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Modified Differential Protection for Transformers in Wind Farms

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Abstract – The liberalization of electricity market and environmental concerns are the major driving forces for the development of Distributed Generation (DG). The mode of grid-connected wind power generation is becoming popular and has matured as a reliable DG technology. The voltage generated by the wind generator is stepped up to the higher voltage by the transformers before connecting to the grid. Operating algorithm of the differential relays for transformer protection used in the wind farms need to be modified to take care of the dynamic nature of fault current caused by the intermittent nature of the wind power. An algorithm for the differential relay is proposed in which dual slope characteristics are adjusted with varying fault level situation according to the wind generator in service as well as with the wind speed. A case study conducted for a typical wind farm shows that the proposed method avoids mal-operation of the differential relay in varying wind power conditions.

Keywords: Distributed generation, Differential relay, Fault level, Transformer, Wind farm

1. Introduction

The world will require increased energy supply in the coming decades, especially from the DG sources which includes renewable energy sources. In recent years, wind energy has become one of the most economical, secure and sustainable source of renewable energy supply [1-3]. Wind based power plants are connected to the power grid through the transformer which is one of the most expensive equipment in the power system [4-5]. Differential protection is the primary protection scheme for the transformers and is designed to operate only for internal faults and not for external faults and other operating conditions like inrush, over-excitation, Current Transformer (CT) saturation, etc. [6].

The tripping of differential relay during external fault is avoided due to the balancing of current in the primary and secondary side. The CT saturation during external fault condition is taken into consideration by slope characteristics of differential protection. The second harmonic component in inrush current is used to detect whether the transformer is experiencing inrush or faulty conditions and fifth harmonic component in the differential current is taken to identify over excitation [7]. The methods like harmonic restraint, harmonic blocking, and wave shape recognition methods are proposed in [8] to distinguish inrush current from internal faults. The combination of harmonic restraint, harmonic blocking, and wave shaped recognition method is suggested in [9] to identify inrush current in which second harmonic component is low. A mathematical morphological algorithm based on time difference method of transformer differential protection during CT saturation is reported in [10]. The second harmonic component of low magnitude due to high saturation caused by the switching of non-linear loads results in mal-function of differential relays [11-12]. The ratio of change in flux linkage in the primary and secondary winding is used to differentiate between internal faults and other operating conditions like inrush, over excitation, etc [13]. The methods like Artificial Neural Network (ANN), fuzzy logic etc. are proposed in [14-15] to discriminate internal fault from other operating conditions. These methods require large computational time and increase the training time exponentially. The various signal processing techniques like Wavelet Transform (WT), ‘S’ transform and hyperbolic ‘S’ transform are described in [16-20] for the differential protection. The positive rate of change of value in the zero sequence differential current is used in [21] to detect CT saturation during heavy fault conditions. The mal-operation of the differential relay is avoided by reshaping the second slope of the transformer differential relay characteristics. The Empirical Fourier Transform (EFT) technique is proposed in [22] to distinguish internal faults, inrush, and CT saturation currents. The low magnitude of EFT of the fundamental component during inrush and CT saturation makes the discrimination between internal faults, inrush conditions, and external fault conditions simple and accurate. The space vector technique like Extended Park’s Vector Approach (EPVA) is compared with negative sequence protection algorithm, and the literature shows EPVA possesses superior performance in fault/inrush and external fault discrimination [23]. In [24] space vector analysis of the differential signal and their time characteristics shapes in Park’s plane is used to discriminate between magnetizing inrush and the internal fault of a power transformer. The result shows that the above method works properly in CT saturation as well as in over flux conditions. The zero sequence current in the

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delta winding is used to distinguish between internal fault conditions and the other operating conditions in the transformer [25]. Adaptive restraint coefficient based differential protection is suggested in [26], which adjusts the restraint coefficient according to the operational and fault conditions of the system. The adaptive scheme for differential protection based on fault component of the current is studied in [27]. Here the parameters like pickup current, restraining current and restraint coefficient are varied based on the fault level. The modified single slope characteristics, which take the upper and lower limit of the value for the relay settings, is proposed to provide higher sensitivity to internal faults as well as higher security towards external faults.

The sensitivity towards internal fault as well as security to the external fault can be improved by adjusting the slope characteristics. However, the conventional single slope and dual slope characteristic needs to be modified in the presence of wind farms. The main drawback of the wind farms is that the wind speed is not constant, and consequently, the generated power varies continuously The wind power is dynamic in nature and the fault current is varying according to the wind generator in service as well with wind speed conditions [28]. The algorithms reported so far for the adaptive protection in the transformer differential protection does not include the dynamic conditions of the wind farms during fault interval. The settings of the differential relay have to be modified in the presence of wind farms due to its intermittent nature. In this paper, an algorithm for transformer differential relay in which a range for dual slope characteristics is suggested with a case study of a typical wind farm. The modified algorithm avoids the mal-function of differential relays during various operating conditions of the wind farm.

The main advantages of the proposed algorithm is that, the dual slope characteristics for transformer differential protection is suggested which can be used in wind farms. The conventional dual slope algorithm for differential relay mal-operates in the transformer connecting wind farm to the grid due to the dynamic nature of wind. The mal-function of the existing differential relay during external fault conditions is avoided by the proposed algorithm. The new algorithm modifies the settings of second slope in dual slope algorithm according to the wind generators in service as well as with the wind speed. The modified algorithm provides sensitivity to minute internal fault and security to major external fault respectively. The proposed algorithm also avoids un-necessary operation of the relays during inrush and over excitation conditions using the harmonic restraint technique.

2. Issues with Conventional Differential Relay with Wind Farm

The percentage differential relay is implemented on the

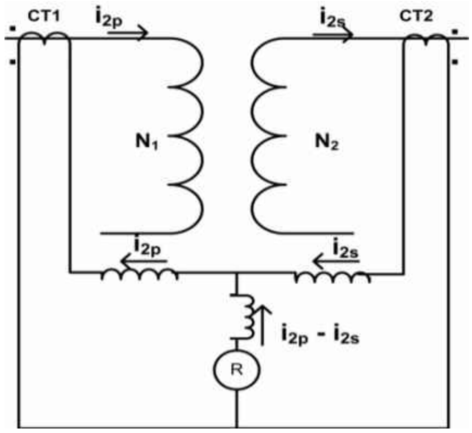

Fig. 1. Transformer differential protection

power transformer with operating and restricting coils as illustrated in Fig. 1 (4). Here N_1 and N_2 are the number of turns in the primary and secondary windings, i_{2p} is the CT secondary current connected to the power transformer primary winding and i_{2s} is the CT secondary current connected to power transformer secondary winding. The differential relay operation is based on two currents, restraining current, i_r and differential current, i_d. In this protection philosophy, CT transformation errors, CT's mismatch and power transformer variable taps can cause a differential current to flow in the operating coil.

To consider these effects, the differential protection formulation compares the value of differential current to a fixed percentage value, named 'K' of the restraining current.

The percentage value is the slope of the percentage differential characteristics and determines the relay trip zone. The slope 'K' value is defined as

$$K = \frac{\left(i_{2p} - i_{2s}\right)}{\frac{\left(i_{2p} + i_{2s}\right)}{2}} \tag{1}$$

The typical value for 'K' varies from 10% to 40%. Differential protection relay identifies internal faults when the differential current exceeds the restraint current percentage value shown by

$$i_d \geq K \frac{\left(i_{2p} + i_{2s}\right)}{2} + I_{pickup} \tag{2}$$

where I_{pickup} is the pickup value of the current and I_{pickup} depends upon the difference in magnetization of the current transformers, inaccurate meter readings, leakage current in the cable connecting CT and relay. However the major contribution of the I_{pickup} is due to the difference in magnetization of the current transformers. The characteristics include a straight line having a slope 'K' starting from the pickup current of the relay. The relay operating region is located above the slope and the restraining region is below the slope [29-30].

Single slope characteristics of differential protection do not provide correct decisions during heavy external fault conditions due to CT saturation and inter turn fault involving less number of turns. During these circumstances, there are chances of unnecessary trip decisions and they are to be avoided. A dual slope characteristic with slopes K_1 and K_2 is required such that unnecessary trip conditions can be prevented [31].

The differential relay does not mal-operate for external faults as long as the CTs secondary current is proportional to the primary current. When one of the CTs saturates or both the CTs saturate at the different level, false operating current results in mal-function of the differential relay. A variable percentage or dual slope characteristics increases the relay security during heavy CT saturation caused by the external fault. In dual slope differential protection, first slope K_1 is based on transformer tap setting and second slope, K_2 depends on CT saturation caused by an external fault. Fig. 2 shows the characteristics of the dual slope differential relay and the tripping zone is shown as the shaded portion. The points 'A' and 'B' corresponds to the operating points for the minimum internal fault current as well as maximum external fault current respectively. The minimum internal fault current occurs during turn to turn fault where fault is less than in 2.5% turns. The low resistance LLL fault result in maximum current in external fault condition. The relay operates only for internal fault and does not operate for external fault as the point 'A' belongs to tripping region (shaded portion) and 'B' belongs to restraining region (non shaded portion).For dual slope characteristics the equation becomes,

$$i_d \geq K_2 i_r + (K_2 - K_1) i_{rt} + I_{pickup} \tag{3}$$

where i_{rt} is the crossover point to the second slope (K_2), which is steeper than the first.

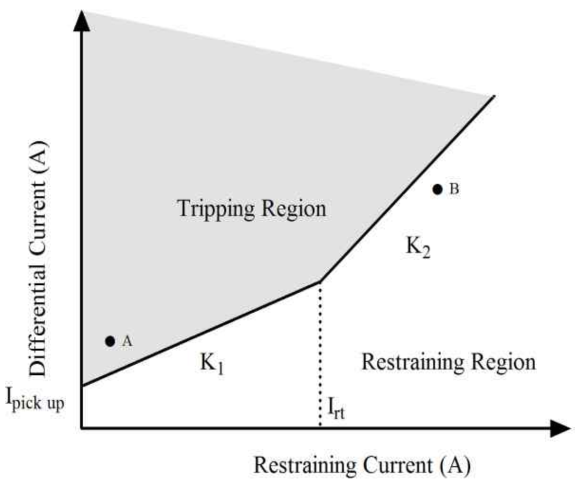

Fig. 2. Dual slope characteristics for differential relay

The slope of K_1 is necessary to provide sensitivity towards the minimum internal fault as the operating point is denoted by 'A', $[(I_{1intmin}+I_{2intmin})/2, (I_{1intmin}-I_{2intmin})]$ where $I_{1intmin}$ and $I_{2intmin}$ are minimum internal fault current at primary and secondary sides respectively. The higher slope K_2, provides necessary security for external fault as the operating point is represented by B, $[(I_{1extmin}+I_{2extmin})/2, (I_{1extmin}-I_{2extmin})]$ where $I_{1extmin}$ and $I_{2extmin}$ are primary and secondary side minimum external fault current respectively.

A dual slope characteristic for the differential relay for transformers with wind farm integration mal-operates during external fault conditions. The wind farm fault current varies according to the number of wind generators in service as well as with the wind speed. This can be explained as follows. The total short circuit current from the wind farm can be written as

$$I_{SCM} = \sum_{k=1}^{N} k I_{scm} \tag{4}$$

where I_{SCM} is the maximum short circuit current from the wind farm, I_{scm} is the maximum current from a single wind generator, N is the total number of wind generators in wind farm and k is the number of wind generator in service. The current I_{scm}, from the wind generator, depends upon the source impedance of each generator. When the wind speed is below the cut-in speed, the power output of the wind generator is zero. The brakes are applied when the speed reaches the cut-out speed, and the machine stops generation. The fault contribution from each wind generator is varying according to wind speed which is between the cut in and cut out speed of the wind turbine. The short circuit current from the wind farm is varying which results in dynamic shifting of operating points in transformer differential protection. The operating point during external fault condition comes in the tripping zone and the differential relay issues unnecessary trip signal. Therefore, the differential relay settings of the transformer have to be altered according to the wind power penetration.

3. Mathematical Model for Modified Differential Relay

The modified dual slope characteristics of differential relay can be written mathematically as two straight line equations (Fig. 3). The initial slope, K_1 and pickup current represented by 'b' in straight line equation are fixed irrespective of the wind generators in operation. The second slope, K_2 and the cross over point to the second slope, S changes according to the operating conditions of the wind farm.

The first equation is

$$y = K_1 x + b \quad \text{when} \quad 0 \leq x \leq S \tag{5}$$

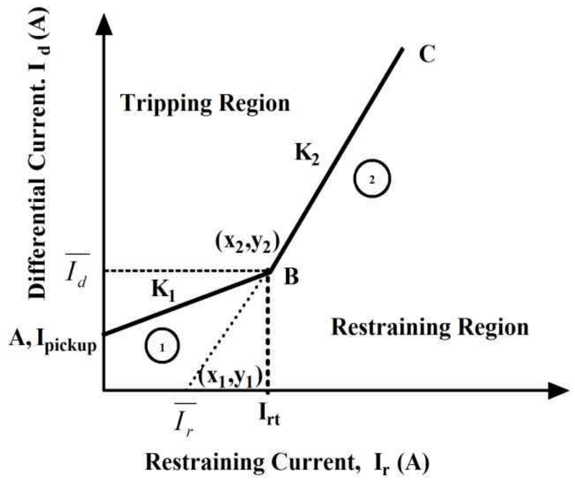

Fig. 3. Mathematical modeling of modified dual slope characteristics

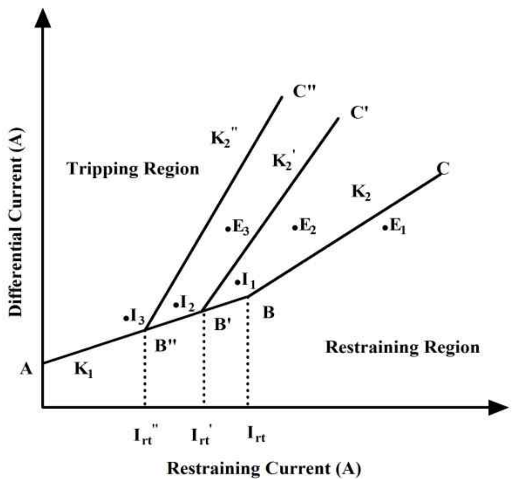

Fig. 4. Modified dual slope characteristics for transformerer differential protection

where b is the pickup current (I_{pickup}), K_1 is the slope, S is the cross over point which is I_{rt}. The value of pickup current is usually 5% of differential current.

$$I_{pickup} = 0.05 \times I_d \text{ and } K_1 = \frac{I_d}{I_r} \tag{6}$$

The value of I_{pickup} and K_1 is selected as 0.15 A and 21% respectively. The equation can be written as

$$I_d = 0.21 I_r + 0.15 \text{ when } 0 \le x \le I_{rt} \tag{7}$$

Beyond the cross over point, S the equation can be formulated as

$$y = K_2 (x - x_1) + y_1 \text{ when } x \ge S \tag{8}$$

where $K_2 = (y_2-y_1)/(x_2-x_1)$ is the slope of the line 2 in the Fig. 3. (x_1, y_1) and (x_2, y_2) are the two points in the straight line 2. The point x_1 represents restraining current at $I_d = 0$ ($I_1 = I_2$) which is shown as $\overline{I_r}$ and the corresponding $y_1 = 0$. The point x_2 is the crossover point, I_{rt} and the corresponding y_2 is $\overline{I_d}$. The equation can be rewritten as

$$I_d = K_2 (I_r - \overline{I_r}) \text{ where } K_2 = \frac{\overline{I_d}}{I_{rt} - \overline{I_r}} \tag{9}$$

The modified characteristic of dual slope differential protection is shown in Fig. 4. The relay operating point is dynamic according to the wind power penetration. Therefore, the dual slope characteristics of the differential relay need to be varied and not to be fixed according to the changing wind farm current. I_1, I_2, I_3 and E_1, E_2, E_3 represent the operating points corresponding to internal and external fault current, according to the variation of wind generators in service.

I_1 and E_1 is the internal and external fault operating point with all wind generators in service and when the wind power penetration is reduced the operating points are shifted to I_2 and E_2. The points I_3 and E_3 show the operating points when the output from the wind farm is zero and only the grid is connected. The operating points are calculated based on the short circuit analysis of the system. To provide the sensitivity of relay operation to internal fault and selectivity towards external fault, the characteristics should be variable according to wind power penetration. Therefore, the characteristics should be in between the limits ABC and AB"C" as shown in Fig. 4.

ABC represent the characteristics of the differential relay with the full installed capacity of wind farm and AB'C' gives settings when the wind generator number is between the maximum and minimum limits. The characteristic AB"C" represents the settings of the relay without any wind farm. The equation for the modified differential relay becomes

$$i_d \ge K_2' i_r + (K_2' - K_1) i_{rt}' + I_{pickup} \tag{10}$$

where K_1 is the initial slope, K_2' is the second slope which is variable according to wind power penetration, I_{pickup} is the pickup current, i_{rt}' is the modified cross over point to the second slope, according to the varying wind farm current, i_d is the differential current and i_r is the restraining current. In the presence of wind farms, the limits for change over point to the second slope and the second slope becomes

$$\begin{aligned} &K_2 = K_2'' \text{when } n_g = n_0, K_2 = K_2' \\ &\text{when } n_0 < n_g < n_{\max} \text{ and } K_2 = K_2 \text{when } n_g = n_{max} \end{aligned} \tag{11}$$

$$\begin{aligned} &I_{rt} = I_{rt}'' \text{when } n_g = n_0, I_{rt} = I_{rt}' \\ &\text{when } n_0 < n_g < n_{\max} \text{ and } I_{rt} = I_{rt} \text{when } n_g = n_{\max} \end{aligned} \tag{12}$$

where K_2, K_2' and K_2'' are the final slopes, I_{rt}, I_{rt}' and I_{rt}'' are the crossover point to the second slope, n_g is the number of wind generators, n_0 means that there are no wind generators in service and n_{max} is the maximum number of wind generators in the wind farm.

4. Algorithm for Modified Differential Relay

The flow chart representation of the algorithm for the modified differential relay is shown in Fig. 5. The currents from the primary side and secondary side CTs of the transformer and the wind farm are measured for calculating the differential and restraining current.

The inrush and over excitation conditions are separated based on the harmonic component of the differential current. The second and the fifth harmonics levels of differential current during inrush and over excitation conditions are always greater than 30% irrespective of the total number of wind generators in operation. So the harmonics component of the current need not be checked for each data window as this procedure makes the proposed algorithm slower. Based on the total installed capacity of the wind farm the setting points of the pickup current, initial and final slopes, change over points of the slopes are fixed. The tripping signal is issued when the differential current exceeds the percentage of the restraining current (Eq. 10). The algorithm updates the set points of the differential relay according to the measured value of wind farm current. In the algorithm, time step is chosen as 50 µs. Hence the sampling frequency will be 20 kHz. We are using Fast Fourier Transform (FFT) windowing technique in which the number of harmonics is selected as 7. For 50 Hz system, the cycle requires 20 ms to complete and therefore the window is of sliding type of 20 ms length which calculates each samples at 2.5 ms.

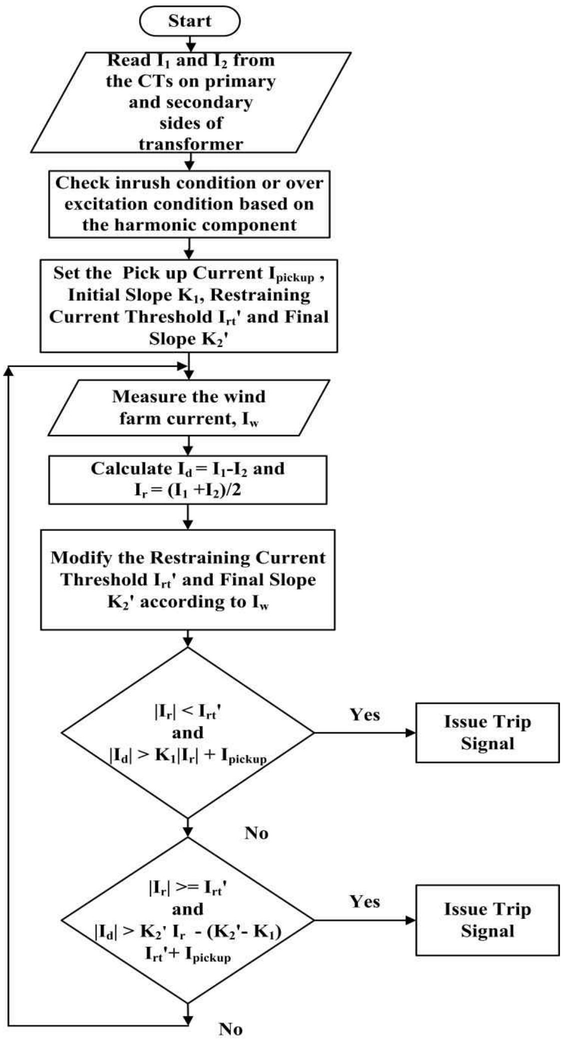

Fig. 5. Flow chart of modified dual slope differential relay

5. Case Study

The proposed algorithm for transformer differential protection has been implemented in various scenarios including IEEE test systems, real systems and the accuracy has been verified.The simulation has been done for various internal and external faults including turn to ground fault, turn to turn fault, winding to core fault, LG, LLG, LLL and LLLG faults. The algorithm is applied to wind farms with Squirrel Cage Induction Generators (SCIG), Double Fed Induction Generators (DFIG) and Synchronous Generators (SG). The case study of only one typical real system (Fig. 6) is presented in the manuscript due to the limitations of space. The detailed results and it's comparison with the conventional algorithms are included under section 6. Different operating conditions including CT saturation, inrush condition and over excitation are taken into consideration and the relay doesn't issue unnecessary trip signal.

The wind farm consists of nine units of Vestas 225 kW wind turbines with a total installed capacity of 2.025 MW. The wind generator associated with the turbine is Squirrel Cage Induction Generator (SCIG). The different conditions according to wind dynamicity are simulated using PSCAD/EMTP software. The simulation parameters are given in Appendix.

The wind generators are connected to the grid through three feeders, and three wind generators are connected to

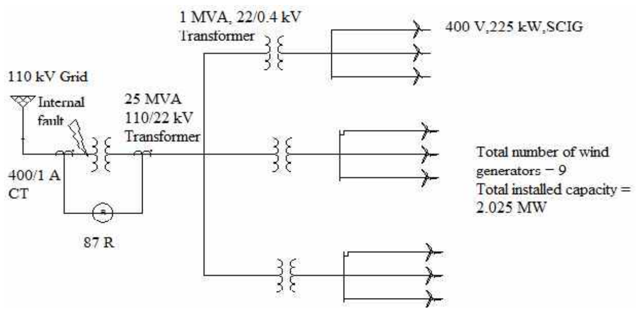

Fig. 6. Layout of a typical wind farm

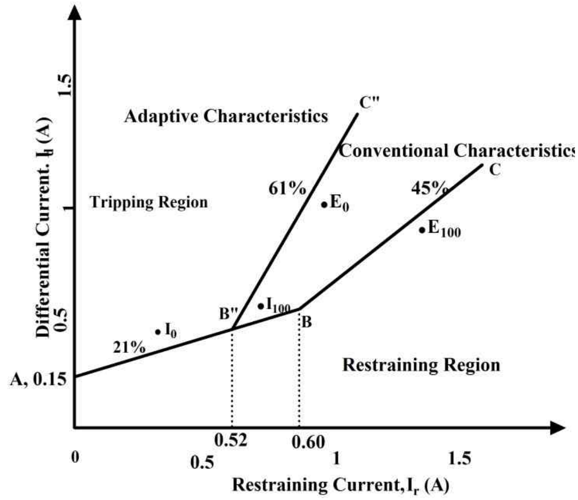

Fig. 7. Operating points during internal fault and external fault conditions according to the variation in wind power penetration

each feeder. The output voltage from each wind generator is 400 V, and it is stepped up to 22 kV with a 1 MVA transformer connected to each feeder. The wind generators are connected to the power grid through 25 MVA, 22/110 kV transformer, where differential protection is employed. The islanding mode of operation is not possible in this case as the wind generator is always connected to the grid and the wind farm is not associated with any isolated load. The reactive power compensation is carried out by 100 kVAr capacitor bank to avoid voltage drop and improve power factor.

The Fig. 7 shows the operating points of transformer differential relay during internal and external fault conditions. The short circuit analysis of the system is carried out to find the operating points during various internal and external fault conditions. Fig. 7 shows the operating points of transformer differential relay during symmetrical fault. E_{100} and I_{100} are the external and internal fault (Three phase short circuit fault) operating point when the total numbers of wind generators are connected to the grid or the wind farm is running at its rated capacity.

The characteristics ABC is fixed based on the total installed capacity of the wind farm. The pickup current, initial slope, final slope and change over point to the second slope is fixed such that I_{100} is in tripping zone and E_{100} is in restraining region. The operating point during internal and external fault condition is shifted when the number of wind generator in operation is reduced due to the non availability of wind. E_0 and I_0 are the operating points during internal and external fault conditions (Three phase short circuit fault) with no wind power penetration to the grid. The characteristics ABC is not suitable at this condition as the point E_0 is in tripping zone and therefore the characteristics is modified to AB"C" at this condition. The cross over point to the second slope i.e. 0.60 A is shifted to 0.52 A and second slope percentage is changed from 45% to 61% in order to obtain new characteristics AB"C" from ABC. The characteristics AB"C" is not reliable during the increased addition of wind generators as the internal fault operating point (I_{100}) is in non tripping zone. Therefore the characteristics should be selected according to the wind generators in service or with the variation in wind speed.

The simulation is carried out for internal and external faults using PSCAD software in the primary as well as the secondary side of the transformer. The various internal faults considered are turn to ground, turn to turn faults and winding to core faults. The minimum and maximum internal fault current values are 5.44 kA and 30.34 kA respectively. The external faults studied are line to ground, line to line, double line to ground and three phase short circuit fault and the minimum and maximum external fault current values are 12.86 kA and 27.84 kA respectively. The fault is maintained for 0.1 s time interval in the simulation. The relay senses the fault and issues the trip signal to circuit breaker immediately after the detection of fault.

The internal fault is simulated at 5 s and the external fault is simulated at 5.2 s in the wind farm side. In a practical case the circuit breaker opens and isolates the wind farm side when the differential relay issues a trip signal immediately after the detection of the fault. The detailed simulation results are presented under the section 6. The current axis in the Figs. 10, 11, 13-15 and 16 refers to the RMS value in the secondary side of the current transformer. The heavy saturation condition of current transformer during external fault condition was taken into consideration and the differential relay did not issue any trip signal.

The relay setting is normally fixed on the assumption that all wind generators are present in the system and are running at their rated capacity. The dual slope differential relay has four settings. Pick up Current Setting – The pickup current setting should be greater than the magnetizing current of the current transformer. The setting can vary from 5% to 20% of the differential current. The pickup current setting is fixed as 0.15 A in this case. Initial Slope – The initial slope is set to allow for off-nominal tap settings and current transformer (CT) mismatch error. Normally 1.25% is provided for each tap. The slope can vary between 10% to 40%. Here the slope is taken as 21%. The beginning of the second slope or the change over point to second slope is greater than the rated current to cater for heavy through fault conditions. The break point can vary from 1.0 to 10.0 pu of current. The change over point is taken as 0.60 A of CT secondary current in this case. Final Slope – The value of slope should be selected such a way that it should provide selectivity towards external fault. The range of the slope can vary from 40% to 70%. The slope value is selected in such a way that it should be sensitive to maximum external fault. The second slope value is fixed as 45% in this case. The wind farm current is fed to the current sensors of the numerical differential relay in which algorithm is written and the setting is updated. When the wind farm is running at its rated capacity, the differential relay operates only for internal faults and does not operate for external faults, and there is no mal-operation.

Harmonic restraint based differential relay, blocks the mal-operation of differential relays during inrush as well as over excitation conditions. The second harmonic component and the fifth harmonic component are used to identify and block the mal-function of the differential relay when the harmonic component exceeds the threshold value of 30%. The second harmonic component helps to detect inrush, and the fifth harmonic component is used to identify the over excitation condition. The transformer differential algorithm will not issue any trip signal at the transformer inrush and over excitation condition. The internal faults are simulated in the presence of energizing conditions and the proposed algorithm issues the trip signal.

The major problem associated with the wind farm is that its output power is not constant, and it is varies continuously based on the availability of wind. The wind generators put in service are reduced due to the non-availability of wind. The differential relay with existing settings mal-operates as it will trip for the external fault which is simulated at 5.2 s. When the wind generators put in service is reduced, the relay mal-operates during external fault conditions as it issues the trip signal.

The Table 1 gives the modification required for dual slope settings for differential protection according to the wind generators put in service. The wind speed is also varied and the modified setting for the differential relay is found out and the result has been given in the Table 2.

Table 1. Modified differential relay setting according to the wind generators in service

Number of wind generators in service	I_{pickup} (Pickup Current, A)	K_1 (Initial Slope, %)	I_{rt} (Bias Current Threshold, A)	K_2 (Final Slope, %)
9	0.15	21	0.60	45
8	0.15	21	0.60	47
7	0.15	21	0.58	49
6	0.15	21	0.56	50
5	0.15	21	0.56	53
4	0.15	21	0.55	55
3	0.15	21	0.54	57
2	0.15	21	0.53	59
1	0.15	21	0.53	60
Nil	0.15	21	0.52	61

Table 2. Modified differential relay setting according to the wind speed

Wind Speed (m/s)	I_{pickup} (Pickup Current, A)	K_1 (Initial Slope, %)	I_{rt} (Bias Current Threshold, A)	K_2 (Final Slope, %)
24	0.15	21	0.55	52
20	0.15	21	0.54	52
15	0.15	21	0.54	57
10	0.15	21	0.52	57
7	0.15	21	0.52	56

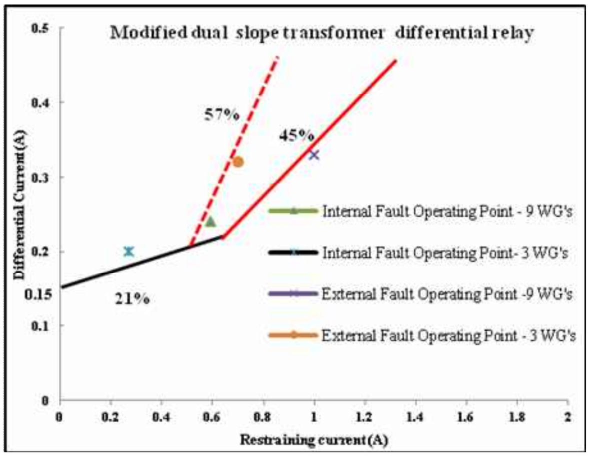

Fig. 8. Modified dual slope characteristics according to varying wind power penetration

The Fig. 8 shows the modification of transformer differential relay characteristics. Instead of single characteristics a limit for the characteristics is provided to avoid differential relay mal-operation. The operating points corresponding to the internal and external fault are in the tripping region and in the restricting zone respectively. The operating points are obtained by calculating fault current using short circuit module in the ETAP software. The characteristics selected for 9 wind generators and 3 wind generators are given in the Fig. 8. The characteristics are selected in such a way that the internal fault operating point is in the tripping zone and the external fault operating point is in the restraining region. The proposed algorithm was also tested during energizing conditions in the presence of internal fault and the relay issues the trip signal. The different conditions including the variation of short circuit currents, changes of taps in the high voltage side, CT saturation and the simultaneous occurrence of internal and external faults are also simulated and the relay operates without any mal-function.

6. Comparison of Modified Dual Slope Algorithm with the Conventional Single Slope and Dual Slope Differential Relay

The proposed modified differential algorithm is compared with conventional single slope and dual slope differential algorithm. The slope value varies between 40% to 80% in single slope algorithm which has been proposed in [29-30]. However this single slope differential relay does not provide correct decisions during low resistance external fault and inter turn fault which involves 2.5% turns at an incipient level. A dual slope algorithm is proposed in [31] which issues trip signal for internal fault and does not operate for external faults. The dual

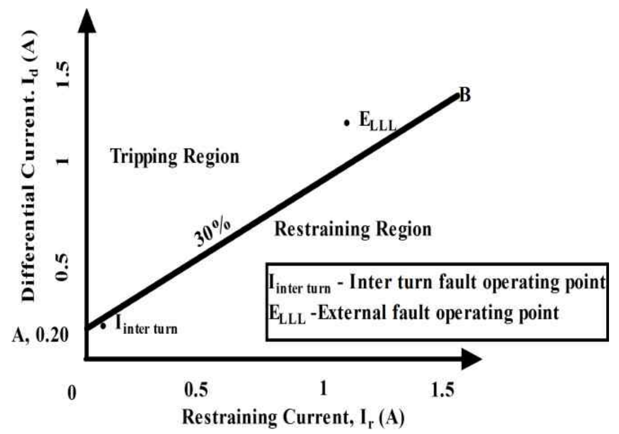

Fig. 9. Single slope characteristics with external fault and internal fault operating points

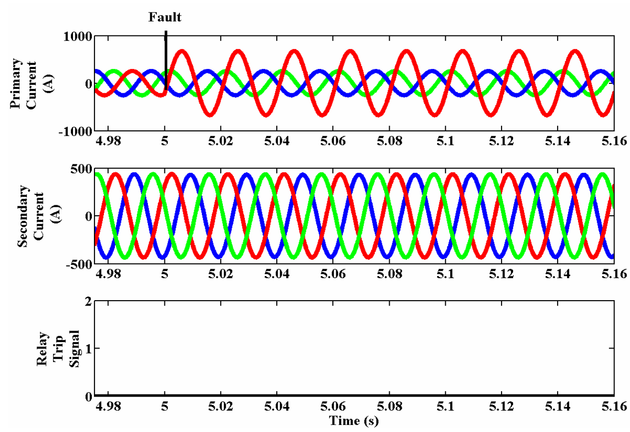

Fig. 10. Primary Current, Secondary Current and Trip signal for the single slope differential relay during inter turn internal fault

slope algorithm mal-functions for external fault in wind integrated system due to the dynamic conditions of the wind farm.

The operating points during the external fault (LLL fault) and internal fault (turn to turn fault) conditions are illustrated in Fig. 9. The graph shows that the single slope differential relay mal-operates for low resistance external fault and inter turn fault as the operating point is in the tripping region and restraining region respectively.

The Fig. 10 shows the primary current, secondary current and trip signal during internal fault conditions. The internal fault taken into consideration is turn to turn fault (2.5% turns) which is less sensitive as the differential current is small. The differential relay does not issue trip signal for internal fault at 5 s.

The Fig. 11 demonstrates that the current signal and relay status for differential relay with single slope algorithm tested with the external fault. The different types of external faults (LG, LLL and LLG) are simulated and it is noted that the differential relay issues unnecessary trip signal for low resistance external fault which is simulated

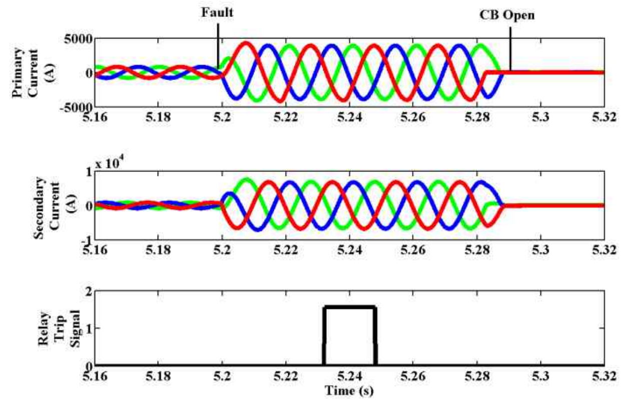

Fig. 11. Primary Current, Secondary Current and Trip signal for the single slope differential relay during low resistance LLL external fault

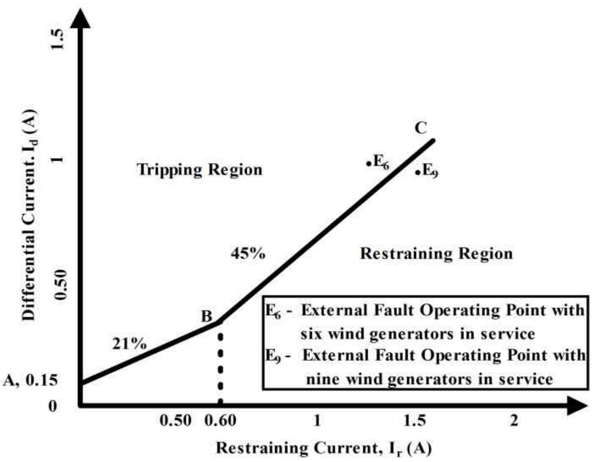

Fig. 12. Dual slope characteristics with the external fault operating point in the presence of wind farms

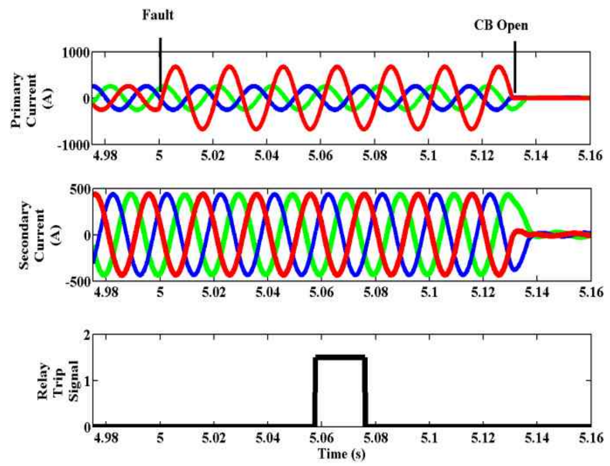

Fig. 13. Primary Current, Secondary Current and Trip signal for the dual slope differential relay during turn to turn internal fault (All the wind generators are not in service)

at 5.2 s. In this case, since the fault current is large, the operating point is in the tripping zone and the relay issues

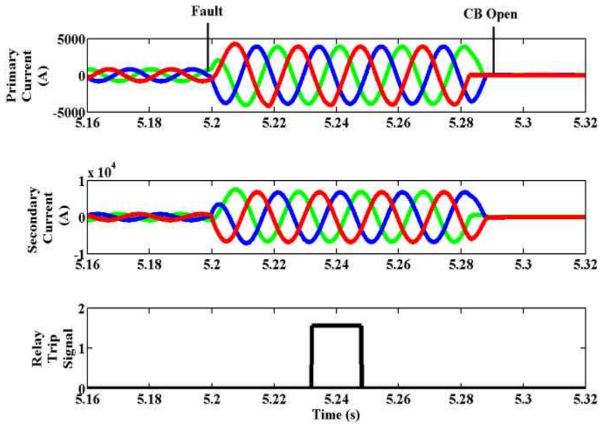

Fig. 14. Primary Current, Secondary Current and Trip signal for the differential relay during low resistance LLL external fault (All the wind generators are not in service)

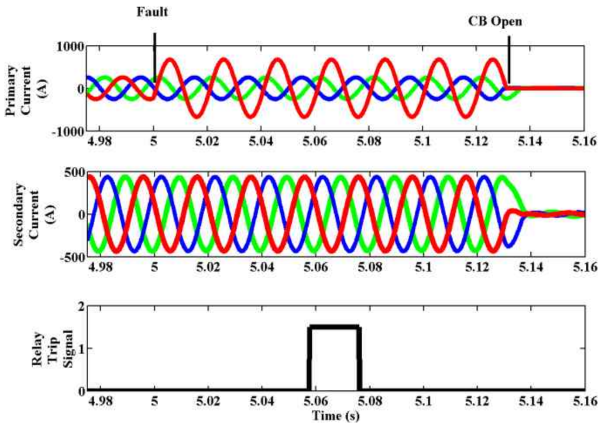

Fig. 15. Primary Current, Secondary Current and Trip signal for the modified dual slope differential relay during turn to turn internal fault (All the wind generators are not in service)

the trip signal.

The mal-function of relays with single slope algorithm can be avoided by dual slope characteristics. However the existing dual slope algorithm [31] is not suitable for wind farms. The fault current will vary according to the operating status of the wind generators. The operating point during external fault conditions when nine and six wind generators in service is shown in the Fig. 12. The operating point E_6 is in tripping zone which causes the mal-operation.

The primary current, secondary current and trip signal of the differential relay for the wind farms which is operating at its reduced capacity is given in the Figs. 13 and 14. The wind generator in service is reduced to six and the relay mal-operates for external fault as operating point is in the tripping zone. The relay issues trip signal for low intensity inter turn fault which is taken into consideration, by the proposed algorithm.

The Figs. 15 and 16 shows the current and trip signal

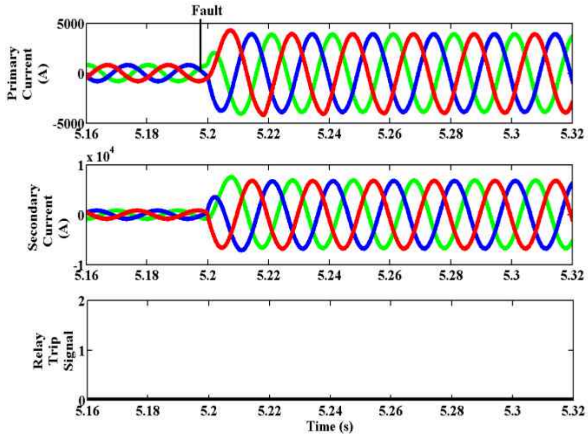

Fig. 16. Primary Current, Secondary Current and Trip signal for the modified differential relay during are low resistance LLL external fault (All the wind generators not in service)

Table 3. Comparison of existing algorithms and proposed algorithm for transformer differential protection

Fault Type	Fault Details	Single Slope [29-30]	Dual Slope [31]	Modified Dual Slope Differential Relay [Proposed]
No Fault	Nil	Restrain	Restrain	Restrain
External Fault	LG	Trip	Trip	Restrain
	LLG	Trip	Trip	Restrain
	LLLG	Trip	Trip	Restrain
	LLL	Trip	Trip	Restrain
Internal Fault	Turn To Ground	Restrain	Trip	Trip
	Turn To Turn	Restrain	Trip	Trip
	Winding To Core	Restrain	Trip	Trip

after incorporating the modified dual slope differential relay algorithm. The relay issues tripping signal for internal faults and will not operate for external faults.

The comparison between conventional single slope, dual slope and modified dual slope algorithm is given in the Table 3. The various fault types considered are LG, LLG, LLLG, LLL (external faults) and turn to ground, turn to turn, winding to core (internal faults). The simulation results for LLL and turn to turn faults are only shown as the modified differential relay algorithm operates in a similar manner for LG, LLG, LLL, turn to ground and winding to core faults.

7. Conclusion

The differential protection provides primary protection for the transformer faults which discriminate internal faults from external faults, CT saturation, inrush condition and over excitation. The mal-functioning of the differential relay due to wind farms has not been addressed in any of the literatures. A typical wind farm connected to the grid is simulated, and as the wind power output changes there is mal-functioning of conventional dual slope transformer differential relay. An algorithm for transformer differential protection is developed in which dual slope characteristics continuously vary with the changes in wind power penetration. Instead of a single set point, a range of set points for the characteristics is proposed in the modified algorithm. The proposed algorithm is validated using case studies and it is satisfactorily working for different operating conditions.

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Appendix

Power Transformer

Parameters	Quantity
Transformer MVA	25
Primary Voltage	22 kV
Secondary Voltage	110 kV
Vector Group	Yy0
Base Operation Frequency	50 Hz
Leakage Reactance	0.0010 pu
Ratio - Yoke/Winding : Limb length	1.22
Ratio - Yoke/Winding : Limb Area	0.8

Current Transformer

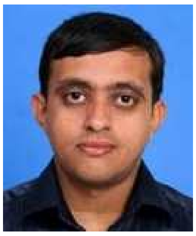
Parameters	Quantity	
	Primary Side	Secondary Side
Primary Turns	5	5
Secondary Turns	3000	120
Secondary Resistance	1.08	0.04
Secondary Inductance	0.8e-3	1.3e-3

Wind Turbine

Parameters	Quantity
Generator Rated KVA	850
Machine rated angular mechanical speed	3.14 rad/s
Rotor Radius	46.2 m
Rotor Area	6716 m^2
Air Density	1.225 kg/m^3
Gear Ratio - Machine: Turbine	1

Wind Generator

Parameters	Quantity
Rated RMS Voltage	0.400 kV
Rated RMS Line Current	1.45 kA
Inertia Constant	6.3 s
Armature Time Constant	0.332 s



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