محور ۲: ارائه روشها و الگوریتم‌های نوین در حفاظت سیستم‌های قدرت

021025

A Novel Communication Aided Approach for Protection of Shunt Compensated Transmission Lines

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Keywords: Shunt compensation, Pilot protection, FACTS devices, Distance relay.

Abstracts

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چهارمین کنفرانس
حفاظت و کنترل
سیستمهای قدرت
4th Power Systems Protection & Control Conference
PSPC

021025

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Abstract:

Increasing the power transfer capability and efficient utilization of available transmission lines, improving the power system controllability and stability, power oscillation damping and voltage compensation make a great interest in FACTS devices in recent decades. On the other hand, the presence of these devices results in new issues in the field of power system protection. Shunt compensators are one type of FACTS devices which their effects on protection system are studied in few papers. Since there is not a robust method in the few studies which are published about the protection of shunt compensated lines, it seems necessary to find a new method in this topic. Thus, the present paper proposes a new communication aided protection scheme which uses the available signals in commercial relays. The performance of this scheme is evaluated using PSCAD/EMTDC software and presented in this paper. The simulation results reveal that this scheme has appropriate immunity respect to fault and system condition and its performance is better than the conventional pilot schemes.

1. Introduction

Power system protection is considered as the first line of defense against power system disturbances such as faults [1], therefore it is a vital requirement of power system to continuous and reliable power delivery. In the other words, a fast, accurate and reliable protection system can enhance the stable operation of power system and diminish the probability of load shedding or blackouts. Study of previous large blackouts reveals that protection system mal-operation can cause or aggravate these problems. As a result, it is very important to study the performance of the protection systems for different operating conditions and system configuration [1]. Since distance protection, due to its simple operating principle, has been widely employed for line protection, study of its performance both in stand alone or communication aided states is necessary and useful.

On the other hand, demand for electrical energy continues to grow steadily and is particularly strong in those countries on the threshold of industrialization [2]. Thus the energy production and transmission capacity of the grid should be increased while demand is growing. Although the transmission capacity increasing could be obtained by new transmission line construction, it can not keep pace with the growing power plant capacity and energy demand, for various reasons [2]. Due to this situation, system operators are interested in utilizing the existing power lines more efficiently. It also has a great importance from economical point of view. Efficient utilization of available transmission lines need to improve the transient and steady state stability especially for long lines. This is because some power lines can not be loaded to near their natural loading –let alone thermal limit rating- due to relatively low stability limits [2].

Considering the above mentioned requirements, the use of flexible AC transmission system (FACTS) controller in power system transmission has been of worldwide interest for increasing the power transfer capability and power system controllability and stability [3]. It is a new technology using power electronics for controlling the parameters of power systems to optimize the transmission flow, reduce energy losses and increase the transient/dynamic stability of the system [2]. In addition, these devices improve damping of different types of power oscillations and voltage stability [4].

Although the use of FACTS devices has different advantages, it introduces new power system issues in the field of power system protection. These issues include rapid changes in line impedance, power angle, load currents and the transients introduced by the fault occurrence and control action of FACTS devices [3].

FACTS devices can be categorized in series, shunt and shunt-series types according to how they are connected to the transmission line. These types have different applications and therefore affect the protection system differently. The effects of series FACTS devices have been studied in considerable papers [5-9]. In contrast, there are a few papers which are related to shunt FACTS impacts and only some of them have considered the FACTS controller system and its dynamic reactions.

Reference [10] has studied the performance of an impedance relay on a shunt compensated transmission line and presented the seen impedance by the relay. It also studied the effect of load angle on the relay performance. Tripping characteristic of distance relay in the presence of a STATCOM at the middle of the line has been studied in [11]. Unfortunately this article derived the required equations by modeling the shunt compensator as constant equivalent impedance. It is not an acceptable assumption because the transient behavior of the STATCOM is neglected. An investigation of various problems is discussed in [12], too.

The most important disadvantage of three above mentioned papers is that they are not considering the FACTS controller system and their dynamic during fault. Considering the recent advances in power electronic switches, the response time of FACTS controller is fast and might overlap with the protective device operating time. That is why the neglecting of FACTS controller system transient is not a correct assumption.

Elaborate model of FACTS controller system and its behavior during fault are discussed in [1, 3-4]. The impact of midpoint shunt-FACTS compensated line on the performance of only a stand-alone single distance relay was studied using EMTDC/PSCAD In [1]. In addition, some results for the performance of a single commercial relay at one bus terminal were presented for only SVC compensated system. The performance of only DCB scheme was presented in [4] and it was studied in [3] for five channel aided schemes using EMTDC/RTDS.

Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are two famous shunt compensators which are employed increasingly in transmission lines. In contrast of SVC, STATCOM has the advantage of continues compensation in low voltage of the point of connection even down to 0.15 of system voltage. It is discussed in the next section considering the characteristics of them.

The location of the shunt FACTS device depends on the application for which they are installed. Shunt compensation FACTS devices are installed at the endpoints of transmission lines (buses) when used for applications, such as, improving system stability, improving HVDC link performance etc. However, for controlling the power flow or increasing the power transfer capability of very long transmission lines (tie lines connecting two major grids) mid-point of the lines is the best location for shunt connected FACTS devices [4].

In the present study a new communication aided scheme, using the available signals in commercial relays, is proposed and its performance is evaluated under various fault and system conditions. The rest of this paper is organized as follows: section 2 reviews the SVC and STATCOM characteristics and the problems of protection systems in shunt compensated lines; the new proposed scheme is presented in section 3, section 4 contains study system and FACTS controller system model description. It also contains the simulation results. Finally, the conclusion is presented in section 5.

2. Shunt compensated line protection:

Shunt FACTS devices can have adverse effects on distance protection both in steady state and transient periods. Sever underreaching is the most important problem of relay which is caused by current injection in the point of connection to the system. Current absorption of compensator leads to overreach of relay, too. In addition, based on the simulation result of [4], the transient behavior of the controller system make protection of this line more complicated which is discussed in detail in this section.

The SVC comprises a thyristor switched capacitor (TSC) and thyristor controlled reactor (TCR) connected in parallel to the compensation point of the system. With proper co-ordination of the capacitor switching and reactor control, the reactive output can be varied continuously between the capacitive and inductive ratings [4]. The V-I characteristic of this FACTS device is depicted in Fig.1.

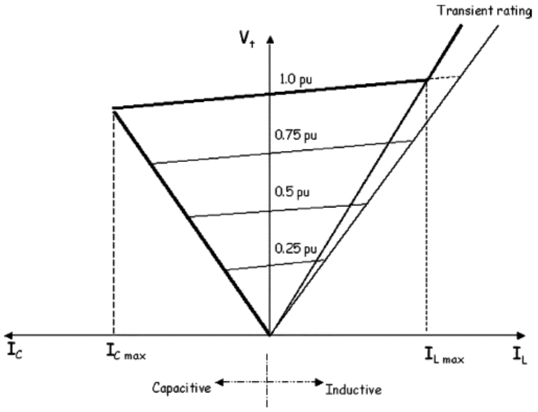


Fig.1. V-I characteristic of a SVC [13].

Depending on the operating point of the SVC, its reactance varies (the slope of the line connecting the operating point and origin in Fig.1 gives the reactance value). Once the maximum capacitive output limit of the SVC is reached, the SVC operates as a fixed capacitor. At this condition, the maximum obtainable capacitive current decreases linearly and the generated reactive power decreases as a square of the system voltage [13,14]. Thus the minimum value of the capacitive reactance is when the SVC reaches its maximum capacitive rating limit. Any further reduction in voltage will only reduce the output rating retaining a constant reactance [4].

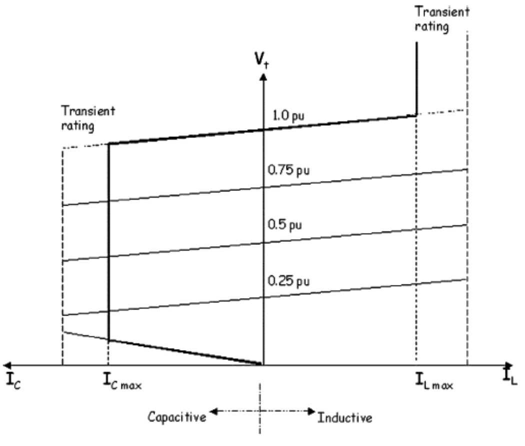


Fig.2. V-I characteristic of a STATCOM [14].

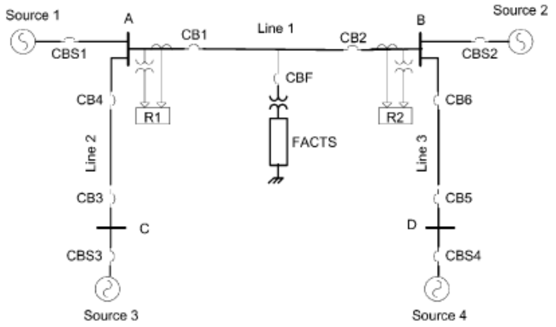


Fig.3. Single line diagram of study system [3].

Fig.2 shows the V-I characteristic of a STATCOM. This compensator is based on voltage source convertor and is able to independently control the absorbed or inserted desired reactive power to the grid irrespective of the amount of ac-system voltage. Unlike the SVC, the STATCOM can provide full capacitive reactive current independent of the system voltage up to a system voltage of 0.15 pu. This would mean that the capacitive reactance of a STATCOM could go to a very low value [13-14].

As discussed earlier, the insertion or absorption of current at the point of FACTS device connection to the system, can affect the seen impedance by the relay. The study system and the simplified faulted network are depicted in Fig.3 and Fig.4, respectively. Assuming Delta connection in one of the two sides of coupling transformer of shunt compensator, the seen impedance from the relay R1 in Fig.3 can be expressed as the following [3]:

$$Z_{\mathrm{Relay}} = mZ_{L1} + (m - 0.5)Z_{L1}\left(\frac{I_{sh}}{I_R}\right) + R_f\left(\frac{I_f}{I_R}\right) \quad (1)$$

Eq.1 implies that resistive and non-resistive fault affected by shunt compensation, differently. In the other words, solid faults are affected lower than the resistive ones. It also expresses that the impact of shunt compensation on seen impedance is directly proportional to the fault distance and the presence of the resistance in the fault loop affects both the relays on the two sides of the line. The last effect is concluded from that the fault current (I_f) is the sum of sending and receiving bus currents in addition of shunt compensator current. Since a higher degree of FACTS device contribution result in more variation of (I_f/I_R) ratio, that in turns increase the underreaching of the relay. The week infeed condition can aggravates this situation.

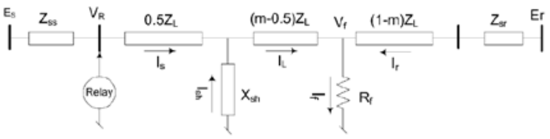
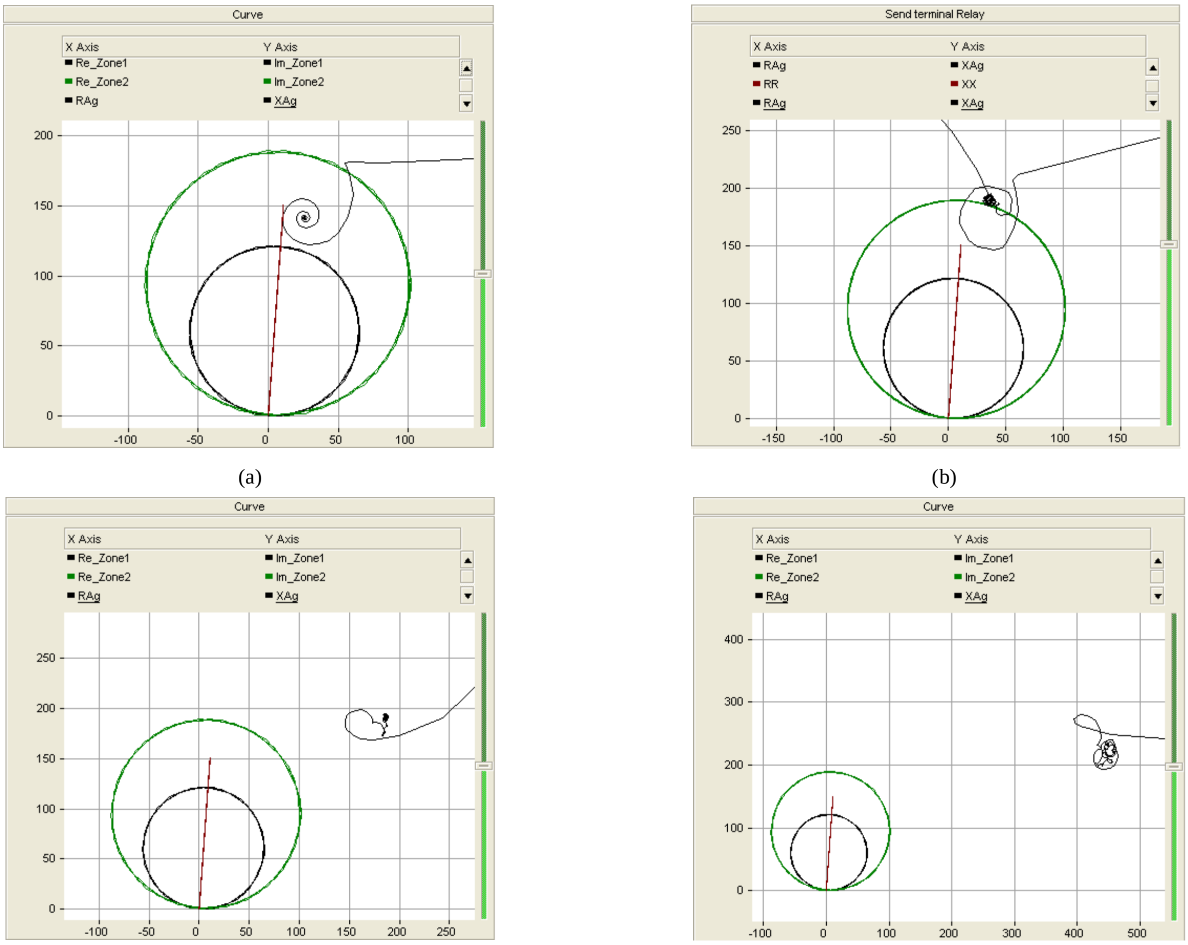


Fig.4. Simplified faulted network for study system [3].

For better understanding of the above mentioned problem, suppose a SLG fault at 90% of the line AB in Fig.5. (The system and STATCOM specifications are presented in the appendix and section 4, in details). The seen impedance for this fault without and with shunt compensation is depicted in Fig.5a and Fig.5b, respectively. The effect of current injection of compensator moves the seen impedance out of the second zone of the distance relay. Fig.5c and Fig.5d show the effect of fault resistance on apparent impedance for two different values 20 and 50 ohms, respectively.

It is obvious from the second term of the Eq.1 that in capacitive mode of operation of FACTS device, injected current increases the seen impedance and in inductive mode the current absorption diminishes the seen impedance. These two events cause the relay under reaches or over reaches respectively.

The other problem which is caused by shunt compensator is related to transient behavior of FACTS controller system. The controller system dynamic reaction maybe delays the convergence of impedance trajectory and makes the transient period of it longer and more complicated. Therefore, the seen impedance comes into the operation area of the relay for a short time and again leaves it after few samples. The relay picks up when the impedance trajectory goes to the operation area and again drops out when it moves out. Therefore a series of short time pickup and dropout of the relay occurs which maybe don't



(a) (b)

(c) (d)

Fig.5. Seen impedance by relay R1 for different Ag faults at 90% of line AB: a. Solid Ag fault without shunt compensation, b. Solid Ag fault with shunt compensation at the midpoint of the line AB, and c,d. Resistive Ag fault in presence of shunt compensator with 20and 50 ohms fault resistor, respectively.

provide appropriate conditions for the relay operation.

Even during unsymmetrical fauts, the STATCOM provides equal compensation for all three phases. This causes to increased voltages in healthy phases. The overcompensation on the healthy phase(s) during unsymmetrical fault condition shall result in increased reactive current in healthy phase(s). This disturbs the angular relationships between different sequence component current vectors and therefore increases the possibility of wrong phase selection particularly for the relays using the current based phase selection. This point was confirmed during the testing of a commercial relay in RTDS [3].

3. New proposed protection scheme

Since the standalone application of distance relay can not provide acceptable performance in some conditions, its performance is enhanced using data channels. Therefore some communication aided schemes emerged in power system protection field. They are categorized on the type of signals which is transferred between two line ends. Four conventional ones which are studied in this study are as the following:

- DUTT
- POTT
- PUTT
- DCB

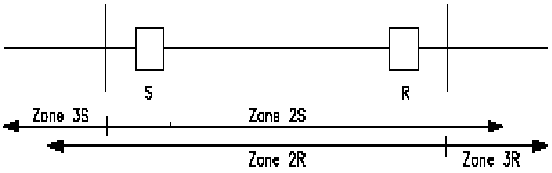


Fig.6. Protective zones used for new scheme.

Among the above schemes, DUTT is direct type which means this issues trip signal once the local or remote zone 1 element picks up. In the other words, there is not any supervision on zone 1 element and it maybe overreached for external faults.

On the other hand, POTT and PUTT schemes are two permissive ones which the received signals from the remote end only carry the permission message and they are supervised with the local signals. Utilization of the reverse zone as a blocking signal is applied in DCB scheme in which the zone 2 element signal is supervised with reverse zone signal of the remote end signal. This scheme has an inherent delay which decreases the accuracy and efficiency of it in some cases.

Based on results which are presented in [3], none of the above mentioned schemes do not have perfect operation for faults on the shunt compensated lines. Although DUTT has had the best performance in compare with the others, it also has not operated correctly in some cases. It becomes worse in case of resistive faults.

Since the under-reach problem is one of the most important difficulties in the protection of shunt compensated lines, utilization of zone2 signal instead of zone1 signal can improve this problem. On the other hand, using of zone 2 element without any supervision results in overreaching of the local relay for faults beyond the far bus. In this condition, using the reverse element signal of the remote end relay can remove the probability of overreaching of local relay. Considering the special conditions occur in shunt compensated transmission lines, preventing both the overreach and under-reach problems can not be done in some cases using one signal from the other end relay.

For better understanding, suppose an internal fault near the remote end of the line. The zones of relays are depicted in Fig.6. Regarding this figure, symbols Z2S, Z3S, Z2R and Z3R stand for “zone2S”, “zone2R”, “zone3S” and “zone3R”, respectively. There are two probable situations in this condition. The first one is related to the situation that zone 2 element picks up for this fault. Therefore the zone 2 and reverse element signal of local relay becomes “1” and “0”, respectively. In this situation the local relay can operate properly using local zone 2 element and only the reverse element signal of the remote end relay.

But if the zone 2 element becomes undereached and does not pickup for an internal fault specially near the far bus, both of Z2S and Z3S will be zero. Since this situation is similar to no fault condition, the local relay without additional signals from the remote side relay can not decide if the fault is occurred or not. In this condition only the Z2R signal can be solve the problem of the local relay.

In the two above mentioned cases, based on weather the Z2S element is undereached or not, both of Z2R and Z3R signal are required for proper operation. Thus according to these discussions the new scheme should be proposed based on the following points:

- The zone 2 element signal should be supervised using another signal like as reverse zone of the remote end relay.
- Zone 2 signal should be used in such a way that under-reaching of one relay does not affect incorrectly on the performance of the other relay.
- Local zone 2 signal should be delayed appropriately until the reverse element signal of the remote end receives to the local one.

Rely on this points the suggested scheme can be implemented using the block diagram presented in Fig.7. This scheme carry zone2 and zone3 (reveres) signal from each end to the another by using one data channel for both of the signals. In this scheme a distinct

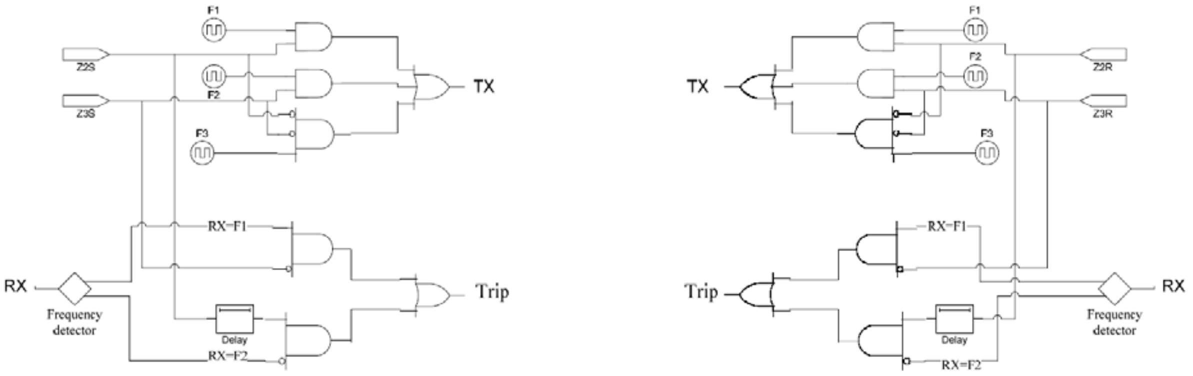
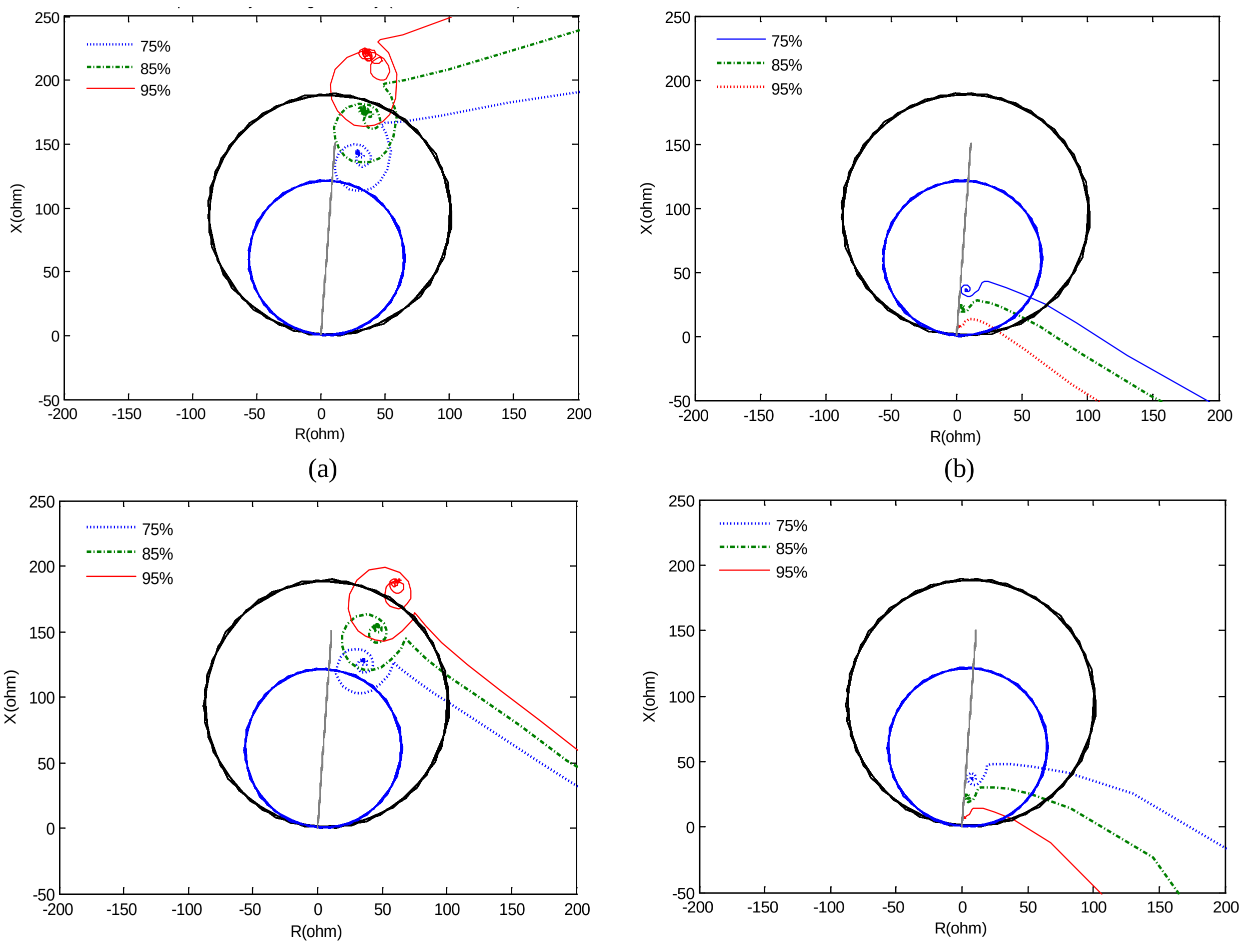


Fig.7. Block diagram of new proposed scheme

frequency is assigned for each signal instead of using segregate channel for each of them. Frequencies F1 and F2 are transferred to the other side of the line once zone 2 or zone 3 (reverse) element picks up, respectively. Another frequency is used in no fault condition for channel testing.

4. Suggested scheme performance evaluation:

In this section the performance of the new scheme is studied in various conditions and



(a) (b)

(c) (d)

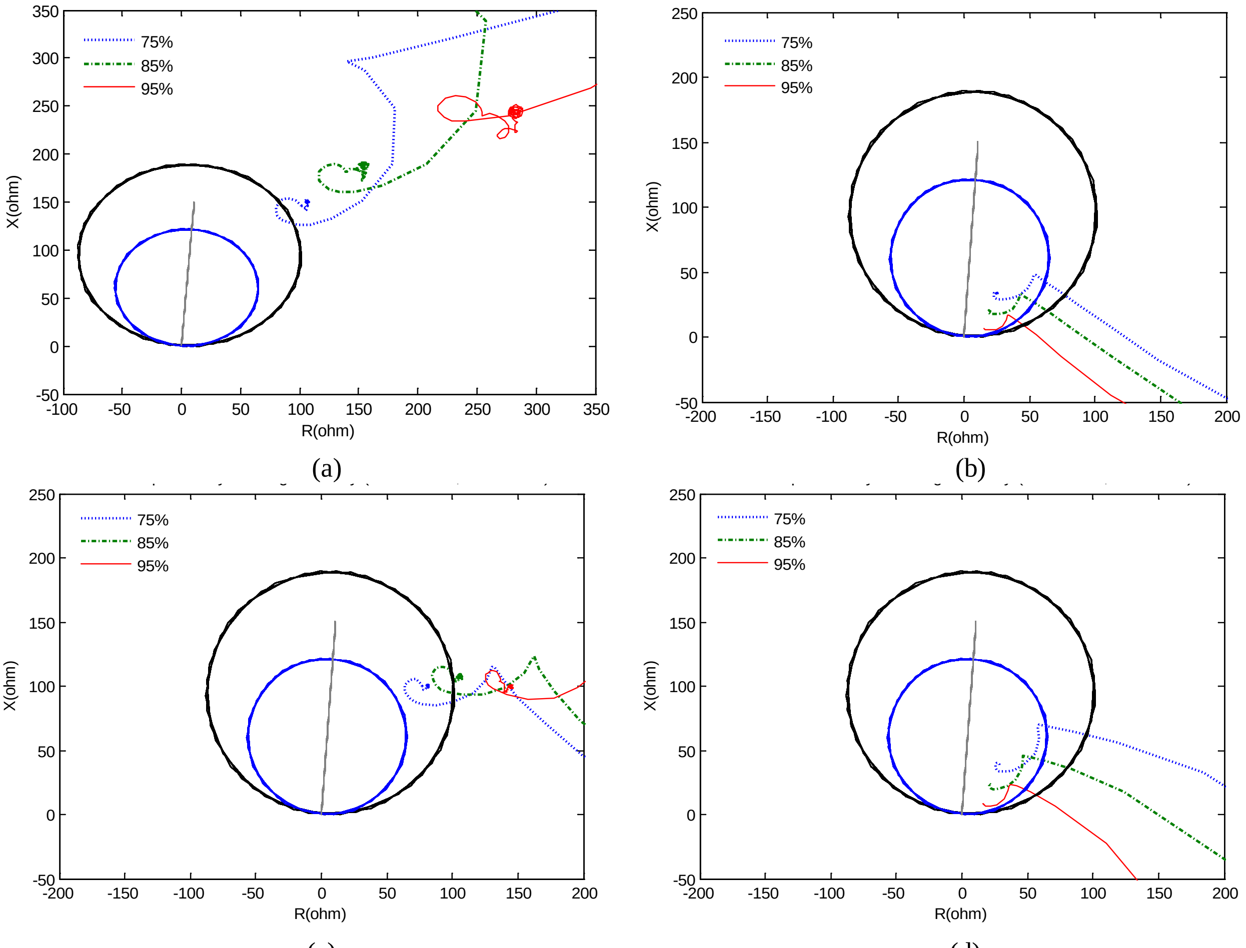
Fig.8 . Seen impedance of solid Ag fault at 75%, 85% and 95% of the line: (a) and (b) for sending and receiving end relay in 25 degree load angle and in reverse direction; (c) and (d) like (a) and (b) but for load flow in forward direction.

compared with other conventional schemes. The system was used for this study is presented earlier in Fig.3. This contains three transmission lines and four sources. A STATCOM is connected to the midpoint of the line AB. This STATCOM is composed of an inverter which is connected across a capacitor and a Wye-Delta coupling transformer is placed between the compensator and the transmission line.

The performance of the new proposed scheme and the other conventional ones are studied under various conditions. These different conditions are provided using the change of some parameters such as fault location, fault resistance, pre-fault load flow, type of fault and data channel delay time.

Since the ability of STATCOM in compare with SVC is much more and its performance is faster, its effects on the protection system is more adverse. Therefore, in this study, the performance of the proposed algorithm is studied and tested for the STATCOM compensated line.

Figures (8) and (9) show the seen impedance by both sending and receiving end buses for Ag faults in different locations, fault resistances and pre-fault loadings. More results of pilot schemes performance are presented in table 1. Fig.8 and Fig.9 reveal that the reverse pre-fault loading has more adverse effect in compare with the forward one. Also, the effect of fault resistance is highlighted in Fig.9. According to this figure, fault resistance can result in severe underreach of distance



(a) (b)

(c) (d)

Fig.9 . Seen impedance of Ag fault at 75%, 85% and 95% of the line with R_f=20 Ω: (a) and (b) for sending and receiving end relay in 25 degree load angle and in reverse direction; (c) and (d) like (a) and (b) but for load flow in forward direction.

Table 1: effect of fault resistance on the performance of pilot schemes

		Fault resistance (Ω)														
		0					20					50				
Fault Location	Fault type	New method	DCB	DUTT	POTT	PUTT	New method	DCB	DUTT	POTT	PUTT	New method	DCB	DUTT	POTT	PUTT
75%	Lg	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×
	LLg	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×
85%	Lg	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	×
	LLg	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	×	✓	×	×
95%	Lg	✓	×	✓	×	✓	✓	×	✓	×	×	✓	×	×	×	×
	LLg	✓	×	✓	×	✓	✓	×	✓	×	×	✓	×	✓	×	×

protection in shunt compensated line which is discussed earlier in section 2. In all the faults showed in figures (8) and (9) the suggested scheme has had proper performance.

Table 1 shows the performance of pilot schemes for 0, 20 and 50 ohm fault resistances. In addition, it presents the effects of Lg and LLg faults, separately. In all test cases, even for resistive ones, the new proposed scheme has had correct operation. It also operates properly in cases that DUTT scheme has not had correct performance. Comparing parts a and c with parts b and d of figures (8) and (9) reveals that although the seen impedance by sending end relay goes out of zone 2 operation area in some cases, it is still in this area for the receiving end relay. In other words, both of the sending and receiving zone 2 element do not undereach simultaneously and it is the basis of the new proposed scheme.

Table 2: Performance of pilot schemes under various faul type and channel delay time.

		Delay (cycle)														
		0					0.5					1				
Fault Location	Fault type	New method	DCB	DUTT	POTT	PUTT	New method	DCB	DUTT	POTT	PUTT	New method	DCB	DUTT	POTT	PUTT
85%	Lg	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	LLg	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	LL	✓	×	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	×
	3PH	✓	×	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓	×	✓
95%	Lg	✓	×	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	×
	LLg	✓	×	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	✓
	LL	✓	×	✓	×	×	✓	×	✓	×	×	✓	×	✓	×	×
	3PH	✓	×	✓	×	×	✓	×	✓	×	×	✓	×	✓	×	×

The performance of the proposed algorithm under various fault type and data channel delay time was evaluated and summarized in table 2. This table indicates the proper performance of proposed scheme even for 1 cycle data channel delay time.

The simulation results which are presented in this section show the appropriate immunity of new scheme respect to fault location, channel delay time and fault resistance. According to table 1, it also operates better than DUTT which has had the best performance among the conventional schemes [3]. The other advantage of proposed scheme over DUTT is the immunity of overreaching for external faults. All of these excellent features are obtained from the fact that the underreaching probability of both zone 2 elements of the two ends relays is too low, even for resistive faults.

5. Conclusion

A new pilot scheme using available signals in commercial relays was presented. The performance of this scheme under various fault condition was evaluated. The simulation results imply that the new scheme has appropriate immunity to fault type, fault resistance and other fault conditions. It has had correct operation for all the test cases even for conditions that DUTT has not operate correctly. Since the operation of STATCOM can affect the seen impedance by relay in a wide range, the utilization of adaptive mho or quadrilateral (for considering fault resistance influence) distance relay may result in considerable improvement in stand alone distance relay performance. The results in this field will be reported in future works.

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