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Transient current similarity based protection for wind farm transmission lines

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HIGHLIGHTS

- Problem of traditional line current differential relay is analyzed.
- A transient current similarity based protection is proposed for wind farm transmission lines.
- The correlation coefficient is adopted to calculate the similarity of fault transients.
- Field testing data is used to prove the proposed method.
- The novel protection offers accurate performance considering all the possible influence factors.

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ABSTRACT

Large-scale wind farms are usually integrated into the transmission system. Applying traditional steady-state power-frequency based protection strategies in these transmission lines creates challenges such as: (1) the fault current of the wind farm might be dominated by non-power-frequency components caused by the activation of their own protection systems during fault ride through (FRT). The frequency of the dominant component is determined by the rotor speed at the fault inception and might vary from 0.7 to 1.3 times the power frequency. This will create errors in phasors calculated at the power-frequency. (2) The steady-state fault current angles of wind farms are fully controlled by their power converters. The variety of control actions of the different converters during FRT makes these phase angles greatly deviate from those of the synchronous generators. Protection systems that use double-ended phasors such as current differential schemes will suffer from low sensitivity or even malfunction when large-scale wind farms are integrated. Therefore, a novel full-time transient current waveform similarity based protection scheme is proposed to deal with these issues. The full-time current protection scheme uses both the power-frequency and non-power-frequency characteristics and can therefore reduce the influence of power-frequency phasor calculation errors to a minimum. The proposed method uses the transient current (within 10 ms after the fault inception) and is ignores the features of the steady-state fault current. In other words, the proposed protection is suitable for wind farms with a variety of controls. In the proposed method, the correlation coefficient index is used to calculate the similarity of the transient current signals at both ends of the line. Both experimental and field testing results show that using a common sampling frequency, the proposed protection scheme only uses current information and can correctly identify all types of external and internal line faults in a short period of time and can offer better performance for high fault resistance and noise, both for different types of wind farms. All these features and contributions make the new protection feasible for industry application.

1. Introduction

As an effective method to handle with the growing fossil fuel crisis and increasing environmental pollution, renewable energies such as wind and solar have been widely exploited [1–3]. Wind power, as an alternative to burning fossil fuels, is renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation [4–7]. Wind power in particular is growing rapidly at high power levels. The total global installed wind power capacity reached 539.6 GW by the end of 2017, with more than 52.57 GW of new capacity installed

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Nomenclature

I_{op}, I_{res}	the operate current and restraint current of differential protection
k	the restraint coefficient of differential protection
I_W, I_S	the current measured at the wind farm side and the grid side
ϕ	a symbol standing for phase A, B or C
K	the control factor denoting the used control strategy
$i_{dq}{}^{+(-)}$, $e_{dq}{}^{+(-)}$	the positive- (negative-)sequence current and voltage amplitudes
P^*, Q^*	the target active and reactive power commands
I_{cap}	the total capacitive current
$E_{q\|0\|}$, x_d	the inner electromotive force and reactance of the generator
x_d'', x_d'	subtransient and transient reactance
T_d'', T_d'	subtransient and transient time constant
$f(*)$, $g(*)$	a functional that is performed on $*$
k_r	the coefficient related with inductances of wind turbine generators
$r(x, y)$	the correlation coefficient of x and y
r_φ	the correlation coefficient of the same phase currents measured at both terminals of transmission lines

[8,9]. Benefiting from advanced manufacturing techniques and reduced cost, centralized large scale wind farms can be of the order of several hundred megawatts and their short-circuit capacity can be close to that of integrated power systems in certain areas [10–14]. However, areas rich in wind energy, especially offshore wind farms, tend to have little demand for loads [15–17]. Without local loads, these large wind farms are usually integrated into transmission networks directly and inevitably are required to be capable of fault ride through (FRT) for stable operation of the power system during faults.

In order to protect the rotor side converter (RSC) of type-III wind turbine generator which is also called doubly fed induction generator (DFIG), the wind generator is allowed to disconnect from the power grid during a fault; the RSC connects active resistances (the "crowbar" circuit) which maintain the transient stability of DFIG based wind turbines [18–20]. The crowbar circuit is not enough to meet the transient stability requirement for the system for high penetration levels of type-III wind farms [21,22]. Many improved RSC control methods have been proposed to suppress the overcurrent and improve transient stability. Parallel static VAR compensators (SVC) or static synchronous compensators (STATCOM) can increase the voltage of the wind farm to a certain extent [23]. However, due to their considerable construction cost and the effects of system parameter variations, they should be replaced by other more economic and more effective methods. Energy storage devices are effective in suppressing the overcurrent [24,25]. However, quantities such as electromagnetic torque (internal control parameters of the DFIG) cannot be improved by external energy storage devices. In addition, the complex control strategies and the high costs limit its large-scale application in DFIG wind farms. Compared with advanced control strategies and additional parallel compensators, utilizing series FCLs is a simple and effective method to improve transient stability, which can limit short-circuit current by increasing impedance during a fault [20,21,26]. Due to the above FRT strategies [27–28], the fault current of the wind farm is dominated by the rotor-speed-related frequency component and it shows limited amplitude and controlled phase angle [29–31]. Those features bring challenges to traditional power-frequency based distance protection and current differential protection. Problems and their solutions concerning distance protection are well studied in [32–36]. The tripping boundaries of the distance relay are designed in a way that all faults (even with different fault resistances) at all points of the transmission line are placed inside the boundaries. It has been shown that the variations of system internal impedance, output voltage, frequency and wind speed are all related to each other and might cause mal-operation of distance relays [33,34]. For line current differential protection, research considers type-III wind farms without any solution. New protection schemes that can theoretically address the all types of problems in wind farms' generally have yet to be reported. In [37], considering a type-III wind farm with a short-circuit capacity much smaller than that of the main grid, simulation results show that a line current differential relay can operate correctly for both internal and external faults, but when the crowbar protection of type-III wind farm is activated, the component of a rotor-speed-related frequency dominates the fault current [38]. This non-fundamental frequency component can lead to inaccurate calculation of the power frequency current and malfunction of differential relays when the wind farm has a comparable short-circuit capacity to the integrated power system [39].

For type-IV wind farms which consists of permanent magnet synchronous generators (PMSG), the fault current can be fully controlled by inverters and its phase angles are fixed to a certain degree during FRT [37]. There can be a large deviation from the phase angle of the synchronous generator and might lead to malfunction of the line current differential relay if the wind farms have a large short-circuit capacity. This issue will be discussed in detail in this paper. The distinctive fault features brought by the FRT strategies will cause malfunction of line current differential relays for both type-III and type-IV large scale wind farms.

Generally, the reasons for the malfunction of existing protection schemes in the transmission system connected with large scale wind farms can be summarized as: (1) the fault current of wind farms might be dominated by a non-power-frequency component because of the converter self-protection system operating during the fault ride through (FRT). This will bring large errors to the calculation of power-frequency current using for example a full-cycle Fourier algorithm; (2) Steady-state fault current angles of wind farms are fully controlled by the power converters and have very different characteristics from those of synchronous generators. Traditional system phasor measurement based protection might malfunction.

Based on these two major issues, this paper proposes a novel full-time transient current similarity based protection scheme for wind farm transmission lines. The contributions are: (1) Unlike traditional protection which relies on system frequency measurement, the full-time current protection uses both power-frequency and non-power-frequency characteristics and avoids power-frequency phasor calculation errors caused by the special fault characteristics introduced by wind farms. (2) The transient current used for protection is immune to steady-state fault current features that can be easily influenced by the different control schemes used by wind farms. In other words, the proposed protection is suitable for wind farms with a variety of controls during FRT. (3) The correlation coefficient index is used to calculate the similarity of transient current signals at both ends of the line. Both experimental and field testing results show that using a common sampling frequency and computation speed, the proposed protection scheme can identify all types of external and internal line faults correctly in a short period time and offers good performance in the case of a high fault resistance and noise. These features make the new protection feasible for industry application.

2. Problem statement for traditional current differential relays

With the advantages of good selectivity and high speed, current differential protection is widely used in transmission lines. This is still the case for lines connected to large scale wind farms. For a clear