Wavelet-based Auto-reclosing Technique for TCSC compensated lines connecting windfarm

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Abstract—Auto-reclosing improves system stability by fast restoration of the line in case of arcing faults. Conventional techniques using harmonics of voltage and current have disadvantages in series-compensation environments because of associated dynamics and control mechanisms. Again, the auto-reclosing process can be affected for systems having large scale windfarm which are very sensitive to grid disturbances. This research work proposes a technique for adaptive autoreclosing in case of phase-to-earth faults for TCSC compensated transmission line connected to windfarm. A technique is devised that utilizes the cumulative sum of wavelet energy (CSW) calculated using wavelet coefficients to derive an index (FTI) which distinguishes between permanent and transient faults. Another extinction index (AEI) is computed using CSW during the secondary arc to identify the arc extinction. This parameter is used to change the dead time set for the recloser and thus, reclosing during fault process is avoided. The performance evaluation of the proposed scheme on the real-time digital simulator (RTDS) platform with shunt compensation and neutral reactor, demonstrates its real-time applicability.

Index Terms—Adaptive Single Pole Auto-reclosing (ASPAR), Thyristor Controlled Series Capacitor (TCSC), Doubly-fed Induction Generator (DFIG), Discrete Wavelet Transform (DWT), Real-time digital simulator (RTDS).

I. INTRODUCTION

Among the faults that occur on transmission lines, 80–90% are transient (arching) faults that mainly fall in single phase to ground category [1]. For a transient fault, a high power line-tripping will bring economic loss to a power utility. In such cases, the faulted phase can be de-energized till the arcing clearance time. Following the fault clearance, the line can be restored by successfully reclosing the breaker. Therefore, continuity of supply can be maintained and the availability of the transmission line can be increased. For cases of phase-to-earth faults, the application of single-phase auto reclosing (SPAR) is required as the other phases keep on transmitting energy. During this time, around 54% and 75% of the pre-fault power flow occurs for single circuit and double circuit lines, respectively [2].

The traditional SPAR methods using a fixed arc extinction time have the following issues. Usually, autoreclosing is applied at pre-determined intervals. Thus, autoreclosing during a permanent fault may generate high current which in turn can damage the elements of the power system. Hence, it is essential to recognize the type of fault before recloser operation. Further, after a fixed time for the secondary arc extinction, the fault might not get cleared and the reclosing gives rise to an overvoltage between the circuit breaker (CB) poles causing arc restrike. A dead time is required after fault extinction to avoid restriking of arc. To deal with such issues in ASPAR techniques, it is essential to recognize the type of fault and calculate the arc extinction instant. Estimation of actual fault extinction time can be utilized to fix the dead time so that reclosing can be activated correctly. Hence, adaptive dead time is crucial for effective autoreclosing.

Methods in [3], [4] utilize the voltage signal extracted at the line side of the concerned circuit breaker to estimate the fault clearance for intelligent autoreclosing. But these methods may fail to determine fault clearance instant for high impedance faults. In [5], the third harmonic voltage amplitude at the measured at concerned bus is utilized to estimate the type of fault. The authors in [6] has proposed an adaptive autoreclosing technique based on zero sequence voltage. Methods in [7] uses total harmonic distortion of the voltage at the faulted phase to recognize the type of fault and the extinction time. In [8], the work proposes a method using harmonic contents of the voltage on faulted phase and currents in healthy phases. Learning based techniques for autoreclosing are also available which utilizes Fuzzy logic [9], artificial neural network [10] and ADALINE [11]. But, these methods need substantial training with large number of sample cases and require to be retrained for a modified system configuration. Also these methods may not operate for an unwarned situation which may happen in a practical system.

With emerging synchrophasors applications, time stamped information can be retrieved from both line ends of the transmission lines for further processing [12]. In [13], authors have proposed a double-ended communication based algorithm that utilizes zero-sequence power flow towards both line-ends to determine the fault arc clearance. A communication based intelligent autoreclosing technique for uncompensated transposed transmission lines based on sequence components is presented in [14]. But, if the autoreclosing approach needs data from line side of the circuit breaker, additional phasors need to be transmitted which will add extra cost and communication burden.

In series compensated network connected with windfarm, the auto-reclosing task becomes critical. Thus, this research work proposes a method for adaptive auto-reclosing for line-to-ground faults on a TCSC compensated line unified with DFIG. Once a single-phase fault is detected, using a fault type index (FTI) based on wavelet analysis, permanent and transient faults are discriminated. Arc extinction index (AEI), calculated using wavelet energy, is utilized to identify the correct time for arc extinction and thus, auto-reclosing during faults can be avoided.
The proposed scheme is not impacted by the series compensation parameters and can be applied for uncompensated line as well. The performance of the proposed method is also not affected for lines with shunt compensation and neutral reactors and double circuit lines as validated in RTDS platform.

II. IMPACT OF TCSC AND WINDFARM ON EXISTING METHODS FOR AUTO-RECLOSING

Series compensation devices are installed to enhance the power transfer capacity of transmission lines, improve the transient stability of the system and dampen the power system oscillations [15]. Among the series compensation devices, TCSC is one of the most effective applications. But the issue associated with TCSC is that it may work at separate operating modes in case of faulted situation i.e. bypass mode, capacitive boost mode, inductive boost mode, and blocked mode. During switching of each mode of operation, extra transients are generated. Again the Metal-oxide varistor (MOV) and sparkgap arrangement supplied for protection of TCSC may operate when fault occurs on a TCSC compensated line and add more transients in the signal information [16]. In such cases, existing techniques using harmonics of voltage and current will face serious challenge.

In current era, wind-farms are also increasingly integrated to the grids for enhancing the reliability of the system. The difficulty that arises is due to continually changing wind speed throughout a day which leads to swing in wind-farm output power. When such a farm is unified to the grid, the transmitted power in the transmission line and the bus voltage fluctuates continually. So the protection function becomes more formidable [3]. Thus, when both TCSC and wind-farms are connected in the transmission line, the system becomes more complex and the traditional auto-reclosing scheme is substantially impacted.

Thus, devising an autoreclosing scheme which is not affected by the TCSC or windfarm dynamics or parameter variation is mandated. This must discriminate between permanent and transient fault and detect the arc extinction with reduced response time.

III. PROPOSED ADAPTIVE AUTORECLOSING SCHEME

This research work presents an adaptive autoreclosing scheme for phase-to-earth faults on TCSC compensated transmission line connecting windfarm. Using the voltage information of the faulted bus, FTI index is calculated using energy of detail wavelet co-efficient to distinguish between permanent and transient faults. For a transient fault, AEI index is evaluated to identify the fault arc extinction instant. The thresholds for FTI and AEI indices have been chosen based on empirical studies and hold true for tests with different system configuration, line, fault, TCSC parameters and wind-speed variation.

A. Discrete Wavelet Transform (DWT)

DWT uses a multi-resolution decomposition technique which separates the input signal into different approximation coefficient (C_a) levels by using scaling functions (father wavelet- F_a(t)) and detail coefficient level (C_d) using mother wavelet (M_d(t)).

\[
F_a(t) = 2^{-k}F(2^{-k}t - n)
\]

\[
M_d(t) = 2^{-k}M(2^{-k}t - n)
\]

where \( n \in Z \), \( k \) and \( l \) are integers. The signal passes through the high-pass and low-pass filters, with filter coefficients \( H(n) \) and \( L(n) \) respectively. Each level is iteratively filtered by same method, to give narrower sub-bands and desired features as shown in Fig. 1. As filters have fewer samples due to down-sampling, it would give better computational performance [17].

Appropriate selection of mother wavelet function and decomposition levels would decide the accuracy and response time of the proposed algorithm. Most suitable mother wavelet candidates for analysis of transient signals with abrupt changes belong to Daubechies family (dbN), where \( N \) is the wavelet function order. However, higher order wavelet function delay the fault detection response time and have a higher command over frequency domain as compared to time domain localization. The proposed method for auto-reclosing should be able to detect permanent faults and arc extinction instant for transient faults for high fault impedance cases and therefore db1 is chosen as most suitable wavelet function as per the requirement. Thus using db1, the sampled signal is decomposed into detail and approximate coefficients.

B. Proposed autoreclosing indices

Detail coefficients as extracted from wavelet analysis provide the most suitable information about transient behavior as represented by high frequency components. Voltage signal measured at the buses connected to the faulted line, is passed...
through DWT analysis and cumulative sum of wavelet energy is determined with a certain window size ‘w’ and for a certain detailed level. Approximately 1/10th of the minimum time to reach peak magnitude during any abnormal condition is chosen as sampling frequency, in order to capture most abrupt changes accurately [18]. Few limitations of wavelet transform application are unable to extract features in noisy atmosphere. However, by using wavelet-based denoising method the input signal can be denoised.

Detail wavelet coefficients are used to extract the energy content of the signal. Absolute Detail Energy for kth detail level is calculated as:

$$E_k = \{ \text{abs} \left( D_k(j) \right) \}^2$$  \hspace{1cm} (3)

The detail energy content of a signal measured at a bus is obtained over a pre-decided window width ‘w’ running over total time frame of the signal given as below.

$$E_{kw}(j) = \sum_{m=0}^{w-1} \{ \text{abs} \left( D_k(j + m) \right) \}^2$$  \hspace{1cm} (4)

The number of samples used in moving window must be judiciously selected as more number of samples would increase the computational burden on the proposed algorithm, whereas lesser samples would increase the detection response time. CSW is the cumulative sum of the E(w) consecutive samples and runs over the entire length of the signal, is given by

$$S = CSW_k(p) = \sum_{p-2}^{n-1} E_k(w)$$  \hspace{1cm} (5)

‘S’ is used to calculate a fault type index FTI which distinguishes between permanent and transient faults. If FTI falls below 2.5% within 200ms of the CB opening, then the fault is detected as permanent fault and three phase opening command is initiated. The threshold time of 200ms is chosen based on the permanent fault detection time and confirmed to be appropriate for various system configurations and line, fault, TCSC, shunt compensation and neutral reactor parameters. FTI is represented by:

$$FTI = \frac{S}{S_{max}} = \frac{CSW_{w}(E_k)}{S_{max}}$$  \hspace{1cm} (6)

Where CSW represents cumulative sum with a window ‘w’. This ‘w’ parameter is decided from the experimental method. ‘Smax’ is the value of ‘S’ at the circuit breaker opening instant.

Once a transient fault is confirmed after 200 ms of CB opening time, then the arc extinction time is to be estimated. For the same, ‘S’ value is monitored throughout the secondary arc and the maximum value is stored. When the arc extinction occurs, the ‘S’ value starts falling. So another index ‘AEI’ is defined using ‘S’ to determine the arc extinction time. If AEI falls below 2.5%, the secondary arc is found to be quenched. AEI represented by:

$$AEI = \frac{S}{S_{x,max}} = \frac{CSW_{w}(\text{abs} \left( FST_{m} \right))}{S_{x,max}}$$  \hspace{1cm} (7)

Where Sxmax is the maximum value of ‘S’ during secondary arc. Figure 2 shows the flow chart of the proposed technique for adaptive autoreclosing.

IV. FAULT ARC MODELLING

Modeling of fault arc and its impact on the power system during transient faults is crucial for designing the transmission line autorecloser. Fault arcs can be separated as primary and secondary arcs taking the features of the arcs into consideration. In an EHV transmission line, the secondary arc starts following the primary arc once the fault is cleared (by opening CB). Thus, the secondary arc is a very complex event, and depends upon various aspects.

In this work, the thermal long arc model of Kizilcay [19]-[20] proposed in (8) and (9), is implemented to analyze the arcing fault.

$$\frac{dg_{arc}}{dt} = \frac{1}{\tau} (G - g_{arc})$$  \hspace{1cm} (8)

$$G = \frac{l_{arc}}{(u_0 + r)|l_{arc}|n_{arc}}$$  \hspace{1cm} (9)

Where g_{arc} stands for the instantaneous arc conductance; τ is the time constant of the arc; G the stationary arc conductance; l_{arc} the instantaneous arc length; u_0 the arc characteristic voltage and r the arc characteristic resistance per arc length.

In case of primary arc, τ and l_{arc} are fixed and are same as the initial time constant τ_0 and initial arc length l_0, respectively. In case of secondary arc, those parameters change with time. ‘τ’ for the secondary arc varies inversely with l_{arc} and can be calculated as

$$\tau = \tau_0 \left( \frac{l_{arc}}{l_0} \right)^{\alpha}$$  \hspace{1cm} (10)

Where α is a coefficient taking a value between -0.1 to -0.6.

The primary arc length (called as flashover length) is taken to be 10% higher than the length of the string of line insulators [19]. The secondary arc length varies with time and a function of wind velocities. However, the change of arc length for low wind speeds (up to 1 m/s), is given as (11) [20]

$$\frac{l_s(t_r)}{l_0} = 1, t_r \leq 0.1$$

$$\frac{l_s(t_r)}{l_0} = 10t_r, t_r > 0.1$$  \hspace{1cm} (11)

The Arc resistance is modeled in RSCAD as a variable resistor between phase and ground conductors. Its value is controlled by solving Eqn. (10) and (11). The block diagram of the arc model is presented in Fig. 3. Table 1 shows the parameters of the arcing fault.
The proposed auto-reclosing technique is tested on RTDS platform for a two bus 400 kV, 50 Hz, 200 km transposed double-circuit transmission system series compensated by TCSC placed at the middle as shown in Fig. 4. RTDS implements parallel processing techniques (a PB5 card) on rack-mounted processors to carry out the continuous real-time digital simulation of a power system. Here, the voltage signals are retrieved at the line side of the breaker for the modeled power transmission system on RSCAD.

One wind farm is connected at substation-2. Wind turbines use a DFIG consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The transmission line has a shunt compensation of 70% connected at both ends. A new neutral reactor (connected between the neutral and ground), is usually placed to reduce the line coupling admittance. Also, the neutral reactor can be varied to achieve the desired secondary arc current along the no-load line (15 and 40 A rms for this case-study). Table 2 presents the neutral reactor parameters for each test.

Related parameters are as follows:

**Wind farm**: consists of 40 numbers of 1.5MW wind turbines each connected to the 400kV system. stator impedance $R_s + jX_s = 0.010 + j0.182$, rotor impedance $R_r + jX_r = 0.009 + j0.144$, magnetizing inductance $X_m = 5.896$ (all those impedance values are per-unit values based on the generator rated parameters); inertia time constant $T_J = 1.5s$; rated wind speed is 10m/s.

**Wind farm set-up transformer**: the rated capacity is 63MVA, the rated voltage is 400kV/38.5kV, and the linkage reactance (%) = 10.5.

**Transmission line**: positive-sequence and zero-sequence series impedance are respectively $Z_{s1} = 0.01273 + 0.29318\Omega/km$ and $Z_{s0} = 0.3864 + 1.3899\Omega/km$; positive-sequence and zero-sequence shunt capacitances are 12.74 nF/km and 7.751 nF/km.

**TABLE I**

<table>
<thead>
<tr>
<th>Test</th>
<th>u0, kV/km</th>
<th>R, mΩ/m</th>
<th>α</th>
<th>$T_a$, ms</th>
<th>$L_o$, m</th>
<th>SAL, increase, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 A rms Compensated</td>
<td>0.9</td>
<td>22</td>
<td>-0.5</td>
<td>1</td>
<td>4.05</td>
<td>60</td>
</tr>
<tr>
<td>40 A rms</td>
<td>0.9</td>
<td>22</td>
<td>-0.5</td>
<td>1</td>
<td>4.05</td>
<td>80</td>
</tr>
</tbody>
</table>

SAL = Secondary Length Increase.

**TABLE II**

<table>
<thead>
<tr>
<th>Test</th>
<th>Resistance (In Ohm/km)</th>
<th>Reactance (In Ohm/km)</th>
<th>Resistance (In Ohm)</th>
<th>Reactance (In Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 A rms</td>
<td>0.04465</td>
<td>17.8572</td>
<td>20.833</td>
<td>833.33</td>
</tr>
<tr>
<td>40 A rms</td>
<td>-</td>
<td>-</td>
<td>3.977</td>
<td>159.09</td>
</tr>
</tbody>
</table>

V. SYSTEM STUDIED

The proposed auto-reclosing technique is tested on RTDS platform for a two bus 400 kV, 50 Hz, 200 km transposed double-circuit transmission system series compensated by TCSC placed at the middle as shown in Fig. 4. RTDS implements parallel processing techniques (a PB5 card) on rack-mounted processors to carry out the continuous real-time digital simulation of a power system. Here, the voltage signals are retrieved at the line side of the breaker for the modeled power transmission system on RSCAD.

One wind farm is connected at substation-2. Wind turbines use a DFIG consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The transmission line has a shunt compensation of 70% connected at both ends. A new neutral reactor (connected between the neutral and ground),
VI. SIMULATION AND RESULTS

In the simulation model, a sampling frequency of 5 kHz (sampling time of 200μs) is considered. Detail level 3 is considered for deriving the proposed indices in order to increase the accuracy level. To test the proposed scheme, line-ground permanent and transients faults are applied in the transmission system.

A. Permanent Fault Case

Figures 5 and 6 presents the test results of the proposed technique for permanent fault. At t = 0.25 s, LG fault occurs at 25% of the transmission line where TCSC is placed at the middle point ‘P’. At t = 0.29 s, the circuit breakers at both ends open. Figure 5 (a) shows the fault current whereas voltage at the sending terminal (the line side of the circuit breaker) is presented in Fig. 7 (b) which is quite distorted. CSW values for detail level 4 are obtained for a window size of ‘10’ as shown in Fig. 6 (a). The value of CSW at 0.29 s is assigned to be $S_{max}$ and FTI index is calculated as shown in Fig. 6 (b). On the same plot, FTI of a transient fault is also shown for comparison. At t = 0.344 s, FTI falls below 2.5% and thus, confirms it as a permanent fault. A 50 ms delay is incorporated to ensure FTI value continues to stay below 2.5% and then, adaptive single-phase auto-reclosing is blocked and the three phase opening can be triggered.

B. Transient Fault Case

Test results of the proposed technique for transient fault are shown in Fig. 7 and 8. At t = 0.25s, LG fault occurs at 45% of the TCSC compensated transmission line and at t = 0.29s, the circuit breaker opens. Figure 7 (a) shows the fault current whereas voltage at the sending terminal (the line side of the circuit breaker) is presented in Fig. 7 (b) which is quite distorted. CSW values for detail level 4 are obtained for a window size of ‘10’ as shown in Fig. 8 (a). The maximum value of CSW during secondary arc is monitored ($S_{max}$) and AEI index is calculated as shown in Fig. 8 (b). At t = 1.005 s, AEI falls below 2.5% and thus, confirming the extinction of the secondary arc. Then a reclosing pulse can be generated. Hence, adaptive single phase reclosing is undertaken and the system can come back to the normal operating condition. The fault extinction is detected around 4 ms after actual arc clearance.

C. Performance with variation of parameters

In Table 3, there is a summary of all tests carried out to verify the behavior of the proposed method for permanent fault. Three different cases of L-G permanent faults with fault resistance ($R_f$) values 1, 10 and 50 Ω were considered. The index FTI is then continuously calculated to find out the instant of permanent fault detection. It can be deduced that the proposed technique is capable of detecting faults even with high fault impedance. The effect of fault distance (FL), percentage series compensation and wind speed on the proposed method is reviewed by simulation of faults at 10, 25, 45, 70 and 90% points of the transmission line with series compensation level varying from 30-70% and wind speed varying from 2-20 m/s. The fault resistance is kept at a particular value. For permanent faults, the detection time falls between 49 and 62ms after the circuit breaker opening. Similarly, Table 4 shows the recorded data for transient fault. The minimum resistance fault value is varied as: 1, 10, and 20 Ω. Keeping that resistance value fixed, the fault location is varied as mentioned in permanent fault case. The detection time varied from 4 to 17ms after secondary arc extinction.

D. Comparative Analysis

Our proposed ASPAR technique is compared with the recent works and the brief analysis is presented. Maximum identification time of permanent fault for our case is 62 ms whereas the method based on THD of fault voltage presented in [12] has an operation time more than 100ms. The same operation time for [14] and [23] are 108ms and 321ms respectively. Maximum detection time of secondary extinction for our case is 17ms whereas the same detection times for [6], [12], [14], [21], [22] and [23] are 9ms, 15ms, 67ms, 20ms, 100ms and 340ms respectively. However, [6], [12], [14], [21] and [23] has not reported the effect of series compensation and windfarm and also not been implemented on double circuit lines. [12], [14] and [22] are communication-based whereas our
The proposed technique with the existing ones shows its superiority in variations of fault parameters. The comparative analysis of our performance is satisfactory as validated on RTDS platform. The superior of the proposed method can be well-observed. Thus form the above analysis, the proposed method does not involve the same, thus reducing extra cost and communication burden. We have reported effect of shunt compensation and neutral reactor as well which [6] and [22] has not mentioned. Thus form the above analysis, the superiority of the proposed method can be well-observed.

VII. CONCLUSIONS

The proposed method for adaptive auto-reclosing deriving indices using energy of high frequency constituents calculated from wavelet detail level shows promising results in TCSC as well as windfarm environments. The test system has considered shunt compensation along with neutral reactor and the performance is satisfactory as validated on RTDS platform. Thus, it enhances applicability of the proposed autoreclosing scheme in real time environment. The performance of the proposed technique is found to be almost independent of wide variations in fault parameters. The comparative analysis of our proposed technique with the existing ones shows its superiority over the conventional techniques for autoreclosing.

REFERENCES


