts will be used for detection of the phases involves fault.

Algorithm for Proposed method:

Step1: Start

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

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

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

Now check for whether two or more phases contain fault or not. This paper is concentrated particularly on the aspect when two or more phases contain fault or not. The computational steps as continues:

Step4 :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.

Step5: Now compute correlation between A&B,B&C,C&A.

Step6: Stop

If at least two values comes between -0.5 to -1 then all the phases involves fault(LLL or LLLG fault), or if any one value comes between -0.5 to -1 then that two phases involve with fault .

Test results obtained from the algorithm are enlisted in TABLE I and TABLE II .

TABLE I

TEST SYSTEM-Series Capacitor Compensated Transmission Line with Protection Unit

Analysis with current variable: Fault Created at 140 KM distance. Faulted time (0.34-0.38sec).Series compensation 40% employed.

Type of fault created	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
LLL	0.14002289	-0.84169	-0.6524	All faulty
AB-G	-0.51618	-0.49752	-0.4861	A,B faulty
LLLG	-0.77963	-0.99386	-0.9938	A,B,C faulty
Ph-CA	0.4555593	-0.455791	-0.9999	A,C faulty

TABLE II

Analysis with Voltage variable: Fault Created at 140 KM distance. Faulted time (0.34-0.38sec).Series compensation 20% employed.

Type of fault created	r_{ab}	r_{bc}	r_{ca}	Faulty phases identified
LLLG	-0.77959	0.723784	-0.99386	A,B,C faulty
Ph-CA	-0.46896	0.790685	-0.92395	C,A faulty
LLL	-0.54237	0.492593	-0.93517	A,B,C faulty

IV.IMPLEMENTATION

Fault location is computed using faulted voltage and current samples that described as below:

Fault impedance $Z_f= (V_f/I_f)$ Ohm (2)

Fault Location= (Z_f/ Z_1) (3)

Emperical formula of fault current

$I_{Fi} = (I_{si} + I_{Ri} Cos(h\gamma_i l) - V_{Ri}/Z_{ci} Sin (h\gamma_i l)) / Cosh(\gamma_i ld)$ (4)

Fault Voltage

$V_{Fi} = V_{Ri} Cos(\gamma_i l(1-d) -Z_{ci}I_{Ri} Sin h(\gamma_i l(1-d)))$ (5)

Fault impedance

$Z_{Fi}=(V_{Fi}/I_{Fi})$ (6)

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 (Z_1 Ohm/Km) present in the system and the value is given in the paper. V_f and I_f are obtained from the sampling of the waveforms after creation of different faults at different lengths.

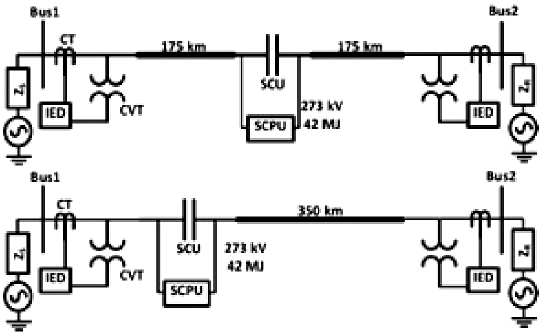
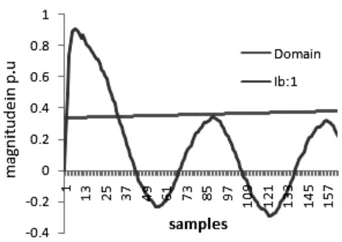


Fig1:series capacitor compensated transmission lines (SCCTLs) with Protection Unit with capacitor at various positions

Test system(Fig1)is simulated using PSCAD/EMTDC software and test different cases with varying fault location, varying capacitor position, varying compensation, varying fault resistance, varying fault duration etc. Then calculated and plotted faulted wave forms and R&X curves(ref. Fig.2 to Fig.12). Sampling frequency maintained here 4KHZ and system frequency maintained here 50 HZ.



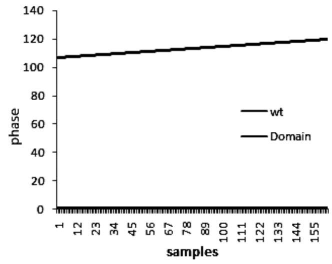
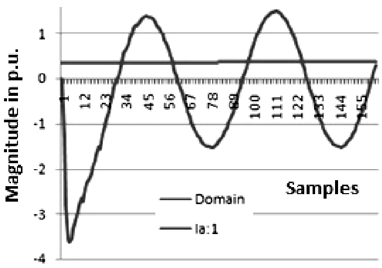


Fig2: Performance of the test system during a Ph-B-G fault at 40% line length



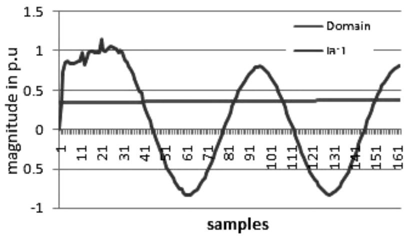
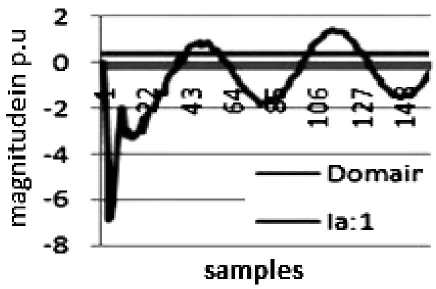


Fig3: Performance of the test system during a Ph-AB-G fault at 40% line length



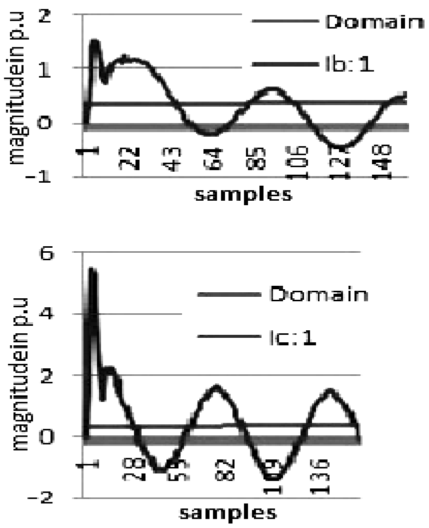
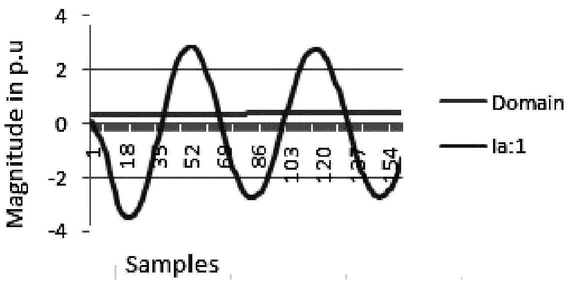
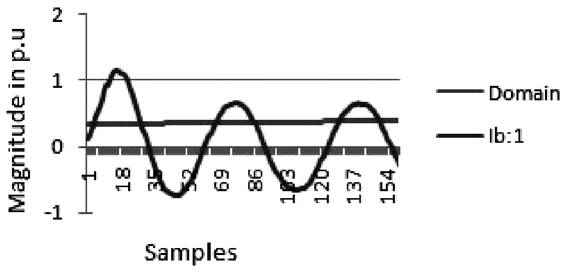


Fig4: Performance of the test system during a LLL fault at 40% line length





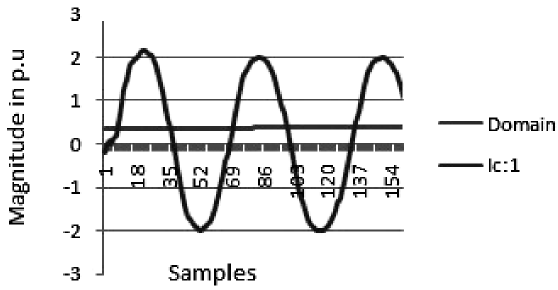


Fig5: Performance of the test system during a LLLG fault at 40% line length

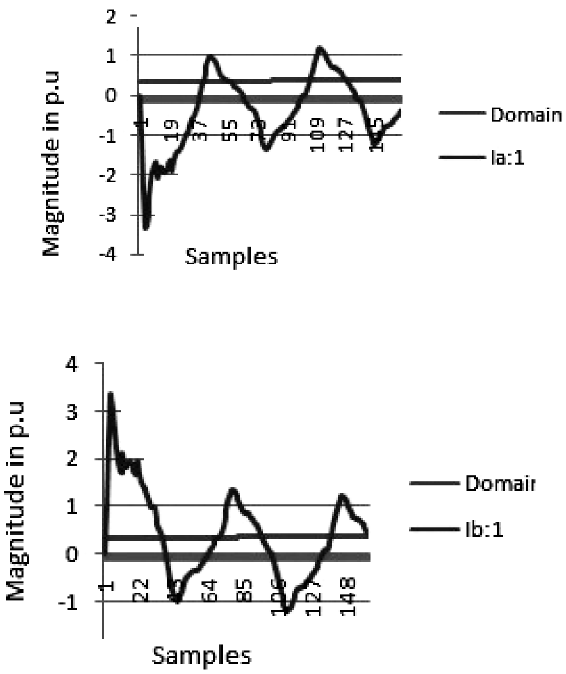


Fig6: Performance of the test system during a LL fault at 40% line length

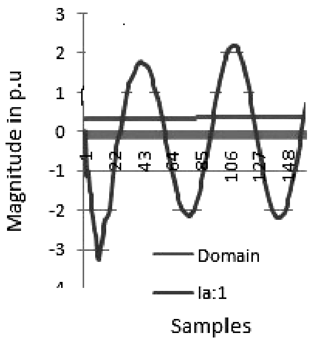


Fig7: Performance of the test system during a AG fault at 40% line length

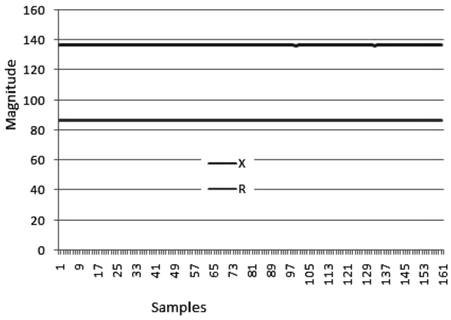


Fig8: Variations of R &X in p.u during a b-g fault

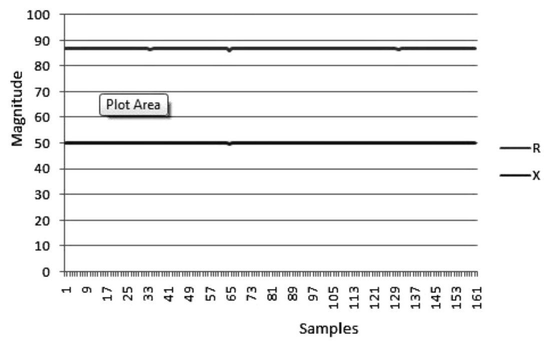


Fig 9: Variations of R&X in p.u During a bc-g fault

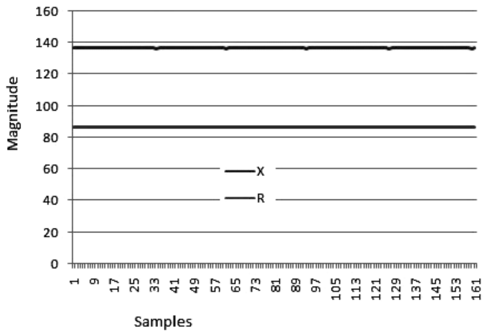


Fig10: Variation of R&X in p.u during a LLLG fault

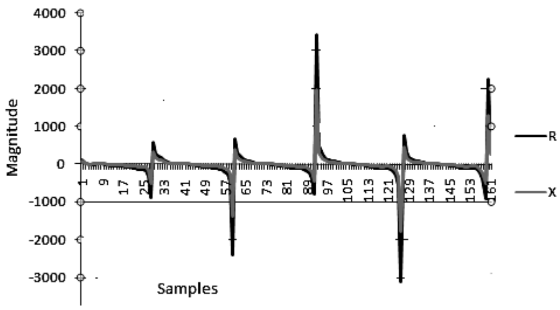


Fig11: Variations of R&X in p.u during a LL fault

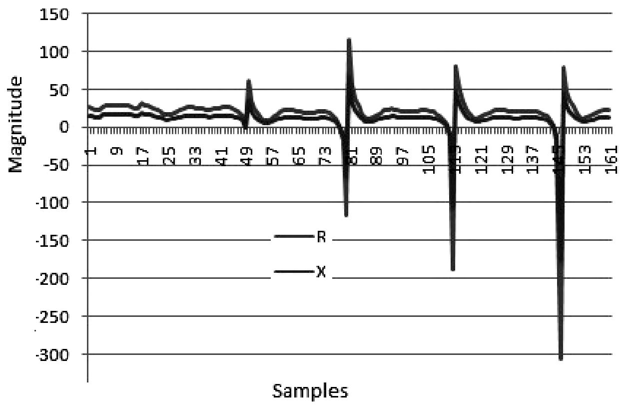


Fig12: Variations of R&X in p.u during a LLL fault

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 shown in TABLE III ,TABLE IV and TABLE V .

TABLE III
Calculation of R&X for a BC-G fault:

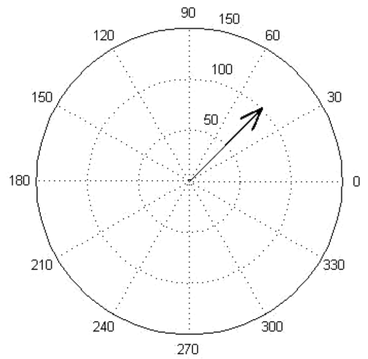
Z(units)	R(units)	X(units)
99.91033	86.52234	49.95516
99.93408	86.54291	49.96704
99.94821	86.55515	49.97411
99.95479	86.56085	49.97739
99.95831	86.5639	49.97916
99.96272	86.56772	49.98136
99.96037	86.56568	49.98018
99.96443	86.5692	49.98221
99.96637	86.57088	49.98319

TABLE IV
Calculation of R&X for a B-G fault

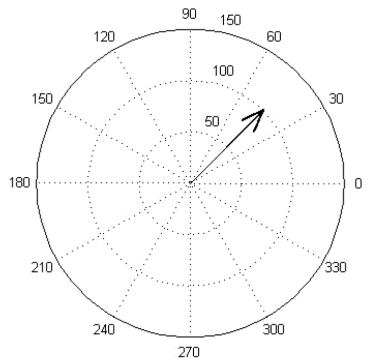
Z(units)	R(units)	X(units)
99.93755	86.54592	49.96877
99.93737	86.54576	49.96869
99.93712	86.54555	49.96856
99.93663	86.54512	49.96831
99.93924	86.54738	49.96962
99.94398	86.55149	49.97199
99.94644	86.55362	49.97322
99.95059	86.55721	49.9753
99.95314	86.55942	49.97657

TABLE V
Calculation of R&X for a LL fault

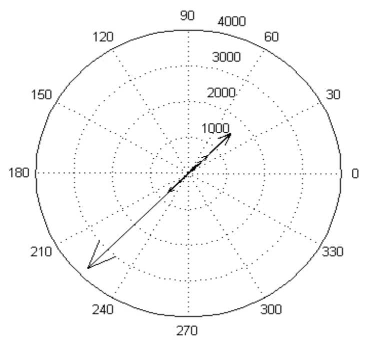
Z(units)	R(units)	X(units)
129.1968	111.8844	64.59838
361.101	312.713	180.55
1015.94	879.807	507.972
2767.65	2396.78	1383.82
3951.639	3422.119	1975.819
3588.58	3107.71	1794.29
894.3192	774.4805	447.1596
2604.014	2255.076	1302.007
1063.61	921.087	531.806



a)



b)



c)

Fig13: 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 R-X plane(ref. Fig 13). Here it is considered up to magnitude 50 unit circle as Zone1, up to 100 unit circle as zone2 and beyond this magnitude as zone3.From the above characteristics it is clear that the fig13(a) LG fault and fig13(b) LLG fault both located at Zone2.But fig13(c) is located at Zone3. So, in fig13(c) case there may be a possibility for involvement of load encroachment problem and distance relay may give a trip signal to the circuit breaker.

i)Implementation of the above method in case of a communication link failure :

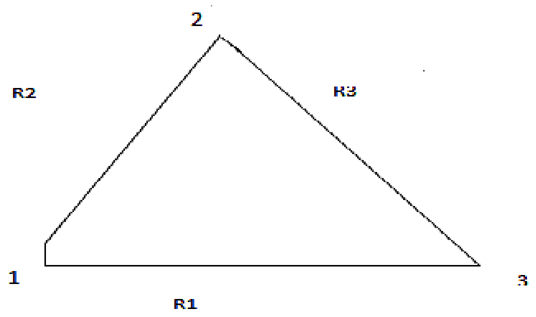


Fig 14 : Data extraction during a communication link failure of a 3-phase system

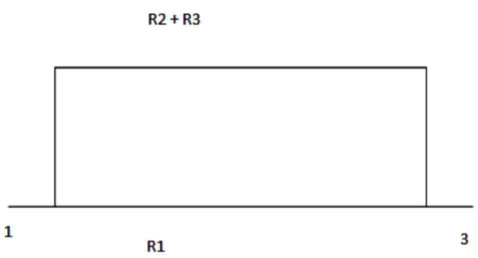


Fig 15 : Equivalent Circuit for Data Extraction when Link 2 fails for the above 3-Phase system

Consider, the case of implementing this method in case of a larger system, where data or samples of voltage or current wave forms are coming from PMUs or Wide Area measurement systems . Suppose link 2 of the above system(ref. Fig. 14) fails and link 1 and link 3 are active .In that case the data can be extracted in the following ways :

Let us consider link i voltage is V_i
Link i current is Ii
And Resistance(or impedance) R_i

where i€{ 0,1,2……n}

Then in case of communication link 2 failure, there will be two parallel paths in the system between 1 to 3 for the above system(same as Fig.15)
Path 1-2-3 and path 1-3
So, R_2 & R_3 will be in series which will be parallel with R_1
So,
Total impedance offered between 1 & 3 point will be

$$Z = (R_2+R_3) \,||\, R_1 \qquad (7)$$

$$= R_1(R_2+R_3) / (R_1+R_2+R_3) \qquad (8)$$

So, if the net voltage difference between path 1& 3 is V
Then net current flowing through the path is

$$I = V/Z \qquad (9)$$

So, according to the current dividers rule,current flowing in the path 1-2-3 is

$$I_2 =(R_1/(R_1+R_2+R_3))* I \qquad (10)$$

$$= (R_1/(R_1+R_2+R_3)) *(V/Z) \qquad (11)$$

$$=(R_1/(R_1+R_2+R_3))*(V)*((R_1+R_2+R_3)/ R_1(R_2+R_3)) \qquad (12)$$

$$= V/(R_2+R_3) \qquad (13)$$

So, between 1-2 link Sample voltage will be

$$= V*R_2 /(R_2+R_3) \qquad (14)$$

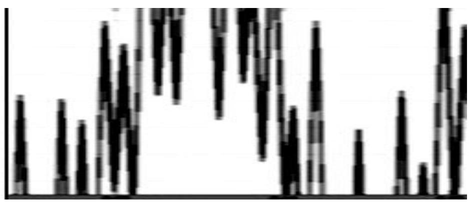
Between 2-3 link sample voltage will be

$= V*R_3 /(R_2+R_3)$ (15)

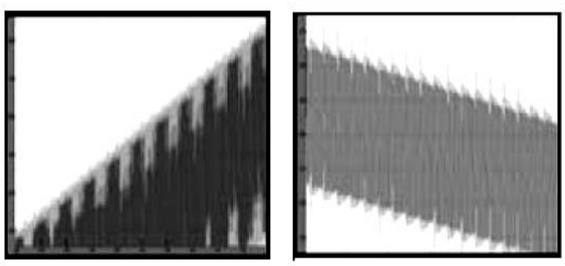
Now, the application of the above method proposed here is possible .

ii) 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 . So, 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 volage or current signal[22-27] .



(a) Voltage Response (Voltage vs time)



(b) Current Response (Current vs time)

Fig 16 : Transient Response from PMUs

A typical Voltage and current response is shown in Fig. 16 (a) & (b).

iii) Stability of the Method :

The method is based on correlation coefficient calculation between two signals . It is totally depend on the sampling process of the signal . It is not having 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 . So, it is stable and also not going to affect the stability of the system.

V.CONCLUSION

The main results regarding MOV protected series capacitor compensated transmission line, obtained by the fault simulation can be summarized as follows:
The variation of R&X is less during ground faults, compared to the phase faults. From the figures it is evident during a bg fault, the maximum value of R&X is confined in the order of 140 unit(ref.Fig.8), while in the case of a Phase-B to Phase-C -g fault, the variation is of the order of 90 units(ref. Fig. 9) and during a LLLG fault the variation is of maximum 140 unit(ref. Fig.10). But in case of phase faults, it is more than two times of ground faults. In case of LL fault, it comes beyond 1000 unit(ref. Fig. 11) and LLL fault it is coming beyond 300 units in negative half (ref. Fig 12).
From polar plot of the fault impedance, it can be concluded which zone the locus is confined and whether distance relay is going to generate any trip signal to circuit breaker or not and if there is any chance for evolving load encroachment problem or not. Faulty phases can be identified when two or more phases involves fault using correlation statistical operator.
Several special cases have been discussed in the context of the Work . e.g- Implementation of the proposed method in case of a communication link failure in the system , the transient performance issues

of the PMUs etc . The stability of the proposed method with respect to the system stability is also addressed.

This work having vivid contributions w.r.t protection of series compensated transmission line .First of all a novel methodology is proposed for phase detection of fault based on correlation factor computation is very simple and effective in correctly predicting the phase of the fault and it is further extended to the analysis of polar plot which is helpful in the assessment of system internal states . It can judge the state of the fault 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 can lead its increase in security and reliability .

This faulty phase identification algorithm gives better result compare to 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. Thus this work is commendable w.r.t the protection of series compensated transmission line .

APPENDIX A

Series Capacitor Compensated Transmission Line system data
Length=350Km
Voltage=500KV
Positive sequence impedance=0.0155+j0.3719 Ω /Km
Zero Sequence Impedance=0.3546+j1.0670 Ω /Km
Positive-sequence admittance= 0+ $j4.4099\times10^{-6}$ mho/Km
Zero-sequence admittance= $(0+ j2.7844 \times 10^{-6})$ mho per km
Positive and zero sequence impedances for sending end source are $Z_{S1} = (1+j15)$ Ω, $Z_{S0} = (2.4 + j25)$ Ω respectively.
Positive and zero sequence impedances for receiving end Source are $Z_{R1} = (1.2 + j18)$ Ω, $Z_{R0} = (2.6 + j26.5)$ Ω, respectively. Load angle is 30 ◦ with receiving end source voltage lagging.

Rated current of 2000A, equivalent of (1750MVA), is considered for sizing Series Capacitor Protection Unit. MOV rating after considering an overload factor of 1.5 is calculated as $273kV$ (= 1.5 ×2000A×91.1Ω).

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