Integrated Adaptive Reach Setting of Distance Relaying Scheme in Series Compensated Lines

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Abstract: The protection of series compensated lines is considered to be one of the most difficult tasks. The paper reviews the series compensated line protection challenges initially and presents state of art solution to improve the distance relay performance. The work describes the development and evaluation of an integrated adaptive distance protection scheme. Development of the adaptive scheme is in the specific area of incorporating the adaptive feature like adaptive reach setting of the relay as the compensation level changes in the series compensated lines, for optimum dependability and security of the protection system. The relay adapts its characteristics according to the informations received from the communication unit. Upon extensive testing on different data set of fault cases with fault resistance and varying percentage compensation level and fault location , performance of the developed method ensures that the proposed scheme overcomes the overreach/underreach problem of the distance relay in series compensated lines and is found to be quite promising.

Index Terms: Adaptive Distance Relay, Adaptive relaying scheme, Digital distance relay, Full Cycle Fourier Transform, Series compensation.

1. Introduction

SERIES compensation plays the vital role in modern heavily loaded grid transmission lines. The series capacitor makes sense because it is simple and could be installed for 15 to 30% of the cost of installing a new line. Series compensation in modern power systems influences the power flow in particular network segment, reduces active power losses prevents system and sub synchronous oscillations, and connects more robustly different subsystems to stronger integrated network .The introduction of series compensation in existing networks requires not only extensive studies into the expected performance of the new system but also into the influence of its introduction on the operation of existing protection control and monitoring systems.

The introduction of the capacitance in series with the line reactance adds certain complexities to the effective application of impedance based distance relays. The protective distance relays, which make use of impedance measurements in order to determine the presence and location of faults, are "fooled" by installed series capacitance on the line when the presence or absence of the capacitor in the fault circuit is not known priori.

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Series Capacitors(SCs) and their overvoltage protection devices (typically Metal Oxide Varistors (MOVs) and/or air gaps), in spite of their beneficial effects on the power system performance, introduce additional problems and make the operating conditions unfavorable for the protective relays that use conventional techniques and include phenomena such as voltage and/or current inversion, subharmonic oscillations, and additional transients caused by the air gaps triggered by thermal protection of the MOVs. The apparent reactance and resistance seen by the relay are affected due to the variation of series compensation voltage

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during the fault period.

As in all relaying, if the problem areas are anticipated and understood, the solution to the problem is achieved with comparative ease. In particular to series compensated lines the problems faced by the distance relay and some of the solution to these problems are researched and published.[1-7], Reach settings for the zones of protection with respect to some of the typical problems and adaptive approach have been discussed in [8]-[14]and [17]-[19].
Relay design progressing is concerned with the improvement of conventional relay algorithms based on phasor concepts The complexities discussed in the protection performance of the series compensated lines call for the early fault detection and high-speed distance relays with good accuracy. We can find some of the advanced techniques with respect to the early fault detection and phasor estimation proposed in [20-24].

Adaptive reach settings of the distance relays for faults involving high arc resistance have been researched for some time now [23-25]. Methods for on-line corrections of the trip boundaries are presented using the wavelet transform in [26-28] and development of integrated protection systems in [29].

Despite constantly increasing power demand, series compensated lines are still quite rare. It is worth to undertake an effort to simulate transient conditions for series compensated applications, fine-tune and verify settings, and finally test the relaying system using digital simulators and/or play back systems.

***"**In conclusion, the reach measurement can be singled out as the main source of problems for the protection of series compensated networks and still poses challenges to researchers. Hence, In view of the above issues and present power system scenarios, room to develop new adaptive techniques is open for research. Hence an attempt is made in this work to develop an Adaptive state of art scheme to meet the requirement of distance relay for optimum reliability in series compensated lines".*

The work describes the development of an adaptive technique and the apparent impedance calculation procedure along with detailed simulation results for distance relaying schemes in which series capacitor comes in the fault loop of the transmission line considered.

2. Proposed Distance Protection Scheme

Considering the protection aspects of series compensated as discussed in the previous section, it is observed that an adaptive relay setting of the distance protection is required to cope up with the problems of overreach or underreach. Also it is deduced from the Literature review that the variations in the series compensation level are found to influence the apparent impedance measurements and trip boundaries. The apparent reactance and resistance seen by the relay are affected due to the variation of series compensation voltage during the fault period [1]-[6].This serves as a basis of this proposed scheme.

The main idea behind the proposed solution is to have a typical digital distance relay scheme with extra information received from other local and remote relay. The relay changes its setting or action based on the received information. The concept of adapting the relay performance based on information from other relays is receiving much more acceptance because the speed of data transfer has increased and the expense of communication systems has declined.

The proposed distance scheme is supplied off-line with detailed network information, e.g. length, impedance of each line in the concerned network. The relay operates normally as a typical digital distance relay. However, with the new information fed to the relay through the communication system, the relay performance will be changed based on this information. This information is received from the local and remote end relays. It includes.

1) Name of the faulty line
2) Series Compensation level
3) Value of running calculated impedance
4) Fault zone (one or two).

The objectives of the work presented in the following section are

1) Development of an Adaptive relaying scheme for varied level of series compensation.
2) Simulation of series compensated system for the Fault data at varied percentage of line length.
3) Distance computation for Zone 1, Zone 2 and the directional unit setting and development of Adaptive Relay logic.
4) Performance Evaluation of the Adaptive Relay of the proposed scheme.

Figure 1. Depicts the procedural steps of the proposed scheme

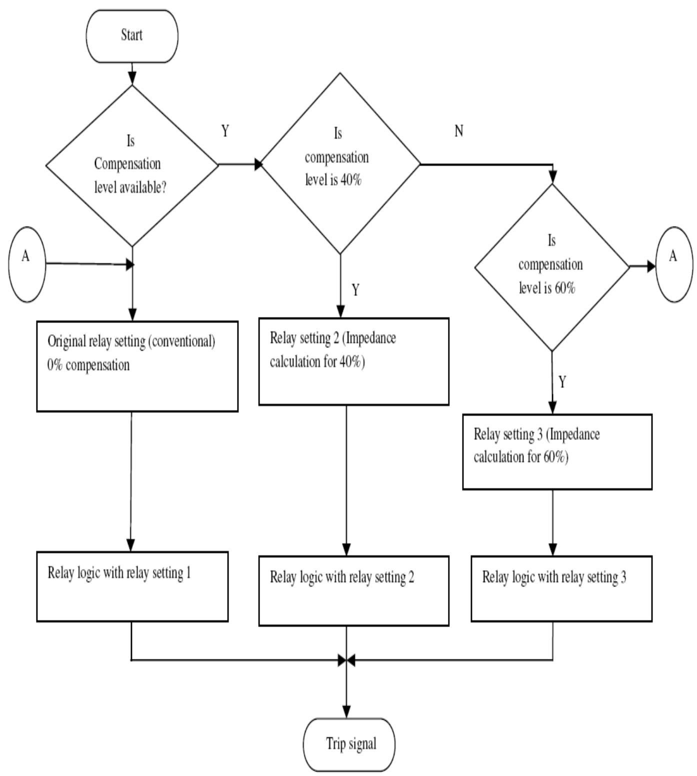

Figure 1. Sequence of proposed Adaptive Distance Protection Scheme

A. Development of an Adaptive Scheme for varied level of series compensation

The proposed adaptive scheme is detailed in the figure 1. First checks to see whether the series compensation level is available .The steady state characteristics are modelled for the three compensation levels like 0%, 40% and 60%. Depending on the availability of the compensation level, the relay adapts its setting accordingly. Then the dynamic characteristics of the relay are obtained using Full Cycle Fourier Algorithm (FCF) to check the status of the particular relay. The capacitance to particular compensation level will be used for faulted line impedance computation, but will not be used in healthy line's impedance calculation. Whenever the required information is not available, the proposed scheme uses the default setting as a conventional relay without the capacitor in the distance computation

B. Simulation Of Series Compensated Transmission System For The Fault Data.

Figure 2, is the single line diagram of series compensated three phase transmission system model considered for the simulation study [15] [16]. The realistic power system is simulated in

MATLAB/SIMULINK platform. Figure 3 depicts the MOV protected series capacitor considered in the system.

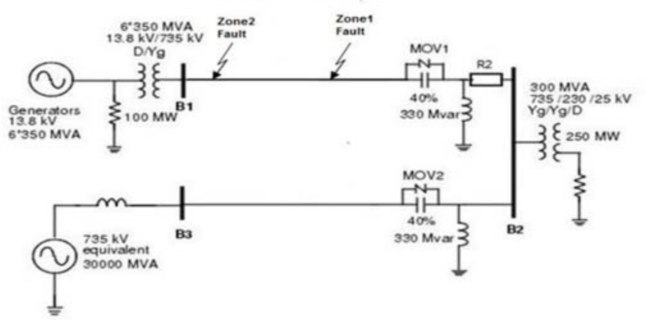

Figure 2. Series compensated transmission system model

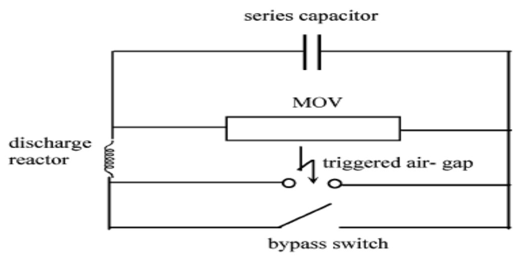

Figure 3. MOV protected series capacitor.

The details of the system simulated are as follows

1) The single-line diagram shown here represents a three-phase, 50 Hz, 735 kV power system transmitting power from a power plant consisting of six 350 MVA generators to an equivalent load system through a 600 km transmission line. The transmission line is split into two 300 km lines connected between buses B1, B2, and B3 as indicated in the system considered.
2) System has been initialized to 1500MW generation at 13.8KV bus. The parameters are measured at buses B1, B2 and B3.
3) Series compensation is done on transmission lines to increase the transmission capability of the system, the system is compensated and studied for different compensation levels like, 0%(conventional), 40% and 60% of the line reactance.
4) Line1 and Line2 are shunt compensated by 330MVar shunt reactance. Series capacitor banks on both the lines are similar. From the network shown we can observe that series and shunt compensation equipment is located at bus B2 station where load is applied. Transmission line inductance, capacitance and resistance considered are

$L = 0.9337 \times 10^{-3}\, Henry / km$

$C = 12.74 \times 10^{-9}\, farad / km$

$R = 0.01273 \Omega / km$.

C. Distance computation and Adaptive relay settings.

In First Zone Evaluation, due to the effect of subsynchronous oscillations caused by series capacitor, during fault conditions the basic evaluation adjustment of the distance protection first zone should be reduced with respect to the conventional criteria, as it is detailed in Fig. 4 [8][9].

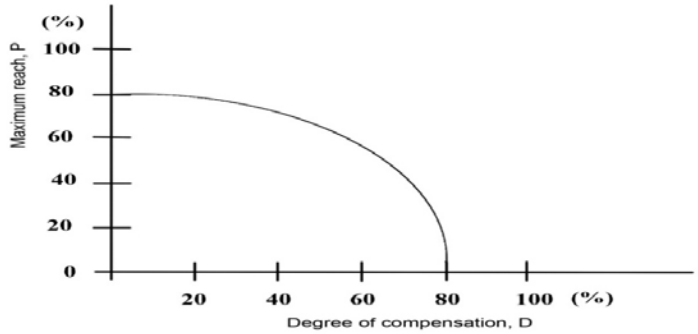

Figure 4. First zone maximum reach as a function of the degree of compensation

"D", the degree of compensation of the line is defined as

$$D = \left[\frac{X_L}{X_C} \right] \times 100 \tag{1}$$

"Xc" and "X_L" being the capacitor bank and the protected line reactances respectively. The ‘p’ value corresponds to the maximum permitted first zone reach, due to subsynchronous oscillations, as a percentage of the line impedance for a given value of "D". In the basic setting evaluation, considering compensated lines, the 'p" value is applied in both extremes to the difference given by figure. 4.

Table 1. ‘P’ value with respect to percentage compensation

D	‘P’ value
0	0.8
40	0.7
60	0.54

The reach setting used for simulation study is a parallelogram characteristic with a forward fault resistance of 10 ohm. The backward reach settings (directional unit setting) used are

$$R_b = -\frac{3}{5}\left(R_f\right) \tag{2}$$

$$X_b = \frac{1}{2}\left(X_f\right) \tag{3}$$

Where, R_b and X_b are backward resistance and reactance reach. R_f and X_f (***X_{reach}***),are their forward counterparts respectively.

The line impedance angle (θ_L) varies between 84°−88°. The calculated reach settings in perunit (pu) on *100 MVA* base for the characteristic of the relay at all the three compensation levels are estimated and shown in Table 2 respectively.

Table 2. Reach setting of the adaptive Relay in perunit

Level of Compensation	Zone 1 setting values in pu				
	R_f	X_f	R_b	X_b	θ_L
0%	0.00555	0.0156	-0.00333	-0.0078	87.92
40%	0.00555	0.0082	-0.00333	-0.0041	86.54
60%	0.00555	0.0042	-0.00333	-0.0021	84.83
	Zone 2 setting values in pu (Conventional)				
	0.00555	0.0293	-0.00333	-0.0146	87.92

The steady state *Relay characteristic* obtained for the proposed adaptive scheme with the respective compensation level considered is shown in figure 5. 0% compensation setting is considered as conventional relay characteristic. The Zone 1 and Zone 2 reach characteristics for the conventional relay obtained is shown in Figure 6.

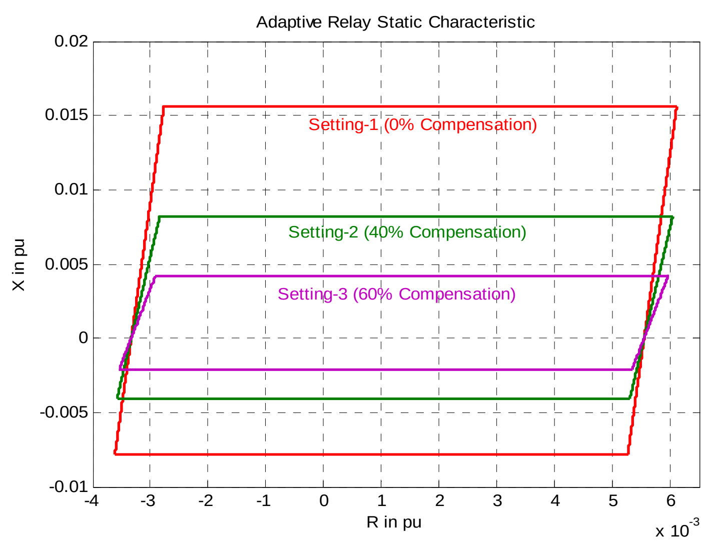

Figure 5. Adaptive Relay characteristic for Zone 1 w.r.t. level of compensation

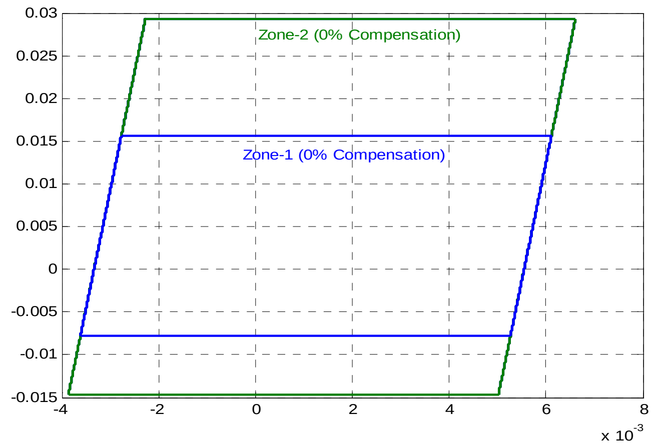

Figure 6. zone 1 and zone 2 of conventional Relay (0 % compensation) characteristic,

C. Performance Evaluation of the Proposed Adaptive Scheme

1. Extensive simulation study is made on the series compensated transmission system (figure 1.6) for the faults like A-G, B-G, C-G, AB-G and ABC for each level of compensation.
2. The simulation study is made at a sampling frequency (Fs) of 6 kHz. The performance evaluation is considered for the fore said faults with minimum inception angle and the fault resistance of 10Ω. The faults are applied on Line 1, on the *line side of the capacitor bank.* The measurement of fault signals for the relay *R2 are made at B2* substation.
3. Performance evaluation of Relay R2 is made in detail as capacitor is in the fault loop .Two cases have been considered for the evaluation at all the three compensation levels.
   1) *Case 1: Performance evaluation for the faults simulated within 80% of Line 1 length (in Zone 1).*
   2) *Case 2: Performance evaluation for the faults simulated at 90% of the Line 1 (in Zone 2 that is 10% outside Zone 1).*
4. For both the case studies, fault is applied at t=1 cycle (0.01667sec), and 4 cycles of post fault data signals are taken. Therefore at the end of the 5th cycle (at 0.083 sec) the breaker is open and the fault is eliminated at the 6th cycle.
5. For all the fault conditions as mentioned, data is recorded at a sampling time of 0.0001667 sec (i.e. 100 samples/cycle)

Adaptive relay logic is developed in MATLAB considering the Full Cycle Fourier (FCF) algorithm for the fault impedance estimation. The relay logic adopted for its dynamic characteristic is developed. The impedance trajectories obtained for both the cases mentioned above are illustrated in respective figures according to their numbers, mentioned in the following tables of results. The figures clearly explain the need of such an adaptive scheme and the optimum performance of the proposed scheme in the modern power system scenarios.

The results of evaluation of the proposed adaptive relay are summarized and illustrated in Table 3, Table 4 and Table 5. The Tables show the detail results of the fault conditions of case1 and case2 for the three compensation levels respectively (0%, 40% and 60%). The results are shown in respect of operation in respective zones to overcome the problem of overreach/under reach (maloperation) of the relay and the operating time. To confirm the tripping, a trip counter is set for 5 samples for zone 1 and 100 samples for zone2 (delay time).The results discussion depicting the need and efficiency of this proposed scheme and the comparative analysis with that of conventional relay are detailed in the following section.

The results obtained illustrate the correct operation of the distance relay for the proposed scheme. The RX plots show that the relay adapts its characteristic to trip in the respective zones at all the three compensation levels according to the information received and the system condition (only plots of some sample cases are presented as indicated in the tables).

It is observed in simulation study that fault signals of AG fault at 40 % compensation, since a line-to-ground (AG) fault is applied and the fault current reaches 10kA, the MOV conducts at every half cycle and the energy dissipated in the MOV builds up to 13 MJ and stays constant at 13 MJ. As the maximum energy does not exceed the 30 MJ threshold level, the gap is not fired. After t=6 cycles the fault current drops to a small value and the line and series capacitance start to discharge through the fault and the shunt reactance. Hence the relay adapts to 40 % compensation characteristic settings.

Similarly it is also observed that during a three phase fault the energy dissipated in the MOV builds up faster than in the case of a AG fault, the energy reaches the 30MJ threshold level as a result the gap is fired and the capacitor voltage quickly discharges to zero through the damping circuit. Here, since the capacitance effect no longer exists, the relay can adapt to its conventional characteristic.

Further extensive study is made by subjecting the adaptive relay with the faults created at different line length 20%, 50%, and 70% on L2 with the capacitor in the fault loop for zone 1 faults. Figures depict the results obtained and they prove the efficacy of the relay to operate in the respective zones with reach adaptability.

Table 3. Results of evaluation for 40% compensation

Type of fault	Location of fault	Fault signals Fig No.		R-X plot Fig No	R-T plot Fig No	X-T plot Fig No	Status of Relay Correct operation * mal operation (overreach)		Operating time in ms
		V	I				Conventional Relay	Adaptive Relay	
AG	Zone 1	7	8	11	12	13	√	√	25.50
	Zone 2	9	10	11	-	-	*	√	43.83
BG	Zone 1	-	-	-	-	-	√	√	22.31
	Zone 2	-	-	-	-	-	*	√	40.33
CG	Zone 1	-	-	-	-	-	√	√	18.17
	Zone 2	-	-	-	-	-	*	√	43.66
ABG	Zone 1	-	-	-	-		√	√	23.33
	Zone 2	-	-	-	-	”	*	√	44.83
ABC	Zone 1	-	-	-	-	-	√	√	21.00
	Zone 2	-	-	-	-	-	*	√	41.01

Table 4. Results of evaluation for 60% compensation

Type of fault	Location of fault	Fault signals Fig No.		R-X plot Fig No	X-t plot Fig No	R-t plot Fig No	Status of Relay Correct operation * mal operation (overreach)		Operating time in ms
		V	I				Conventional Relay	Adaptive Relay	
AG	Zone 1	-	-	14	-	-	√	√	22.57
	Zone 2	-	-	14	-	-	*	√	47.51
BG	Zone 1	-	-	-	-	-	√	√	22.17
	Zone 2	-	-	-	-	-	*	√	47.11
CG	Zone 1	-	-	-	-	-	√	√	27.00
	Zone 2	-	-	-	-	-	*	√	48.84
ABG	Zone 1	-	-	-	-	-	√	√	21.56
	Zone 2	-	-	-	-	-	*	√	43.01
ABC	Zone 1	-	-	-	-	-	√	√	21.83
	Zone 2	-	-	-	-	-	*	√	43.51

Table 5. Results of evaluation for 0% compensation

Type of fault	Location of fault	Fault signals Fig No.		R-X plot Fig No	R-T plot Fig No	X-T plot Fig No	Status of Relay √ Correct operation * mal operation (overreach)	Operating time in ms
		V	I				Adaptive Relay/ Conventional Relay	
AG	Zone 1	-	-	15	-	-	√	23.01
	Zone 2	-	-	15	-	-	√	40.49
BG	Zone 1	-	-	-	-	-	√	13.00
	Zone 2	-	-	-	-	-	√	35.33
CG	Zone 1	-	-	-	-	-	√	15.33
	Zone 2	-	-	-	-	-	√	38.83
ABG	Zone 1	-	-	-	-	-	√	15.83
	Zone 2	-	-	-	-	-	√	43.34
ABC	Zone 1	-	-	-	-	-	√	14.17
	Zone 2	-	-	-	-	-	√	35.66

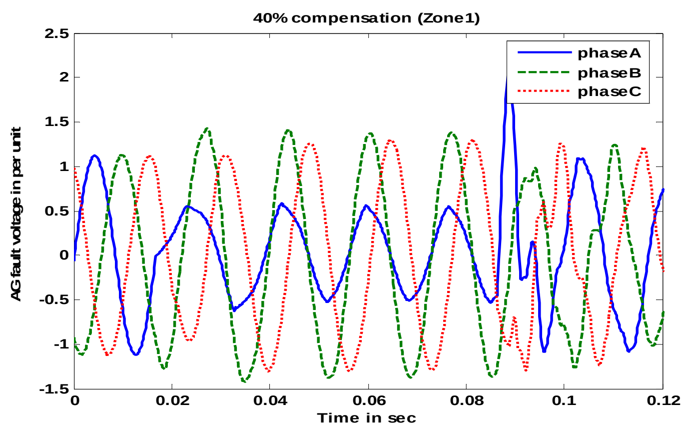

Figure 7. AG fault voltage for case1 at 40% compensation

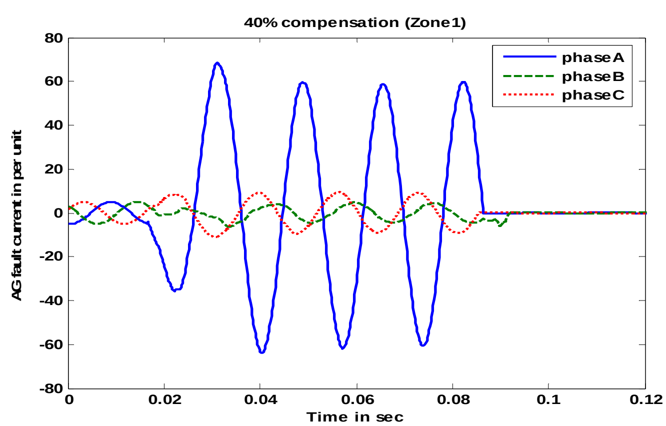

Figure 8. AG fault current for case1 at 40% compensation

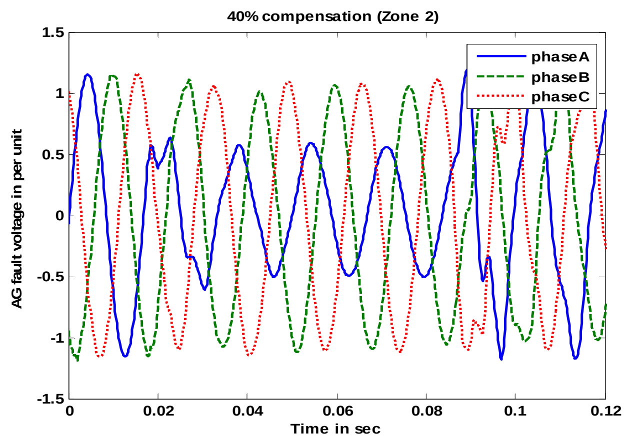

Figure 9. AG fault voltage current for case2 at 40% compensation

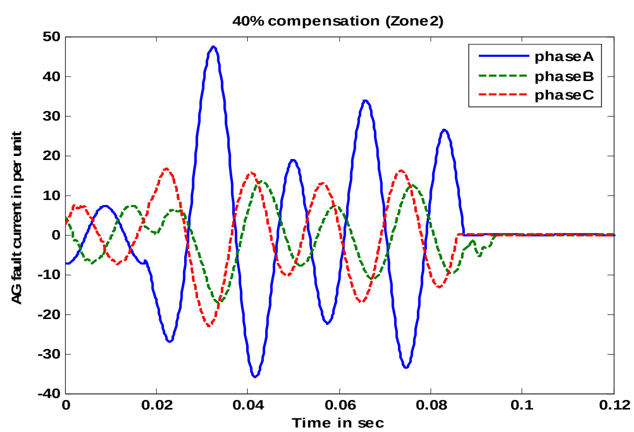

Figure 10. AG fault current-case2-40% compensation

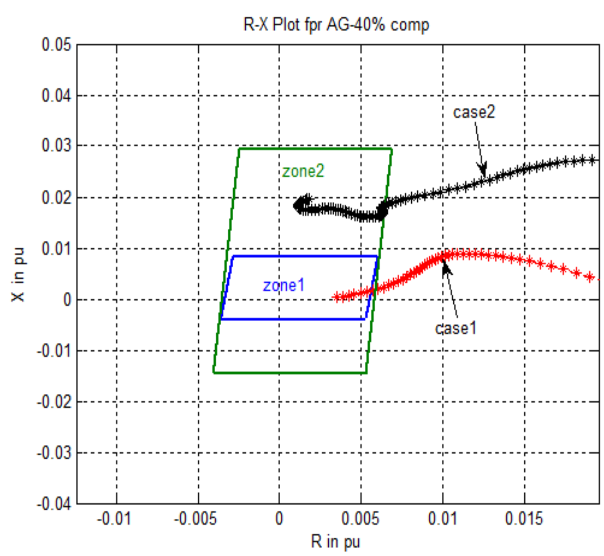

Figure 11. RX plot AG –case 1 and case 2-40% compensation

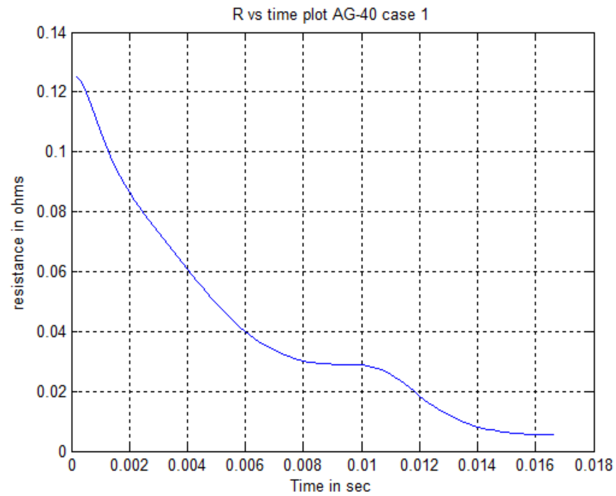

Figure 12. R Vs T plot for case 1 at 40% compensation

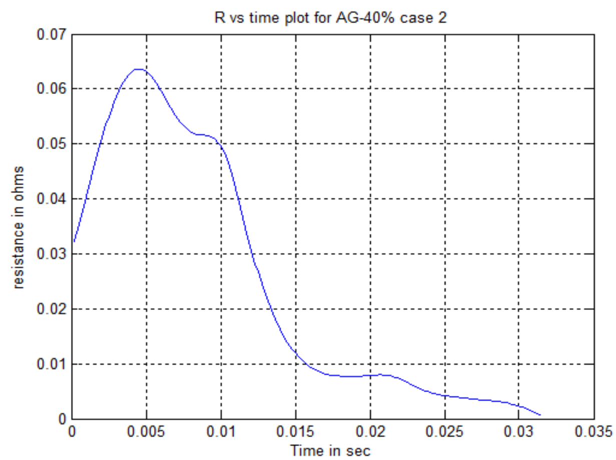

Figure 13. R Vs T plot for case2 at 40% compensation

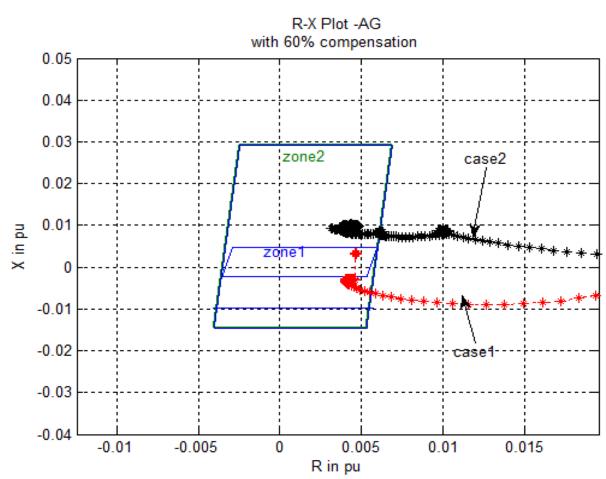

Figure 14. R X plot for case1 and case2 at 60% compensation

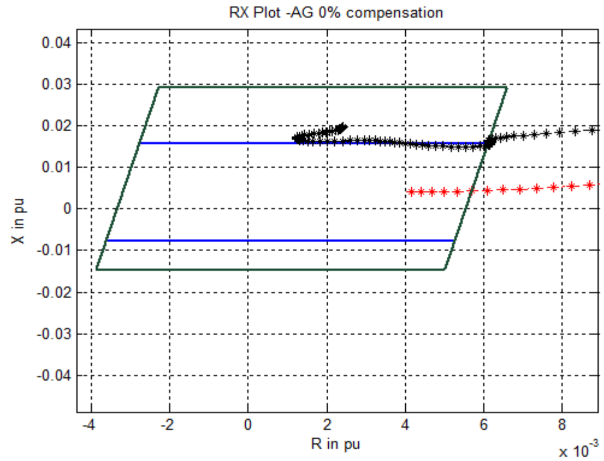

Figure 15. RX plot for case1 and case2 at 0% compensation

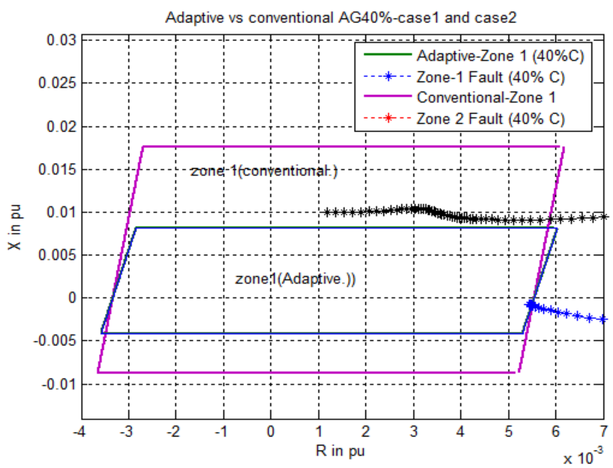

Figure 16. R X plot for Adaptive relay Vs Conventional relay for case1 and case2 at 40 % compensation

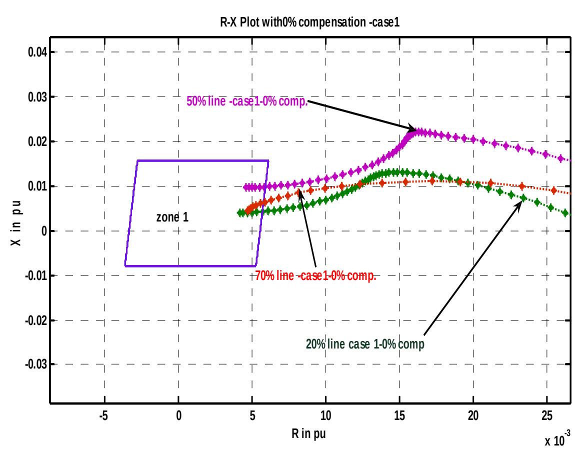

Figure 17. R X plot for Adaptive relay for case1 at 0 % compensation for varied fault distance.

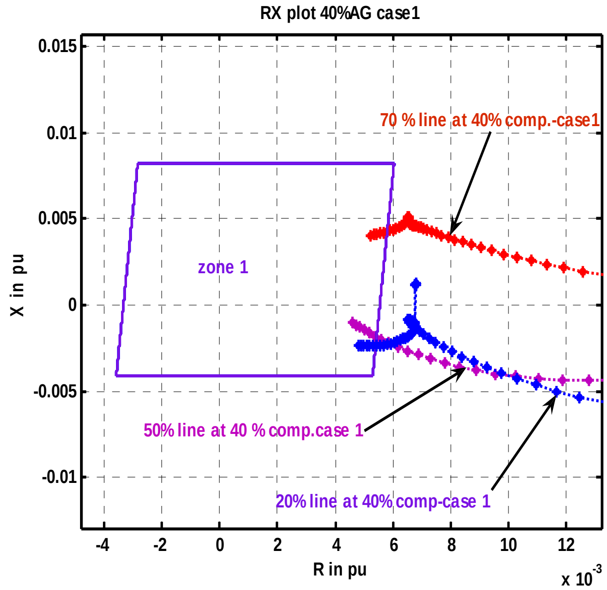

Figure 18. R X plot for Adaptive relay for case1 at 40 % compensation for varied fault distance.

Conclusions

The results illustrate the correct operation of the distance relay for the proposed scheme. The RX plots show that the relay adapts its characteristic to trip itself in the respective zones for all the three compensation levels, according to the information received on the system condition, which the conventional relay is incapable of handling. In particular, we can observe overreaching problem in Figure 16 where the conventional relay trips in zone 1 for the fault in zone 2 where as the adaptive relay trips precisely in zone 1 only for the case1 conditions as indicated by the RX plot.

Even with the fault location is changed, the relay adapts its characteristic to maintain the security of the power system.

Extensive comparative analysis made here with conventional relay proves the need of the proposed scheme in series compensated lines in the present day power system scenarios for optimum protection.

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