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Wavelet Transform Based Protection of Transmission Lines with Four Quadrant Operation of STATCOM

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Abstract*: This paper proposes a new wavelet transform based relay logic for the protection of transmission lines compensated with a static synchronous compensator incorporating energy storage device (STATCOM – ES). STATCOM with energy storage systems can operate in any of the four quadrants in P – Q plane. A conventional distance relay with standard settings may not be reliable to identify and categorize short circuit faults in such systems. A simple, fast acting and reliable wavelet based relay logic is presented to accurately identify and categorize transmission line faults in shunt compensated lines. The developed relay discriminates between internal and external faults accurately. It provides reliable protection for the transmission line considering the entire four quadrant operating range of STATCOM – ES and is immune to the value of fault resistance.

Index Terms*: Fault index, line protection, STATCOM with Energy Storage, Wavelet transform.

I. INTRODUCTION

Long transmission lines normally require both series and shunt compensation to utilize the line close to its thermal limit and to improve the voltage regulation [1], [2]. For economic reasons, hybrid series – shunt compensation provided by a passive series capacitor and voltage source converter (VSC) based shunt connected STATCOM is preferred [3]. STATCOM provides provision to include an energy storage device like battery or fuel cell at its DC bus and facilitates exchange of real power with the network. Real and reactive power flow in the system can therefore be controlled in a better way [4]. However, operating region of a STATCOM with energy storage device covers all the four quadrants in P – Q plane. Angle of injected current by STATCOM – ES with respect to STATCOM bus voltage can be any angle between 0° and 360°.

Distance protection schemes are widely used to protect long transmission lines [5]. Good number of reported work is available which study the influence of various VSC based FACTS controllers on the performance of distance relay. Effect of Static Synchronous Series Compensator (SSSC) on the performance of distance relay is studied in [6]. In [7], effect of Static Var Compensator and STATCOM on the operation of distance relay is investigated and possibility of mal operation of the relay is discussed. Very little reported work is available in analyzing the impact of integrating an energy storage device at the DC bus of VSC based FACTS controllers on the performance of distance relay. Influence of Super conducting Magnetic Energy Storage (SMES) with SSSC and Unified Power Flow Controller on the performance of line protection relay is reported in [8], [9]. Reactance and resistance contribution by SSSC - ES during normal condition is presented in [10]. Adaptive distance setting to avoid the mal operation of distance relay in SSSC compensated systems is described in [11]. In [12], adaptive distance protection for STATCOM compensated systems is presented. Adaptive relay setting for lines with Unified Power Flow controller (UPFC) is discussed in [13]. However, adaptive distance relay setting for transmission lines with STATCOM – ES considering the entire four quadrant operation is practically challenging and difficult. Hence a conventional distance relay may not be reliable for such systems and may mal operate. Thus alternate methods based on wavelet transform are proposed for the protection of transmission lines. In [14], current and voltage signals at both the ends of an uncompensated line are utilized for wavelet based fault detection and classification. Adaptive threshold value selection is proposed for different values of fault resistance, which may be difficult to implement practically. Summation of wavelet detail coefficients is used for fault detection and classification of uncompensated lines in [15]. Impact of fault resistance on relay performance is not described.

Few researchers have analyzed the efficacy of wavelet transform based methods for the protection of lines compensated with VSC based FACTS controllers. In [16], Discrete Wavelet Transform (DWT) based technique is employed to detect and classify faults in SSSC compensated lines. Effect of fault resistance and operating mode of SSSC on the relay performance is not investigated. Wavelet entropy based method is proposed for the detection and classification of lines compensated with SSSC and UPFC in [17], where signals from both ends are necessary. Effect of fault resistance and operating mode of FACTS controller on the performance of wavelet based relay is not investigated.

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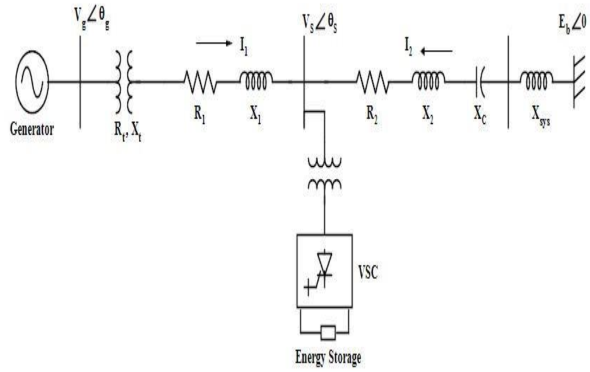
Detection and classification of transmission line faults in the presence of STATCOM using wavelet based summation index is discussed in [18]. However, effect of fault resistance and change in operating mode of STATCOM on the relay performance is not investigated. Investigations carried out in [16 – 18] mainly focusses on FACTS controllers without energy storage device. Wavelet transform based protection for the protection of lines in the case of STATCOM with energy storage device is not being reported and is carried out for the first time in this work.

II. SYSTEM MODEL

A. Test System

Fig.1 shows the test system adapted from IEEE first benchmark model. $V_g\angle\theta g$, $V_s\angle\theta s$ and $E_b\angle 0$ represent



generator terminal voltage , STATCOM bus voltage and the infinite bus voltage respectively. X_t is the transformer reactance, R_t, the resistance of transformer. R_L +j X_L ((R_1+ R_2) + j ((X_1+ X_2)) is the positive sequence impedance of the line. X_{SYS} is the system reactance on the infinite bus side.

Fig. 1 System considered for analysis

B. System model

A DQ model of STATCOM with energy storage device is employed for the analysis. A three level, twelve pulse converter is used for STATCOM.

The converter output voltage is given by,

$$V_s^i = \sqrt{{V_{sQ}^i}^2 + {V_{sD}^i}^2} \quad (1)$$

where ,$V_{sD}^i = K_m * V_{dc} * Sin(\theta_s + \alpha)$ (2)

$$V_{sQ}^i = K_m * V_{dc} * Cos\,(\theta_s + \alpha) \quad (3)$$

Where $K_m = K*\cos\beta$; $K = \frac{2\sqrt{6}}{\pi}$ for a 12 pulse converter.

Angle of STATCOM bus voltage,

$$\theta_s = tan^{-1}(\frac{v_{sD}}{v_{sQ}}) \quad (4)$$

STATCOM bus voltage,

$$V_s = \sqrt{V_{sQ}^2 + V_{sD}^2} \quad (5)$$

$$\frac{di_{sD}}{dt} = -\frac{R_s\,\omega_B}{X_s}\, i_{sD} - \omega_0\, i_{sQ} + \frac{\omega_B}{X_s}\left[v_{sD} - v_{sD}^i\right] \quad (6)$$

$$\frac{di_{sQ}}{dt} = -\frac{R_s\,\omega_B}{X_s}\, i_{sQ} + \omega_0\, i_{sD} + \frac{\omega_B}{X_s}\left[v_{sQ} - v_{sQ}^i\right] \quad (7)$$

Real current (I_P) and reactive current (I_R) injected by STATCOM-ES,

$$I_P = I_{sD}\, Sin\,\theta + I_{sQ} Cos\theta \quad (8)$$

$$I_R = -I_{sD}\, cos\,\theta + I_{sQ} Sin\theta \quad (9)$$

Here 'θ' is the angle of STATCOM current.

It should be noted that, positive I_P implies STATCOM – ES drawing real power and positive I_R specifies inductive mode of operation of STATCOM – ES.

Real and reactive power of STATCOM – ES,

$$P_s = I_{sD} * V_{sD}^i + I_{sQ} * V_{sQ}^i \quad (10)$$

$$Q_s = I_{sQ} * V_{sD}^i - I_{sD} * V_{sQ}^i \quad (11)$$

C. Control strategy for STATCOM - ES

Type 1 controller shown in Fig. 2 is used for STATCOM – ES in the present work. As shown, here reference for I_P is obtained from real power controller. I_R is either kept constant or is adjusted to maintain V_S at the desired value. It should be noted here that, when STATCOM – ES draws real power from the network, P_{ref} is positive and when it supplies real power, P_{ref} is negative.

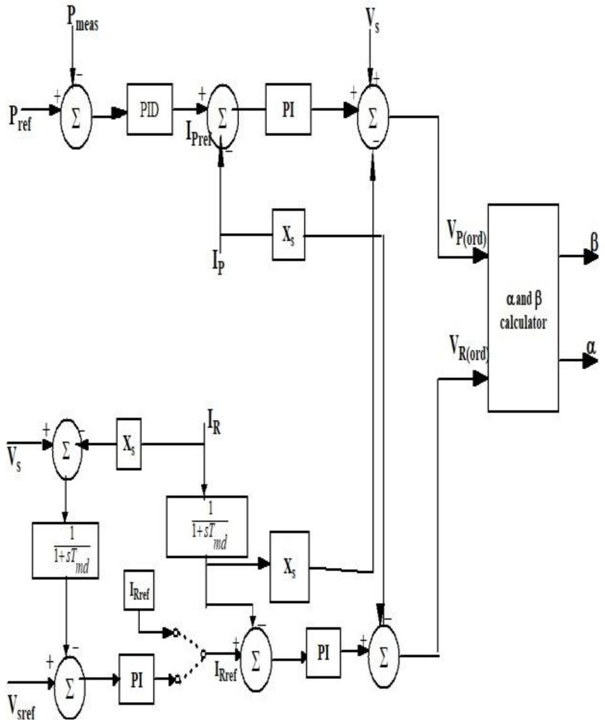


Fig. 2 Control strategy for STATCOM – ES

Necessary values of phase angle 'α' and dead angle 'β' are calculated as,

$$\alpha = \tan^{-1}\left(\frac{V_{R(ord)}}{V_{P(ord)}}\right) \quad (12)$$

$$\beta = \cos^{-1}\left(\frac{\sqrt{V_{P(ord)}^2 + V_{R(ord)}^2}}{k*V_{dc}}\right) \quad (13)$$

D. Operating modes and range of STATCOM - ES

As mentioned already, operating region of STATCOM with energy storage device encompasses all the four quadrants in P – Q plane and is a circle. Possible operating modes in each of these four quadrants is mentioned below.

- I quadrant: Capacitive mode, absorbing real power.
- II quadrant: Capacitive mode, supplying real power.

- III quadrant: Inductive mode, supplying real power.
- IV quadrant: Inductive mode, absorbing real power.

Rating of the STATCOM is considered as 150MVA. Hence, on a base of 892.4MVA, assuming $|V_S|$ of 1 pu, STATCOM can inject a maximum current (magnitude) of 0.1681 pu. In the various case studies considered for analysis, reactive and real power exchange by STATCOM – ES are selected such that STATCOM operates with in its rated capacity.

E. Wavelet transform

Fourier transform gives information about frequency components in a time varying signal. However, it does not provide time information. Short Time Fourier Transform provides both time and frequency information, but has a limitation of fixed window length. Selecting a suitable window length to obtain better time and frequency resolution simultaneously is very difficult. Thus wavelet transform which uses a varying window length i.e. short window length for high frequencies and large window for small frequencies is better suited for the analysis of non-stationary signals like fault current and voltage.

A mother wavelet with short duration is preferred for the analysis of transient fault current and voltage signals. Daubechies (DB) series mother wavelets are best suited for detecting transients associated with fault events as the associated transforms are fast, stable and accurate [19]. DB5 mother wavelet closely resembles fault current signal and hence DB5 is considered as the mother wavelet in the present work.

Multiresolution discrete wavelet transform analysis is used to decompose the three phase currents at the relay location to approximate and detail coefficients. In this work, sampling frequency used is 24Khz. Detail coefficients at level 3 (frequency band of 1501 – 3000Hz.) is used to determine the fault index which helps to detect classify short circuit faults.

III. METHODOLOGY

A. *Fault index*

In this work, L1 norm based summation fault index for the reconstructed three phase current signals using wavelet detail coefficients at level 3 is used to accurately detect and classify line faults.

For a continuous time varying signal, u(t), L1 norm is defined as

$$\|u\|_1 = \int_{-\infty}^{\infty}|u(t)|\ dt \tag{14}$$

Similarly, for a discrete time signal, u(n),

$$|u|_1 = \sum_{n=i}^{i+N} |u(n)| \tag{15}$$

where 'N' is the number of samples over a desired time period.

L_1 norm based fault index for phase 'A' current is defined as,

$$I_{afi} = \sum_{n=1}^{N}|DI_{a3}(n)| \tag{16}$$

Where DI_{a3} is the phase 'A' current, reconstructed using wavelet detail coefficients at level 3 and 'N' is the number of samples over half a cycle of power frequency. In a similar way fault index for phase 'B' and phase 'C' currents, I_{bfi} and I_{cfi} are determined.

B. Algorithm for wavelet based detection and classification of line faults

- Select the desired operating mode for STATCOM- ES
- Obtain the three phase current signals at the relay location.
- Decompose the current signals using multi resolution wavelet analysis with DB5 mother wavelet.
- Use detail coefficients at level 3 to obtain L_1 norm summation fault indices for the three current signals.
- Compare the fault index values with the selected threshold values to detect and classify fault.
- Compute zero sequence current and compare it with the selected threshold value to detect ground faults.
- Compare the fault index value with the relay zone boundary threshold value for the detected fault type, to discriminate between within and outside zone faults.

IV. RESULTS

A. *Fault index*

Table 1 to 4 show the L1 norm fault summation fault index computed using equation (16) for the following operating conditions.

Case 1: Normal condition

Case 2: Symmetrical and unsymmetrical faults at 20%-line length with STATCOM – ES in capacitive mode and no real power exchange (Qs = -0.16248, Pref = 0)

Case 3: Symmetrical and unsymmetrical faults at 60%-line length with STATCOM – ES in capacitive mode and no real power exchange (Qs = -0.16248, Pref = 0)

Case 4: Double line to ground (ABG) fault at 60%-line length with various operating modes of STATCOM – ES.

Table. 1 Fault index under normal condition

Operating mode	**I_{afi} (pu)**	**I_{bfi} (pu)**	**I_{cfi} (pu)**
No STATCOM	$2.37*10^{-6}$	$2.37*10^{-6}$	$2.37*10^{-6}$
Qs = -0.11094, Pref = 0.08	$2.35*10^{-6}$	$2.35*10^{-6}$	$2.35*10^{-6}$
Qs = 0.11094, Pref =- 0.08	$2.38*10^{-6}$	$2.38*10^{-6}$	$2.38*10^{-6}$

It is seen from table 1 that fault index values of all the three currents during normal condition, when there is no fault are negligibly small and are almost independent of the operating mode of STATCOM – ES.

Table. 2 Fault index for fault at 20%-line length

Fault type	**I_{afi} (pu)**	**I_{bfi} (pu)**	**I_{cfi} (pu)**
3 Phase	**0.050025**	**0.1338**	**0.083848**
LLG (ABG)	**0.056954**	**0.12687**	$78*10^{-5}$
LL(AB)	**0.091896**	**0.091971**	$9.436*10^{-5}$
SLG (BG)	$13.63*10^{-4}$	**0.12161**	$13.63*10^{-4}$

It is to be noted that fault index values computed using wavelet detail coefficients for half a cycle of power frequency, after the occurrence of fault are tabulated in table 2 to 8. It is interesting to note that fault index values of faulty phases, during fault are substantially higher than those of healthy phases.

Table. 3 Fault at 60%-line length, Qs = -0.16248, Pref = 0

Fault type	I_{afi} (pu)	I_{bfi} (pu)	I_{cfi} (pu)
3 Phase	**0.0059317**	**0.057199**	**0.056902**
LLG (ABG)	**0.0063827**	**0.051128**	$20*10^{-5}$
LL(AB)	**0.028747**	**0.028802**	$8.291*10^{-5}$
SLG (BG)	$21.23*10^{-5}$	**0.050341**	$21.64*10^{-5}$

It is interesting to note from table 3 that as the distance of fault on the line from the relay location is increased, fault index values of faulty phases are decreased. They are however, much higher than those of healthy phase fault indices.

Table. 4 LL(AB) Fault at 60%-line length, Effect of operating mode

Operating mode	I_{afi} (pu)	I_{bfi} (pu)	I_{cfi} (pu)
No STATCOM	**0.028782**	**0.028845**	$4.965*10^{-5}$
Qs= - .16248, Pref = 0	**0.028747**	**0.028802**	$8.291*10^{-5}$
Qs= .1569, Pref = 0	**0.028864**	**0.028922**	$10.76*10^{-5}$
Qs= - .11094, Pref = 0.1	**0.028673**	**0.028814**	$20.91*10^{-5}$
Qs= .11094, Pref = -0.1	**0.028977**	**0.028924**	$14.90*10^{-5}$

It is observed from table 4 that for a given fault type and fault location, fault index of faulty phases does not change significantly with the change in operating mode of STATCOM - ES. This is due to the fact that STATCOM – ES does not contribute significantly to the high frequency component in the current signal.

B. *Fault index threshold values for fault detection and classification*

I_{afi}, I_{bfi} and I_{cfi} values are computed for all possible fault type with various operating modes of STATCOM –ES, at varying line length covering the entire zone of operation of the relay. By analyzing these values, considering maximum fault index of healthy phases and minimum fault index of faulty phases during fault, threshold values It_{ha}, I_{thb} and I_{thc} are selected such that

- If I_{afi}, I_{bfi} and I_{cfi} are less than their respective threshold values, it is identified as normal (no fault) condition, else it is identified as a fault condition.
- In the case of fault condition, fault index values higher than respective threshold are identified as faulty phases and rest are healthy phases.

Threshold selected for fault index of three currents are

$I_{tha} = 25 * 10^{-4}$, $I_{thb} = 25 * 10^{-4}$ and $I_{thc} = 25 * 10^{-4}$.

With these threshold, the developed wavelet based relay logic is tested with various test cases and the results obtained are encouraging. The wavelet based relay is very accurate in detecting short circuit faults and identifying faulty phases. Two sample results are shown in Fig.3 and Fig.4.

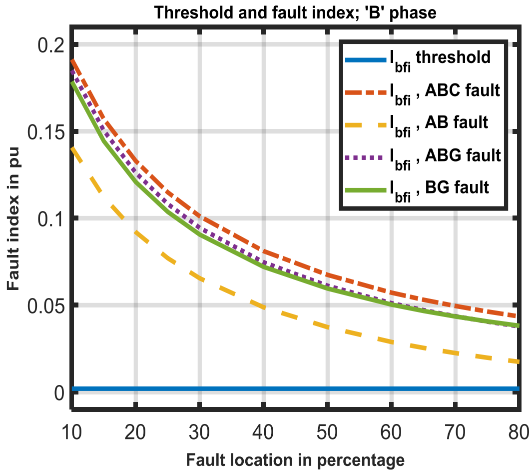


Fig. 3 Fault index for faulty phase

Fig.3 shows I_{thb} and I_{bfi} values with symmetrical and unsymmetrical faults. Note that in all the (four) fault types considered 'B' is a faulty phase. It is interesting to note that computed fault index is more than the threshold for all four fault type and for fault anywhere in the entire zone of operation of the relay. Hence the relay identifies faulty phase accurately.

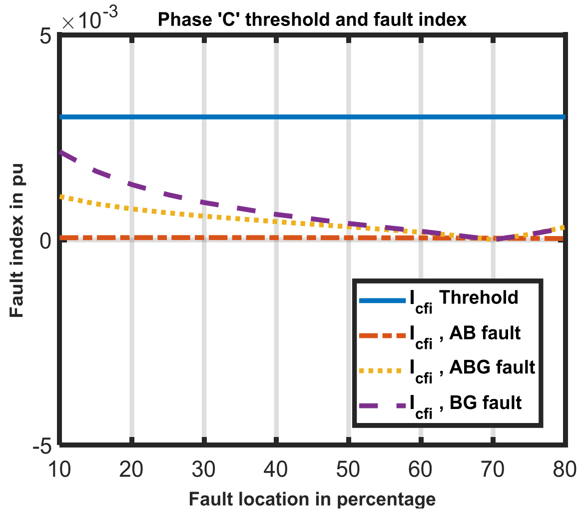


Fig. 4 Fault index for healthy phase

Fig.4 shows I_{thc} and I_{cfi} values with symmetrical and unsymmetrical faults. Note that in all the (three) fault types considered 'C' is a healthy phase. It is interesting to note that computed fault index is less than the threshold for all three fault type and for fault anywhere in the entire zone of operation of the relay.

Hence the relay identifies healthy phase correctly.

C. *Detection of Ground faults*

To determine whether the line fault involves ground or not, zero sequence component of current is determined using equation (17).

$$I_0 = \frac{I_{a1} + I_{b1} + I_{c1}}{3} \qquad (17)$$

Digital mimic impedance based filter is used to remove the DC offset from fault current [20] and Discrete Fourier Transform is used to compute fundamental, positive sequence components of phase currents, I_{a1}, I_{b1} and I_{c1} [21]. Negligible value of I_0 during fault signifies that fault does not involve ground.
The developed relay logic is able to detect ground faults with 100% accuracy. A sample result is shown in table 5. It is found that I_0 is negligibly small in the case of faults not involving ground and is substantially high in case of ground faults.

Table. 5 Fault at 40%-line length, Ground fault detection

Qs= - .11094, Pref = 0.1

Fault type	I_{afi} (pu)	I_{bfi} (pu)	I_{cfi} (pu)	I_0 (pu)
3 Phase	**0.015**	**0.081**	**0.066**	$46*10^{-9}$
LLG (ABG)	**0.022**	**0.074**	$4.8*10^{-4}$	**0.553**
LL(AB)	**0.048**	**0.048**	$2.4*10^{-4}$	$1.6*10^{-5}$
SLG (BG)	$6.6*10^{-4}$	**0.072**	$6.9*10^{-4}$	**0.697**

D. *Discriminating internal and external faults*

Zone 1 reach of wavelet based relay is considered to cover 80%-line length from relay location. Fault index value during fault for each fault type at the boundary of zone operation is taken as the boundary threshold. If the computed fault index is more than the threshold, it is an internal fault, else it is an external fault. Zone boundary fault index (for I_{bfi}) is tabulated in table 6 for the following operating modes of STATCOM – ES.

Case 1: NO STATCOM
Case 2: QS = -0.11094, Pref = 0.1
Case 3: QS = 0.11094, Pref = - 0.1

Table. 6 Relay Zone boundary condition fault index

Operating mode → / Fault type ↓	Case 1	Case 2	Case 3	Average value
3 Phase	0.0434	0.0430	0.04407	**0.043549**
LL(AB)	0.0174	0.0175	0.0173	**0.017437**
LLG (ABG)	0.0377	0.0374	0.03816	**0.037784**
LG (BG)	0.0381	0.0377	0.03862	**0.038184**

Having separate threshold for various operating modes of STATCOM – ES is practically not feasible. Hence average value of zone boundary fault index for each fault type shown in the last column of table 6 is used as the threshold, irrespective of the operating mode of STATCOM – ES. Efficacy of wavelet based relay in discriminating internal and external faults is tested considering various operating modes of STATCOM –ES with symmetrical and unsymmetrical faults. Relay output for the following operating modes of STATCOM – ES is shown in table 7.

Case 1: No STATCOM
Case 2: Qs = - 0.16248, Pref = 0
Case 3: Qs = 0.1569, Pref = 0
Case 4: Qs= - 0.11094, Pref = 0.1
Case 5: Qs = 0.11094, Pref = - 0.1

Table. 7 Under reach and over reach with wavelet based relay

	Wavelet based Relaying algorithm output				
	Fault at 78%	Fault at 79%	Fault at 80%	Fault at 81%	Fault at 82%
Case 1	Within zone	Within zone	**Outside zone**	Outside zone	Outside zone
Case 2	Within zone	**Outside zone**	**Outside zone**	Outside zone	Outside zone
Case 3	Within zone	Within zone	Within zone	**Within zone**	Outside zone
Case 4	Within zone	**Outside zone**	**Outside zone**	Outside zone	Outside zone
Case 5	Within zone	Within zone	Within zone	**Within zone**	Outside zone

It is observed from table 7 that, relay under reaches and does not operate in the case of capacitive mode and capacitive mode with absorbing real power. Similarly, it over reaches in the case of inductive mode and inductive mode with supplying real power. However, the under reach and over reach is less than 2%, considering the entire four quadrant operation of STATCOM – ES, which is negligible

E. *Impact of fault resistance*

One of the major problem with conventional distance relaying is that the measured impedance by the relay changes significantly with the increase in the value of fault resistance, R_F. Four quadrant operation of STATCOM –ES coupled with high value of fault resistance may lead to unreliable operation of the distance relay. Immunity of wavelet based relay to fault resistance is tested by considering different values of fault resistance for various operating modes of STATCOM –ES, fault type and fault location. Results obtained showed that the impact of fault resistance on the performance of wavelet based relay is negligible.

A sample result for a three phase fault at 50%-line length from relay location, with STATCOM – ES operating in third quadrant i.e. inductive mode, supplying real power (Q_S = 0.11094, P_{ref} = -0.1) with four different values of R_F is shown in table 8.

Table. 8 Impact of fault resistance on relay performance

R_F (Ω)	I_{afi} (pu)	I_{bfi} (pu)	I_{cfi} (pu)
0	0.006668	0.06704	0.060391
2	0.0066712	0.06706	0.060409
5	0.0066761	0.06709	0.060436
10	0.0066844	0.067139	0.060482
15	0.0066926	0.067187	0.060527

It is interesting to note that the change in fault index values with increase in value of fault resistance is negligible and hence the developed wavelet based relay is immune to fault resistance.

F. *Performance of wavelet based relay*

The efficacy of the developed wavelet based relay logic is tested with 2400 test cases, considering all 10 possible fault types at different locations, five operating modes of STATCOM - ES and with four different values of R_F. Results obtained showed that the proposed relay logic is able to detect fault with 100% accuracy and identify faulty phases with 98.5% accuracy. Few sample relay output are shown below.

Case 1: Symmetrical fault at 10%-line length, No STATCOM, $R_F = 0\ \Omega$

```
Fault index values During fault
0.090018      0.19124      0.10134
Zero Sequence current :1.6353e-10
Type of Fault: Symmetrical fault
Trip all 3 breaker poles
Fault with in Zone1
```

Case 2: Single line to ground (AG) fault at 35%-line length, $Q_S = -0.16248$, $P_{ref} = 0$, $R_F = 5\ \Omega$

```
Fault index values During fault
0.019542   0.00018823   0.00019416
Zero Sequence current: 0.74374
Type of fault: Unsymmetrical fault
Faulty Phase: A
Trip breaker pole A only
Fault involves ground!
Fault with in Zone1
```

Case 3: Double line (BC) fault at 55%-line length, $Q_S = 0$, Pref = 0.15, $R_F = 10\ \Omega$

```
Fault index values During fault
0.00013359      0.06021      0.060228
Zero Sequence current: 1.1669e-05
Type of Fault: Unsymmetrical fault
Faulty Phases: B and C
Trip breaker poles B and C only
Fault with in Zone1
```

Case 4: Double line to ground (ABG) fault at 82%-line length, $Q_S = 0.11094$, Pref = -0.1, $R_F = 15\ \Omega$

```
Fault index values During fault
0.0044859      0.037278   0.00046259
Zero Sequence current: 0.13279
Type of Fault: Unsymmetrical fault
Faulty Phases: A and B
Trip breaker poles A and B only
Fault involves ground!
Fault outside Zone1
```

V. CONCLUSION

In this paper a new wavelet transform based relay logic is developed for the protection of STATCOM – ES compensated lines, using L1 norm summation fault index for the three phase currents at the relay location. Wavelet detail coefficients of just half a cycle of power frequency is sufficient to compute fault index values and hence the relay logic developed is very fast. The results obtained through various case studies indicate that the wavelet based relay is highly accurate in detecting short circuit faults and identifying faulty phases. It discriminates between internal and external faults with less than 2% error. It provides reliable protection for the transmission line considering the entire four quadrant operating range of STATCOM – ES and is immune to fault resistance. Reliable operation of the relay is ensured without changing relay settings corresponding to change in operating mode of STATCOM – ES. Implementation of the proposed wavelet based relay logic helps in utilizing STATCOM in any of the four quadrants to its rated capacity, ensuring reliable protection and transiently stable system, in the event of short circuit line faults.

APPENDIX

Test system is adapted from IEEE first benchmark model

System Data (All values in pu; Base MVA = 892.4, Base Voltage = 500KV).

Generator data

$R_a = 0$; $X_d = 1.79$; $X_q = 1.71$; $X_d' = 0.169$; $X_d'' = 0.135$; $X_q' = 0.228$; $X_q'' = 0.2$; $T_d' = 0.4$; $T_d'' = 0.0259$; $T_q' = 0.1073$; $T_q'' = 0.0463$; $f = 60$; $H = 5$; $D = 0$;

Transmission system data

$R_t = 0.0$; $X_t = 0.14$; $R_L = 0.04$; $X_L = 1$; $X_c = 0.45$; $X_{sys} = 0.06$; $V_g = V_g\angle\theta$; $E_b = 1\angle 0$;

STATCOM data: 150MVA; $R_s = 0.01$; $X_s = 0.15$; $V_{dc} = 0.7$

REFERENCES

1. K.R. Padiyar, *FACTS controllers in Power transmission and Distribution*, New Age International, 2008.
2. N.G. Hingorani and L. Gyugyi, *Understanding FACTS*, New York: IEEE press, 2000.
3. K.R. Padiyar and Nagesh Prabhu "Design and Performance Evaluation of Sub Synchronous Damping Controller with STATCOM", *IEEE Transactions on Power Delivery*, Vol. 21, NO. 3, July 2006
4. Zhiping Yang, M.L. Crow, Chen Shen, Lingli Zhang, "The steady state characteristics of a STATCOM integrated with energy storage'", *in proc. IEEE Power engineering society summer meeting*, July 2000.
5. Ravindra P. Singh, *Digital Power System Protection*, PHI, 2007.
6. Jamali, S., Shateri, H., "Locus of apparent impedance of distance protection in the presence of SSSC", *European Transactions on Electrical Power*, vol.21, Issue 1, pp. 398-412, 2011.
7. A. H. Mohammadzadeh, I. Dabhagiyan Amiri, "The impact of shunt FACTS devices on distance relay performance", 2nd *IEEE International Conference on Knowledge-Based Engineering and Innovation* (KBEI), November 2015.
8. A. Kazemi, S. Jamali and H. Shateri, "Effects of SMES Equipped SSSC on Distance Relay Tripping Characteristic", *Transmission and Distribution Conference and Exposition, IEEE/PES*, April 2008.
9. S. Jamali, A. Kazemi and H. Shateri, "Effect of SMES Equipped UPFC on Distance Relay Tripping Characteristic", *Power System Technology and IEEE Power India Conference, POWERCON*, 2008.

10. .V. Gururaja Rao, Dr. Nagesh Prabhu, R.C. Mala, "Emulated reactance and resistance by a SSSC incorporating energy storage device", *International Journal of Electrical and Computer Engineering* (IJECE), Vol. 9, No. 2, April 2019, pp. 840~850
11. Koteswara Raju Dhenuvakonda, Arvind Singh, Mohan P. Thakre, Raghavendra Reddy, Karasani Raj Naidoo, "Adaptive digital distance relay for SSSC-based double-circuit transmission line using phasor measurement unit", *International Transactions on Electrical Energy Systems*, Vol. 29, Issue 4, April 2019.
12. Sham M V, Chethan K S and K P Vittal," Development of adaptive distance Relay for STATCOM Connected Transmission Line", *IEEE PES Innovative Smart Grid Technologies* – India, 2011.
13. Mehrjerdi, H., Ghorbani, A," Adaptive algorithm for transmission line protection in the presence of UPFC", *International Journal of Electrical Power and Energy Systems*, vol. 91, 1, pp. 10-19, October 2017.
14. Valsan S. P, Swamy K.S, "Wavelet transform based digital protection for transmission lines", International journal of electrical power and energy systems, vol.31, Issue 7-8, pp. 379 – 388, Sept.2009.
15. Jaya Bharata reddy, M. Venkata Rajesh, D. Mohanti, "Robust transmission line fault classification using wavelet multi resolution analysis", *Computer and electrical Engineering*, vol.39, Issue 4, pp.1219 – 1227, May 2013.
16. Geetanjali M, Alias M.A, Pandy T.K.S, "Discrete wavelet transform based fault detection and classification in a static synchronous series compensated transmission system", *Advances in intelligent systems and computing*, vol.258, pp. 85 – 94, 2014.
17. El. Zankoly A.M, Desovic H, "Wavelet entropy based algorithm for fault detection and classification in FACTS compensated transmission lines", *International journal of electrical power and energy systems*, vol.33, Issue 8, pp.1368 – 1374, October 2011.
18. Rao P. V, Gefoor S.A, Venkatesh, "Detection of transmission line faults in the presence of STATCOM using wavelets", *IEEE India conference, INDICON*, December 2011.
19. Jittiphong Klomjit, Atthapol Ngaopitakkul, Bancha Sreewirote, "Comparison of mother wavelet for classification fault on hybrid transmission line systems", *IEEE 8th International Conference on Awareness Science and Technology* (iCAST), Taiwan, November 2017.
20. Rahul kirpane, P.P. Bedekar, "Removal of DC offset using digital mimic filtering technique", *IEEE International Conference on Global Trends in Signal Processing, Information Computing and Communication*, December 2016.
21. Kumarraja Andanapalli, Nazeer Shaik, Srinivas Vudumudi, Bhanu Chandar Yenugu, "Fault Detection, Classification and Location on Transmission Lines using Fundamental Phasor Based Approach", *International Journal of Recent Technology and Engineering (IJRTE)* , Volume-8 Issue-1S3, June 2019.

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