Abstract—Although the shunt Flexible AC Transmission System (FACTS) devices improve voltage profile, Shunt FACTS Devices (SFDs) may mal-operate the protection schemes due to reactive power injection. This study presents a phasor estimation-based pilot relaying for the SFD-compensated line. For a loaded line, the phase difference between the shunt FACTS device voltage and current is close to -90° as it injects the reactive power. However, it also draws small active power to meet the losses which deviates the working angle of SFD towards positive direction by some angle. Hence, the working angle of SFD depends on active and reactive power. During normal operation, this working angle can be estimated at both the relay locations. However, it is not possible to estimate exact working angle of shunt FACTS device at both the relay locations during an internal fault. The analysis reveals that estimated phase angle will largely tend towards positive direction during an internal fault. This criterion has been used to distinguish internal and external faults. The proposed relaying is robust against all real limits. Furthermore, the scheme is unaffected by the dynamics of SFD.

Keywords—Estimated phase angle, pilot protection, shunt compensation, transmission line

I. INTRODUCTION

Different types of Flexible AC Transmission System (FACTS) devices are used for different purposes in the transmission systems. The Shunt FACTS Devices (SFDs) are used to improve voltage profile and to push more power through the transmission line. To achieve these objectives, SFD injects reactive power into the transmission line. The variable shunt compensation creates a large number of issues in protection schemes due to its dynamic nature. Impacts of Static Compensator (STATCOM) and Static VAR Compensator (SVC) have been discussed in [1]-[5]. Distance relays are mostly used to protect the long transmission lines. Nevertheless, in the presence of shunt device, distance relay may mal-operate due to under-reaching/over-reaching effect [6]. To avoid these adverse effects of under/over-reaching, unit protection (a kind of pilot protection) can be employed in the transmission line.

The conventional differential current scheme is found susceptible to the high resistance faults [7]-[10]. A pilot-based relaying algorithm for SVC-compensated line has been proposed in [10] which is able to detect even high resistance faults. Nonetheless, complete knowledge of power system is required which makes the relaying vulnerable to the system changes (as equivalent source impedance of the power system may change time to time). In [11], [12], cross differential protection of shunt-compensated line has been proposed using Fast Discrete S-Transform. However, the scheme is applicable to a double circuit line only as scheme uses cumulative differential signal (which depends on the current difference between two parallel lines). In [13], [14], adaptive distance protection settings have been obtained using synchronized phasors of local and mid-point. Conversely, only single-phase faults have been taken into consideration. An Artificial Neural Network-based (ANN-based) protection scheme is proposed in [15], which is quite accurate. However, it requires lots of computational efforts and training data. Further, with small changes in the network, the ANN-based scheme has to be re-trained. A fault location estimation method has been proposed in [16] which uses unsynchronized measurements of both the ends. Both the series and shunt-compensated line have been considered to find the fault location. Nonetheless, fixed shunt reactor was used for shunt-compensated line.

To address these limitations, this study presents a new pilot relaying scheme for mid-point shunt FACTS-compensated line. The SFD always deals with the reactive power and to do so the phase difference between the voltage of SFD \( (V_{sh}) \) and current through the SFD \( (I_{sh}) \) should ideally be 90°. Practically, this phase difference cannot be exactly 90° and depends on the active component of current drawn by the SFD to meet the losses. Mostly, capacitive mode of operation is required for a loaded transmission line which means that the current drawn by shunt FACTS device should lead the device voltage. In other words, the working angle of SFD \( (\angle V_{sh} - \angle I_{sh}) \) should be between -90° to -80° (the exact value depends on the SFD losses). Under the healthy condition, the voltage at the device and current drawn by the device can be estimated easily from both the relay locations. The phase difference between these voltage and current phasors will nearly be equal to the working angle of SFD (between -90° to -80°). However, in the event of an internal fault, it can be proved that the phase difference between
estimated voltage and current will not be equal to the working angle of SFD at either sending end or receiving end. This special feature has been used to differentiate between internal and external faults. First, the positive sequence voltage and current phasors are estimated at both the relay ends. Then the phase difference between these two estimated phasors has been calculated at each end which is called Estimated Phase Angle (EPA). If the EPAs at both the sending and receiving ends are equal to the working angle of SFD, it is an external fault else it is an internal fault.

\[ V_{es} = V_s - jI_s, Z/2 \]  
\[ V_{er} = V_r + jI_r, Z/2 \]  
\[ I_{es}^E = I_s + I_r \]

where, \( V_s \) and \( V_r \) are the sending and receiving end voltage phasors respectively, \( I_s \) and \( I_r \) are the sending and receiving end current phasors respectively, \( Z \) is the line series impedance (\( Z = X \), line series reactance), \( V_{es}^E \) and \( V_{er}^E \) are the estimated voltage phasors of SFD, estimated at sending and receiving ends respectively, \( I_{es}^E \) is the estimated current phasor of SFD.

To avoid the mutual coupling effect in the case of any asymmetrical fault, positive sequence phasors have been calculated and used in (1), (2) and (3). Both the external and internal faults have been considered and analyzed separately.

A. External fault and healthy condition

If there is no fault in the power system, the corresponding phasor diagram is shown in Fig. 1(b). It is clear that (1), (2) and (3) will give the actual phasors of SFD voltage and current, i.e.

\[ V_{es} = V_{er} \]  
\[ I_{es} = I_{er} \]

where, \( V_{es} \) and \( V_{er} \) are the actual voltage and current phasors of the SFD respectively.

Now, the EPA (using \( V_{es}^E \) and \( I_{es}^E \)) at sending end and EPA (using \( V_{er}^E \) and \( I_{er}^E \)) at receiving end are nearly equal to the working angle of SFD. Ideally,

\[ \alpha_s = \alpha_r = -90^\circ \]

where, \( \alpha_s \) and \( \alpha_r \) are the EPAs at sending and receiving ends respectively.

In the event of an external fault, phasor diagram will be different from the phasor of Fig. 1(b) as there will be changes in the magnitudes of voltages and currents. However, (1), (2) and (3) will still give the actual phasors of SFD voltage and current, i.e. (4), (5) and (6) are also valid for external fault. Again, the EPAs at both the ends are nearly equal to the working angle of SFD.

B. Internal fault

To consider the impact of the different fault locations, two cases of fault location have been considered, one, near the SFD and another, between sending end and SFD.

1) Fault near SFD

For an internal fault created near SFD, Fig. 2(a) shows the equivalent power system. The corresponding phasor diagram is also depicted in Fig. 2(b). It is clear from the phasor diagram that for a fault near SFD, voltage phasors of SFD can be correctly estimated from both the ends and then results have been obtained. The corresponding phasor diagram under the healthy condition is shown in Fig. 1(b), which has been drawn by assuming \( Z \approx X \). Following equations can be used to estimate SFD voltage and current phasors:

\[ V_{es} = V_s - jI_s, Z/2 \]  
\[ V_{er} = V_r + jI_r, Z/2 \]  
\[ I_{es}^E = I_s + I_r \]

Fig. 1 (a) Test power system in the presence of STATCOM and (b) corresponding phasor diagram under healthy condition

II. PROPOSED PILOT RELAYING

A single-phase circuit diagram of shunt-compensated line is depicted in Fig. 1(a). In this figure, Shunt Charging Components (SCCs) have been neglected and ideal SFD has been considered. However, practical models of the transmission line (with distributed series and shunt parameters) and SFD (which also consumes active power to meet the losses) have been considered later and then results have been obtained. The corresponding phasor diagram under the healthy condition is shown in Fig. 1(b), which has been drawn by assuming \( Z \approx X \). Following equations can be used to estimate SFD voltage and current phasors:

\[ V_{es}^E = V_s - jI_s, Z/2 \]  
\[ V_{er}^E = V_r + jI_r, Z/2 \]  
\[ I_{es}^E = I_s + I_r \]

where, \( V_s \) and \( V_r \) are the sending and receiving end voltage phasors respectively, \( I_s \) and \( I_r \) are the sending and receiving end current phasors respectively, \( Z \) is the line series impedance (\( Z = X \), line series reactance), \( V_{es}^E \) and \( V_{er}^E \) are the estimated voltage phasors of SFD, estimated at sending and receiving ends respectively, \( I_{es}^E \) is the estimated current phasor of SFD.

To avoid the mutual coupling effect in the case of any asymmetrical fault, positive sequence phasors have been calculated and used in (1), (2) and (3). Both the external and internal faults have been considered and analyzed separately.
The equivalent power system for a fault between sending end and mid-point are depicted in Fig. 3. In this case, the mid-point voltage phasor can be estimated at receiving end side. However, the mid-point voltage phasor estimated at sending end side and estimated shunt current phasor are not equal to the actual phasors of SFD. Therefore, EPAs measured at both the sides will not be equal to working angle of SFD. The exact values of EPAs will largely depend on the fault resistance and fault location as it will change the phasor. However, in any case, one of the EPAs (either at sending end or at receiving end) will certainly be very much different than working angle of SFD. Therefore, following outcome is expected:

\[ V_{sb}^{Es} \neq V_{sh} = V_{sh} \]  

(10)

C. Practical scenario and effect of FACTS device losses

The criteria of (4)-(13) have been established by assuming ideal FACTS device. Practically, FACTS device also consumes real power to meet the losses (as there are neither ideal switches nor ideal parameters). The EPA depends on the active and reactive power of the shunt FACTS device. If there is no active power consumed by the FACTS device (ideal condition), the EPA will almost be -90°. However, FACTS device will continuously consume active power to meet the losses (which are almost constant). Hence, the EPAs measured at sending and receiving ends can never be exactly -90° and depend on the active power consumed and reactive power supplied by the shunt FACTS device. Under the healthy condition, injected reactive power is small and under the faulty condition, injected reactive power is large. Therefore, working phase angle of FACTS device is relatively small in healthy condition and relatively large in faulty condition. EPAs are equal to the working phase angle of FACTS device during healthy condition and external fault condition. Therefore, EPAs will be small for healthy condition and relatively large for an external fault condition. However, for an internal fault condition, EPAs are not equal to the working phase angle of the FACTS device as described in (9) and (13) and depend on the faulty conditions.

D. Effect of mode of operation of FACTS device

Both the STATCOM and SVC are able to operate in inductive as well as capacitive modes. Mainly, the requirement of these FACTS devices is to compensate the loaded transmission line (usually at mid-point). In this condition, voltage sag is found in the middle of the transmission line. Now, the FACTS device is supposed to operate in the capacitive mode as it has to lift the mid-point voltage. For this mode of operation, the criterion has been established and the results are obtained. However, in lightly or marginally loaded conditions, voltage swell may occur in the middle of the line. To overcome voltage swell, shunt FACTS device is supposed to operate in inductive mode. In this condition, the EPAs at both the relay ends will be nearly +90° (ideally) which can lead to failure of the proposed relaying. To avoid this possible failure, differential current (\(I_d\)) is calculated and compared with the threshold (1.1*I_{dpre}). If differential current is below the threshold, the protected line is said to be healthy and no further calculations have been made (during this condition SFD may operate in capacitive or inductive mode depending upon the requirement) else EPAs are calculated and compared with corresponding threshold. During faulty conditions (no matter it is internal fault or external fault), SFD operates in capacitive mode only.
E. Application of the proposed phasor-based relaying

Flow chart for the application of proposed relaying has been depicted in Fig. 4. After measuring the voltage and current at both the relay locations, the differential current \( I_d \) is compared with threshold \( 1.1*I_{dpre} \); where \( I_{dpre} \) is the pre-fault differential current. This comparison is just to provide an alert signal to the proposed relaying which indicate disturbance in the transmission system. If \( I_d \) is found more than \( 1.1*I_{dpre} \), EPAs (\( \alpha_s \) and \( \alpha_r \)) are calculated using (1)-(3). Now, EPAs are compared with the threshold value and if any of the EPAs is found greater (i.e. relatively positive) than the threshold, it is an internal fault else if both the EPAs are lower than the threshold, it is an external fault. For the case studies of this paper, threshold, \( \alpha_{th} \) is chosen as -70° (with a great degree of safety margin and with an aim to detect faults having fault resistances up to 500 Ω). This threshold is applicable to both STATCOM-compensated line and SVC-compensated line.

Fig. 4. Flow chart of the proposed phasor-based relaying

III. RESULTS

The proposed scheme has been tested on three-phase, 50 Hz, 300 km, 400 kV power system compensated with a) STATCOM and b) SVC. The transmission line data of [10] is used. The Source-to-line-Impedance-Ratio (SIR) for a long transmission line is supposed to be less than 0.5 and for the medium transmission line, it is between 0.5 to 4.0 [17]. In this paper, SIR is kept nearly 0.15 and at the later stage, results are obtained with the SIR of 0.6 (nearly). A six-pulse STATCOM of ± 200 MVAR rating has been used in voltage control mode with a droop of ±3% and connected in series with a transformer of 400/25 kV. An SVC with Full TSC/TCR rating of 167 MVAR/100 MVAR has been used as another type of shunt compensating device. The test systems along with shunt FACTS devices have been simulated in PSCAD/EMTDC [18] with a sampling frequency of 1000 Hz. The performance of the proposed scheme has been tested for STATCOM-compensated line with different fault locations, fault types, and fault resistances. Later, SVC-compensated line has been considered to investigate the impact of the change in the type of SFD.

Table I

<table>
<thead>
<tr>
<th>Fault Location (km)</th>
<th>Fault Type</th>
<th>EPA at sending end, ( \alpha_s ) (degrees)</th>
<th>EPA at receiving end, ( \alpha_r ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A-G</td>
<td>-33.55</td>
<td>65.52</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>-82.42</td>
<td>65.08</td>
</tr>
<tr>
<td>50</td>
<td>3-ph</td>
<td>-83.00</td>
<td>23.09</td>
</tr>
<tr>
<td></td>
<td>AB-G</td>
<td>-40.22</td>
<td>62.79</td>
</tr>
<tr>
<td>200</td>
<td>A-G</td>
<td>52.19</td>
<td>51.88</td>
</tr>
<tr>
<td></td>
<td>AB-G</td>
<td>55.68</td>
<td>44.26</td>
</tr>
<tr>
<td>300</td>
<td>3-ph</td>
<td>85.75</td>
<td>-86.09</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>60.66</td>
<td>-87.49</td>
</tr>
<tr>
<td>External</td>
<td>A-G</td>
<td>-88.26</td>
<td>-87.91</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>-88.56</td>
<td>-87.91</td>
</tr>
<tr>
<td></td>
<td>3-ph</td>
<td>-87.51</td>
<td>-87.50</td>
</tr>
</tbody>
</table>

Fig. 5. EPAs at sending and receiving ends for A-G fault created at 150 km from sending end for STATCOM-compensated line

A. Performance analysis for different fault locations

The results obtained for different fault locations with different fault types are included in Table I. The standard value of tower footing resistance is 10 Ω or less [19]. However, in this study, it is considered to be 5 Ω. It is clear that for all type of external faults, EPAs at both the ends are close to the working angle of SFD (and varying between -87.50° to -88.56°). However, for internal faults, the EPAs at both the relay locations are not close to the working angle SFD. For example for an internal three-phase fault at 50 km,
EPA at sending end is -83.00° (negative than the threshold, i.e. -70°) whereas EPA at receiving end is +23.09°. Hence, the relay detects an internal fault as EPA at receiving end is positive than the set threshold (-70°). Fig. 5 presents the EPAs at sending and receiving ends for A-G fault created at 150 km from sending end at 0.7 sec. It is clear that fault inception, EPAs at both the ends shifts towards the positive direction.

For an external A-G fault, EPAs at sending and receiving ends are depicted in Fig. 6. The pre-fault value of EPA at sending end is -88.00° and at receiving end, it is -87.49°. These values are not exactly -90° because the converter consumes active power to meet the losses. The post-fault values of EPAs are given in Table I (-88.26° at sending end and -88.20° at receiving end). It is clear that in the response of an external fault, EPAs at both the ends further shift towards -90° as shunt FACTS devices inject more reactive power during a fault.

B. Performance analysis for different fault resistances

To investigate the performance for different fault resistances, single-phase (A-G) faults have been created at different locations with different fault resistances. The outcome is presented in Table II. Again, it is clear that for all fault locations and resistances, either one or both the EPAs are greater than -70°. The negative most value of EPA is -69.90° (close to the set threshold -70°) for a close-in internal fault with 500 Ω fault resistance (measured at sending end). However, EPA at receiving end for the same case is -66.92° (positive than the set threshold). So the internal fault is detected even at the high fault resistance of 500 Ω. For external faults, the EPAs at both the relay locations are within the range of working angle of SFD (i.e. more negative than the threshold).

C. Performance analysis for SVC-compensated line

To investigate the impact of different SFD, proposed scheme has been applied for the protection of SVC-compensated line. The results obtained for different fault locations with different types are included in Table III. It is clear from the table that for all types of internal faults, either one or both the EPAs are greater than -70°. If the internal fault is detected by the relay as EPA at sending end is much positive than the threshold. For external faults, the EPAs at both the relay locations are within the range of working angle of SFD (i.e. more negative than the threshold).

D. Performance analysis for source impedance variations

The effect of source impedance variations has been analyzed and for STATCOM and SVC-compensated line, the results are included in Table IV and Table V respectively. The impedance of sending end side source has been increased four times of its previous value (i.e. SIR is 0.6). From the results, it is clear that proposed phasor-based relaying is unaffected by the source impedance variations. For all internal faults, either one or both the EPAs are greater than the threshold (-70°). For an internal 3-phase
fault at 250 km, EPA at receiving end is -86.76°. However, the EPA at sending end is much positive than the threshold (+58.38°) which indicates an internal fault. For all external faults, both the EPAs are smaller than the threshold (i.e. -70°) and are equal to the working angle of the SFD.

### TABLE IV
EPAS FOR STATCOM-COMPENSATED LINE WITH CHANGED SOURCE IMPEDANCE (SIR of 0.6)

<table>
<thead>
<tr>
<th>Fault Location (km)</th>
<th>Fault Type</th>
<th>EPA at sending end, ( \alpha ) (degrees)</th>
<th>EPA at receiving end, ( \alpha ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A-G</td>
<td>-30.29</td>
<td>45.50</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>-76.33</td>
<td>50.22</td>
</tr>
<tr>
<td>50</td>
<td>3-ph</td>
<td>-83.03</td>
<td>22.98</td>
</tr>
<tr>
<td></td>
<td>AB-G</td>
<td>-37.48</td>
<td>42.53</td>
</tr>
<tr>
<td>200</td>
<td>C-G</td>
<td>53.49</td>
<td>52.53</td>
</tr>
<tr>
<td></td>
<td>CA-G</td>
<td>54.83</td>
<td>42.61</td>
</tr>
<tr>
<td>300</td>
<td>AB</td>
<td>85.71</td>
<td>-86.08</td>
</tr>
<tr>
<td></td>
<td>3-ph</td>
<td>60.73</td>
<td>-87.52</td>
</tr>
<tr>
<td>External</td>
<td>A-G</td>
<td>-88.79</td>
<td>-88.25</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>-88.82</td>
<td>-88.25</td>
</tr>
<tr>
<td></td>
<td>3-ph</td>
<td>-87.69</td>
<td>-88.38</td>
</tr>
</tbody>
</table>

### TABLE V
EPAS FOR SVC-COMPENSATED LINE WITH CHANGED SOURCE IMPEDANCE (SIR of 0.6)

<table>
<thead>
<tr>
<th>Fault Location (km)</th>
<th>Fault Type</th>
<th>EPA at sending end, ( \alpha ) (degrees)</th>
<th>EPA at receiving end, ( \alpha ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A-G</td>
<td>11.24</td>
<td>21.45</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>11.62</td>
<td>53.11</td>
</tr>
<tr>
<td>50</td>
<td>3-ph</td>
<td>-68.80</td>
<td>51.13</td>
</tr>
<tr>
<td></td>
<td>AB-G</td>
<td>17.76</td>
<td>54.83</td>
</tr>
<tr>
<td>200</td>
<td>C-G</td>
<td>68.01</td>
<td>52.11</td>
</tr>
<tr>
<td></td>
<td>CA-G</td>
<td>79.16</td>
<td>-80.79</td>
</tr>
<tr>
<td>300</td>
<td>AB</td>
<td>55.51</td>
<td>-80.69</td>
</tr>
<tr>
<td></td>
<td>3-ph</td>
<td>-81.27</td>
<td>-80.86</td>
</tr>
<tr>
<td>External</td>
<td>A-G</td>
<td>-81.70</td>
<td>-81.31</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>-81.15</td>
<td>-81.41</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

A pilot relaying scheme based on phasor estimation of shunt FACTS device has been proposed. Analysis and results proved that for an external fault, both the EPAs are equal to the working angle of the SFD, which is between -90° to -80°. For an internal fault, both the EPAs are not equal to the working angle of the SFD. The proposed scheme has been tested for different shunt FACTS devices, source impedances, fault locations, fault types and fault resistances. The scheme successfully detects the internal faults under all possible uncertainties. The scheme is also unaffected by the working angle of the SFD. The proposed scheme has been proved that for an external fault, both the EPAs are equal to the working angle of the SFD. However, for an internal fault, both the EPAs are smaller than the threshold (i.e. -70°) and are equal to the working angle of the SFD.

REFERENCES