A Novel Differential-based Protection Scheme for Intertie Zone of Large-Scale Centralized DFIG Wind Farms

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Abstract- ***Doubly Fed Induction Generator (DFIG) wind farms as a reliable source of renewable energy have been increasingly integrated to power grid in the last two decades. Distance protection relay has continuously been the most common protection scheme implemented for wind farm intertie zone, however, nowadays with the enormous penetration of large-scale DFIG wind farms, these relays are no longer reliable, due to their incapability of providing accurate impedance measurement during internal and external faults, thus, causing maloperation, false tripping or delayed operation. In this study, a differential-based protective relay scheme is developed in Matlab/Simulink in order to provide reliable protection for wind farm intertie zone. Also, an aggregated model of a large-scale centralized wind farm has been designed to examine the performance of the proposed protection technique by imposing numerous internal and external faults at different locations. The results proved that differential-based protection relays (DBPR) are able to provide reliable, efficient and robust protection for the intertie zone of wind farms. Because, the differential relays provide high sensitivity, swift operation, immunity to power swings, and also inherently being a unit protection-based scheme that is extremely advantageous compared to distance relays. Moreover, unlike distance relays DBPRs do not require to cope with "underreach" and "overreach" characteristics, resulting in no false tripping during external faults.***

Index Terms- ***Distance relay, Differential relay, Overcurrent relay, Wind farm protection, Power system protection, Intertie system, Protective relays coordination***

I. INTRODUCTION

Wind farms as a small scale distributed generation (DG) source in microgrids, or as large-scale centralized power plant have emerged to become a crucial part of power generation in recent years [1]. The accumulative wind turbine capacity installed worldwide has reached to a staggering rate of 600 GW by the end of 2018, according to World Wind Energy Association, where 59,449 MW and 53,890 MW have been added in year 2017 and 2018 respectively as shown in Fig. 1. It is estimated that 6% of the global energy demand can be provided by all wind turbines installed by the end of 2018 and this rate is slowly but steadily increasing annually which signifies the eminence of wind energy as a reliable source of power [2]. The leading countries in harnessing wind energy, in order, by the end of 2018 are: China, US, Germany, India, Spain, UK, France, Brazil, Canada and Italy [3].

The recent advancement in utilization of wind farms specifically Doubly-Fed Induction Generator (DFIG) based wind farms, have led to carrying out abundant research on improving the power quality, control, stability and Maximum Power Point Tracking (MPPT) of wind turbines, however, limited research were dedicated to power system protection and protective relaying [4] & [5]. Simple protection schemes are being used for wind farms and this would result in huge protection and security failure during fault and abnormality incidents [6]. Moreover, since wind turbine fault analysis behavior during fault is different from conventional synchronous generators, the simple settings for relays would result in maloperation and miscoordination between relays [7] & [8]. A recent report by North American Electric Reliability Corporation (NERC) has inferred that 28% of protective relays misoperation are due to improper settings and logic errors. These errors prevalently resulted from the existing relay testing procedures that do not provide a proper mechanism to easily and effectively evaluate the performance of all settings, logics, and the protection system as a whole [9]. Thus, protection schemes for wind farms need to be significantly improved to provide adequate protection and security for power apparatus in a wind farm.

Defining zones of protection is a common practice during designing protection schemes and settings of protective relays. Wind farm intertie system is among the most crucial zone of protection that have recently been addressed due to its significance and impact on the main grid and critical loads. The intertie system depending on the wind turbine technology and specific grid requirements, typically includes a step-up power transformer (usually 34.5 KV to 110 or 220 KV), transmission line, grounding transformer, VAR compensator, shunt capacitor bank, switchgear and Static Transfer Switch (STS) where the last two components are always installed at the end of intertie system on the grid side [10]. Distance protection relay is the most effective method implemented for power transmission lines, thus these protection relays are also being applied to wind farm transmission lines. Overcurrent relays are used as backup protection scheme and are coordinated with the distance protection relay and also with the next overcurrent relay in either upstream or downstream depending on the topology of the wind farm [11]. Transformer protections within the intertie system is equipped with differential relay as the

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primary protection and overcurrent relay as backup protection.

In a recent study [12] conducted for DFIG protection system, distance protection relays were used as the primary protection unit for intertie and collector system, however the fault analysis inferred that distance protection relay failed to operate properly for faults on intertie section connected to DFIG wind turbines. The maloperation of the relays were resulted from incorrect impedance measurement due to difference in frequencies of voltage and current which stem from the DFIG-based wind farm unique behavior. In another research [13] carried out using distance-based protection comprising both distance principle and pilot distance protection for a large-scale wind farm, performance of distance protection relay was unsuccessful and did not operate due to small power source characteristic of wind farm. At the very beginning of fault cycles, the decaying DC offset component has a large current and frequency magnitude, while the power frequency component is rather negligible and unstable. This would result in inaccurate power frequency component extraction from Fourier Algorithm by distance protection, consequently, the impedance between the relay and fault location is derived incorrectly, leading to misoperation of distance protection relay. Incompetency of distance relays is not only limited to DFIG-based wind farms, but also in a research carried out on SCIG-based wind farms, the impedance measured by distance relay, failed to represent the fault location and caused misoperation of the relay on zone 1 of protection [14].

The performance problems of distance protection relays can be successfully solved by implementing differential-based protection relay (DBPR) for intertie system due to its high sensitivity, swift operation and, immunity to power swings. Moreover, the differential based protection acts like a unit protection-based scheme that is extremely advantageous compared to distance relays since it is not required to cope with “underreach” and “overreach” characteristics, resulting in no false tripping. In this research, a differential-based protection scheme has been developed in Matlab/Simulink and a large-scale wind farm has also been designed to examine the effectiveness of the proposed method. These results have shown that the differential relay can be successfully implemented for protection of intertie system with robust and efficient performance for different types of faults including symmetrical and unsymmetrical types occurring within the defined zone (internal fault) of protection. It is also found that the proposed DBPR has not operated for the faults out of its designated zone (external fault) which is the desirable behavior for differential relays required for wind farm protection.

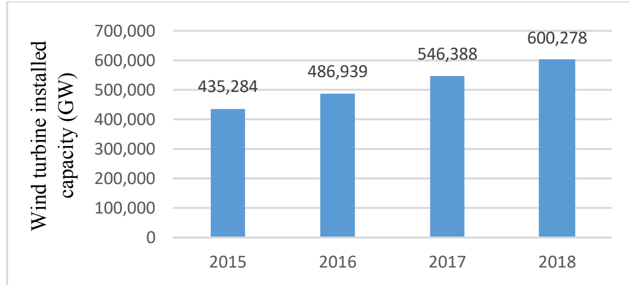

Fig. 1. Total worldwide wind turbine installed capacity.

II. DISTANCE PROTECTIVE RELAYS PERFORMANCE ISSUES IN WIND FARM INTERTIE SYSTEM

Distance protection relays are an inevitable part of transmission lines and provide proper protection in the presence of faults or grid abnormalities [15]. Distance protective relays as the name suggests, rely on the impedance at each relay which is simply measured by the division of voltage over current at the relay location [16]. During setting the distance relay, one important procedure that should be carried out is to define several zones, usually 3 zones based on the priority and significance of that particular section, and also set the settings of protection for each zone by considering the “overreaching” characteristic of relay to provide adequate and reliable protection which is of substantial importance in power system protective relaying. Although these relays are extremely effective for stable power systems, they are not as equally effective and reliable for the power systems that the source is unstable and drastically intermittent e.g. wind farm intertie systems. This is mainly due to the reason that the distance protection relay performance is drastically affected by variations in the output voltage of wind farms, source impedance and the frequency variations of the turbine [17].

According to the research in [18]-[19], distance protection relays poor performance are mainly due to poor selectivity, low sensitivity and miscoordination between distance and overcurrent relays during fault incidence. Poor selectivity is resulted from weak feed characteristics of wind generator, the proportion of positive and negative sequence components is much smaller than the proportion of zero sequence component in the collector system side short circuit current. Thus, the traditional distance protection relay may operate incorrectly. Meanwhile, since the lengths of the collector lines differ from one another, it is not easy for the setting values of line distance protection to cooperate with each other, thus poor selectivity may result. Low sensitivity is due to the reason that since wind farm intertie section are grounded via resistance or arc suppression coil, consequently during fault occurrence, the fault resistance will greatly affect the operation performance of distance protection and result in lower sensitivity to unsymmetrical faults specifically single line to ground fault due to its smaller fault current magnitude compared to symmetrical three phase faults. Lastly, miscoordination among several distance relays and with other overcurrent relays may also occur due to aforementioned problems, which would result in wrong tripping and catastrophic maloperation of relays within or outside the intertie system. Moreover, distance protection relays may operate at a longer time, and if its operation is delayed to an extent that the backup overcurrent protection acts instead of primary distance protection relay, it could cause miscoordination, compromised power quality and also unnecessary disconnection of extended healthy feeders. Thus, based on the existing problems associated with distance protection relays for the intertie section, it is clearly evident that distance protection has failed to provide proper protection and subsequently clear the fault fast and accurately. Hence, it is extremely essential to study new protection schemes to guarantee the safe operation of wind farm intertie system and power grid [20].

III. DIFFERENTIAL PROTECTION RELAY

Differential protective relays are usually employed to provide protection for a single unit commonly employed for power transformers, generators, buses, and recently, power transmission lines. However, in wind farms since there is a necessity to provide adequate protection for several zones rather than only a single unit, differential zone protection including ideal numbers of relays and measurement sensors i.e. Current Transformers (CTs) and Voltage Transformers (VTs), for each specific zone must be implemented. Differential protection operation is reliably fast, usually close to 5 ms, which could contribute to fast tripping and provide robust security for the wind farm intertie section.

The protection technique implemented for power transformers relies on the power rating of the transformer. Usually protective fuses are employed for small size power transformer that the apparent power rating is less than 10 MVA, whereas differential relays are usually used for transformers with apparent power rating above 10 MVA. A simple differential protection for a 2-winding power transformer is illustrated in Fig. 2. N_1 & N_2 are the winding turns of primary and secondary side, I_1 is the incoming current that enters the primary side of the winding while I_2 is the outgoing current from the secondary side of the transformer. I_1' & I_2' are the currents measured by the respective Current Transformers (CTs), indicated as CT_1 and CT_2. Relay restraining coil and relay operating coil are indicated as R and O respectively which are the particular fundamental structure of the differential relay where for electromechanical differential relay also known as balance beam relay, this phenomenon is shown in Fig. 3. By symbolizing the CT turn ratios of the primary and secondary as $1/n_1$ and $1/n_2$ (CT with 1 primary turn and n secondary turn), the CT secondary currents and the current passing through the relay operating coil would be:

$$I_1' = \frac{I_1}{n_1} \quad (1)$$

$$I_2' = \frac{I_2}{n_2} \quad (2)$$

$$I' = I_1' - I_2' = \frac{I_1}{n_1} - \frac{I_2}{n_2} \quad (3)$$

Differential relays are simply designed in a way that for the internal faults where $I' = I_1' - I_2' \neq 0$, the relay should trip and send a signal to the corresponding circuit breaker to disconnect the faulty section. However, for external faults where $I' = I_1' - I_2' = 0$ the relay should not operate.

According to Fig. 3, the electromagnetic force on the right and left side are $[N_0(I_1' - I_2')]^2$ & $[N_r(I_1' + I_2')/2]^2$ respectively. Thus, the differential relay operation condition can be verified as below:

$$[N_0(I_1' - I_2')]^2 > [N_r(I_1' + I_2')/2]^2 \quad (4)$$

By defining $K = \frac{N_r}{N_0}$, as slope ratio, the above equation is simplified as follows:

$$|I_1' - I_2'| > K|(I_1' + I_2')\ /\ 2| \quad (5)$$

This equation represents the tripping condition of differential relay and the relay will only trip if an internal fault occurs within the protection zone and the above equation is verified, otherwise the relay will not trip which is the desirable performance required for wind farm intertie protection system. Thus, it is rational to implement differential-based protection schemes for the step-up power transformer and transmission lines located at intertie section, to provide sufficient, reliable and robust security for the wind farm during internal faults and avoid unnecessary disconnection of healthy feeders against external fault in another location.

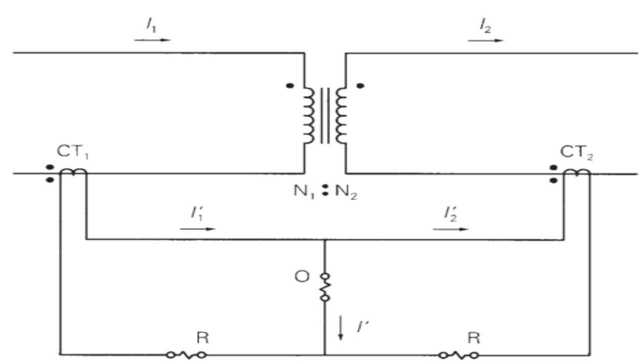

Fig. 2. Differential protection for a 2-winding power transformer.

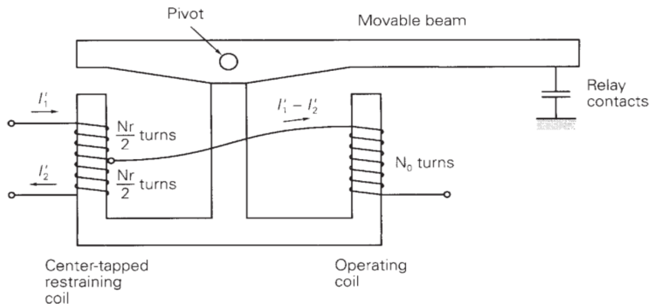

Fig. 3. Balance beam differential protection relay structure.

IV. PROPOSED DIFFERENTIAL-BASED PROTECTION SCHEME FOR INTERTIE ZONE

In order to realize the effectiveness of differential relay, a novel differential-based protection scheme has been developed in Matlab/Simulink by considering the differential relay theory presented in the previous section. The graphical interface of the developed relay has been established where presented in Fig. 4. According to this figure, in order to set the differential-based protection relay, the CT primary and secondary of both incoming and outgoing currents to the protected power apparatus, along with slope ratio, pickup current and operation time settings must be all determined accurately.

In this method, the CT primary of both incoming and outgoing current are calculated as the following:

$$CT_{pri} > 1.5 * I_{maxload} \tag{6}$$

Where CT_{pri} is the primary current of CT which is then set according to IEC or IEEE standards, while $I_{maxload}$ is the maximum current flowing through the relay during normal operation mode of wind farm. The secondary current of CTs are usually selected as either 1 or 5 A. Slope ratio (K), has also been added to the developed relay to increase or decrease the sensitivity of the relay performance against fault current. Differential relay slope ratio usually varies in range of 0.1 to 0.4 based on the protection setting needed. Furthermore, pickup current is a part of the relay setting in which the relay should operate for the current above the preset threshold value. Pickup current is usually set as 1.25 to 1.5 times of maximum load current. Finally, in order to provide coordination between differential relay and overcurrent relay as backup protection, an operation time setting has been devised, so that the relay would operate after a delayed time or even instantaneously based on the defined settings.

The developed relay logic function operates according to Eq. 5, however, we have introduced the pickup current (I_{Pickup}) and CT ratio (CT_r) to the formula as well. Additionally, the incoming and outgoing current to a power apparatus (I_1 & I_2) has been considered instead of incoming and outgoing current of CT (I_1' & I_2'). The reason we have implemented these changes is to generalize the developed differential-based protection scheme for various power systems including power transformer and transmission line within the intertie section of wind farms. The relay logic operation formula has been accordingly modified as follows:

$$\left|\frac{I_1 - I_2}{CT_r}\right| \geq k \left|\frac{I_1 + I_2}{2CT_r}\right| + \frac{I_{Pickup}}{CT_r} \tag{7}$$

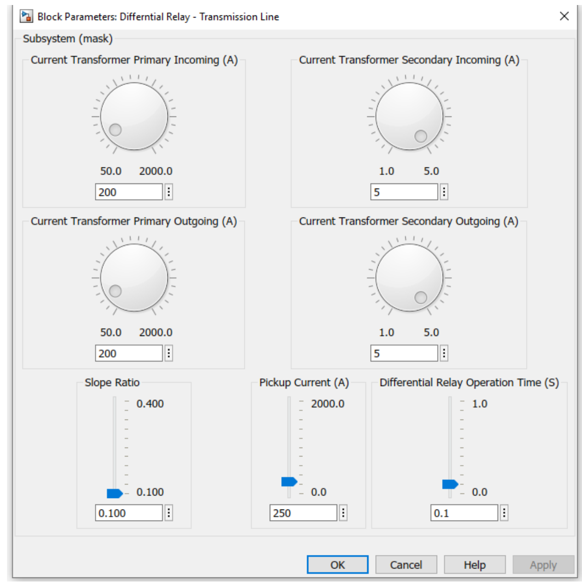

Fig. 4. Developed graphical interface of differential-based protection scheme for wind farm intertie protection zone.

V. LARGE-SCALE CENTRALIZED DFIG-BASED AGGREGATED WIND FARM MODEL UNDER STUDY

A large-scale centralized DFIG-based wind farm has been designed in Matlab/Simulink in order to study the fault analysis and examine the effectiveness of the developed differential-based protection scheme for the intertie section against various types of fault at different locations. The particular wind farm under study, consist of 40 wind turbines, each generating 1.25 MVA apparent power, operating at voltage level 575 V and frequency of 60 Hz. The local wind turbine step-up power transformer power rating is 1.5 MVA, boosting the wind turbine voltage from 575 V to 35KV, in Y-Δ connection where Y side is earthed. The whole wind farm feeds an accumulative 50 MVA to the main utility grid through a step-up power transformer and transmission line. The intertie power transformer power rating is 60 MVA, stepping up the wind farm voltage from 35 KV to 220 KV in Δ-Y connection where Y side is earthed. The intertie power transmission line has 50 KM length and has been modelled as a three phase PI line consisting of RL series impedance and two sets of shunt capacitances lumped at the beginning and end of the line.

For simplicity of the design and also faster and smoother simulation analysis, an aggregated model of the wind farm has been considered where all the 40 DFIG wind turbines are modelled as only one wind turbine, which is a common practice among researchers for conducting fault analysis and protection study. The simplified version of designed wind farm model for intuitive comprehension is illustrated in Fig. 5. Circuit Breakers have been indicated as CB1 to CB5 where CB3 and CB4 are the intertie breakers that are exclusively responsible for disconnecting the power transformer and transmission line respectively, by receiving tripping signal from the developed differential-based protection relays during internal fault incidence as depicted in this figure. Moreover, a grounding transformer has also been installed next to the intertie line in order to manage the unbalanced load on the power system as well as to handle high magnitude of excessive current during single line to ground fault.

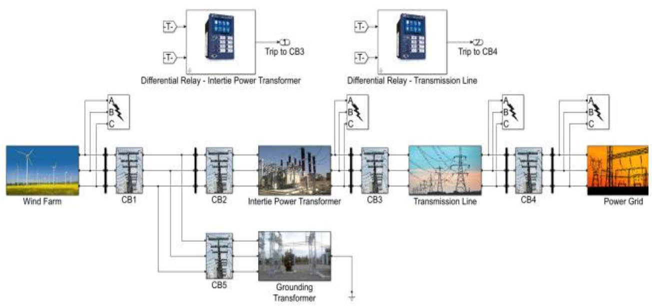

Fig. 5. Large-scale centralized DFIG-based aggregated wind farm model for protection study.

VI. WIND FARM CURRENT FLOW AND PROTECTION ANALYSIS DURING NORMAL CONDITION AND FAULT INCIDENCE

In this section, the behavior of the modelled wind farm during normal operation and fault incidence, occurring at various locations, along with the protection operation of differential-based protection scheme has been analyzed to examine the efficiency and reliability of the proposed protection scheme for various fault types including unsymmetrical faults i.e. single line to ground, double line to ground, line to line, and also symmetrical fault i.e. three phase fault. However, for simplicity of the presentation, only symmetrical 3 phase fault has been investigated in this paper.

A. Wind Farm Current Flow during Normal Operation Mode

The load flow analysis of the wind farm during normal operation when the wind velocity is 15 m/s is presented in Figs. 6-8. At this stage, no fault has been imposed to the system and the wind farm operates at a normal state. During wind farm start-up, there is a massive inrush current lasting for a few milliseconds which is absolutely common. It is worth mentioning that since the inrush current magnitude may sometimes reach as the same magnitude of fault current, the modern microprocessor-based relays are designed properly to have the capability of distinguishing between inrush current and fault current to prevent unnecessary disconnection of healthy feeders during DFIG start-up. Additionally, it takes a few seconds for wind turbine to reach the stable operation mode where in this study, it has taken approximately 9.45 seconds. After the start-up process is settled, the wind turbine continues to operate in a stable mode and provide the required power to the utility grid.

B. Wind Farm Current Flow during Internal Fault Incidence

In order to assess the performance of the developed differential-based protection relays during internal faults, two faults scenarios have been studied.

Firstly, an internal fault located on the intertie power transformer have been considered, where the imposed fault lasted for 1 second, starting at time 15 to 16 seconds. The wind farm current flow during three phase fault on the transformer, which is the most severe fault condition, have been depicted in Figs. 9-11. During internal fault on the transformer, the ideal operation of the relay on the transformer, is to disconnect the faulty section at the shortest possible time, while the second relay on the transmission line should not operate at all since the fault seen by the relay at the power transmission line is an external fault and the relay should ignore the fault and avert any unnecessary tripping signal to the circuit breaker. The operation of the differential relays at the intertie system for both the power transformer and power transmission line are shown in Figs. 12 and 13 respectively, where the relays have reacted successfully to the fault.

Secondly, an internal fault located on the intertie power transmission line have been considered, where the same as the last scenario, the imposed fault lasted for 1 second, starting at time 15 to 16 seconds. The results of fault analysis located at power transmission line has been illustrated in Figs. 14-16. During internal fault on the transmission line, the ideal operation of the relay on the transmission relay, is to disconnect the faulty section at the shortest possible time, while the second relay on the transformer should not operate at all since the fault seen by the relay at the power transformer is an external fault and the relay should ignore the fault and avert any unnecessary tripping signal to the circuit breaker. The operation of the differential relays at the intertie system for both the power transformer and power transmission line are shown in Figs. 17 and 18 respectively, where the relays have reacted accordingly to the fault.

C. Wind Farm Current Flow during External Fault Incidence

Differential-based protective relays are zone protection relays where they should only operate if an internal fault occurs in their zone of operation, and should be able to ignore any external fault occurring outside their operation zone. This phenomena has been tested for the developed relay by considering two external faults outside the intertie systems, one located at wind farm aggregated model and the other at the grid side. The fault current analysis for the wind farm has been presented in Figs. 19-21 for the fault incidence at the power grid. Since the fault has occurred outside the zone of differential protection relays, neither the transformer relay nor the transmission line relay reacted to the fault which is simply due to the reason that the condition expressed in Eq. 7 has not met. Also, for external faults, the difference between incoming and outgoing current of the relays is almost zero and the relay do not detect any fault, consequently, the circuit breaker do not disconnect healthy feeders, which is an extremely significant aspect in power system protection signifying that the relays must be able to extinguish between internal and external faults to operate properly. Reluctance of relays to operate during external faults are shown in Fig. 22.

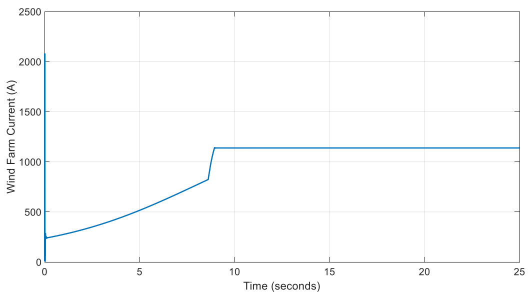

Fig. 6. Aggregated wind farm current flow during normal operation.

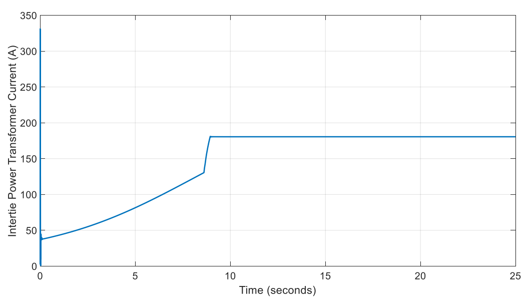

Fig. 7. Intertie power transformer current flow during normal operation.

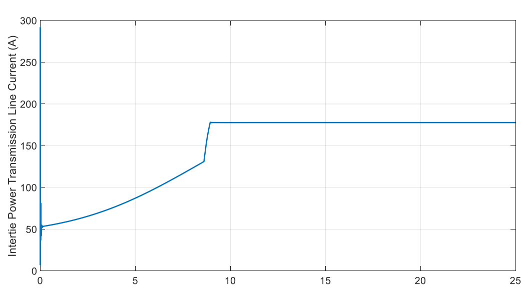

Fig. 8. Intertie power transmission line current flow during normal operation.

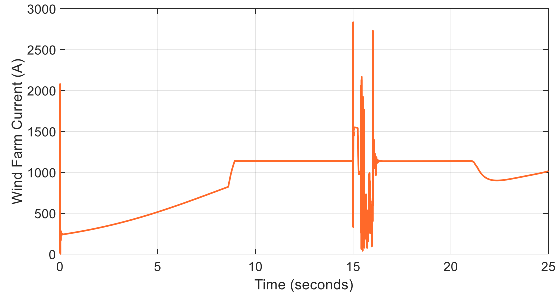

Fig. 9. Aggregated wind farm current flow during internal three phase fault on intertie power transformer.

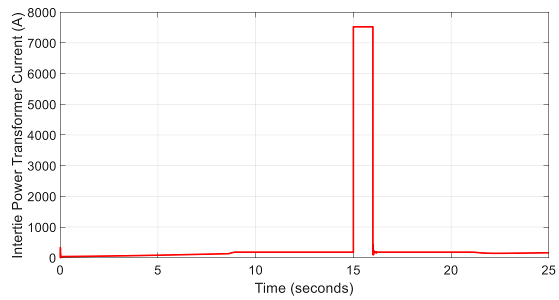

Fig. 10. Intertie power transformer current flow during internal three phase fault on intertie power transformer.

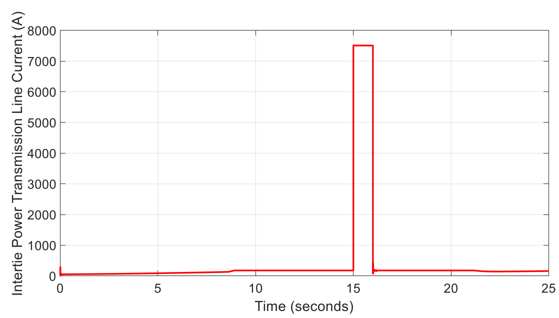

Fig. 11. Intertie power transmission line current flow during internal three phase fault on intertie power transformer.

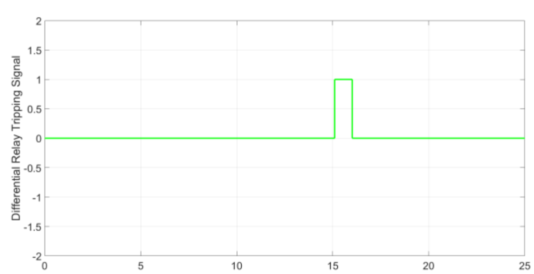

Fig. 12. Transformer differential relay successful operation during internal fault at the intertie power transformer.

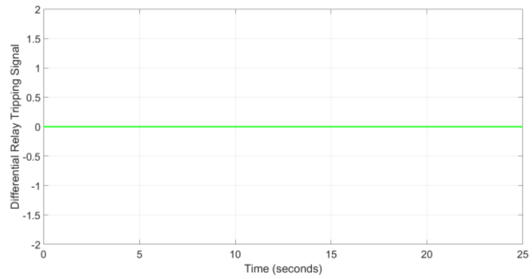

Fig. 13. Transmission line differential relay successfully ignoring fault at the intertie power transformer by considering it as an external fault.

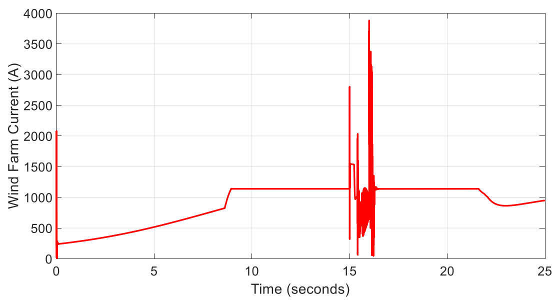

Fig. 14. Aggregated wind farm current flow during internal three phase fault on intertie power transmission line.

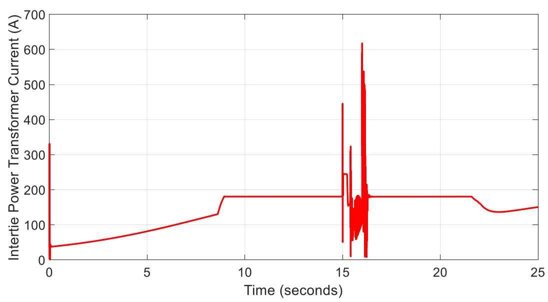

Fig. 15. Intertie power transformer current flow during internal three phase fault on intertie power transmission line.

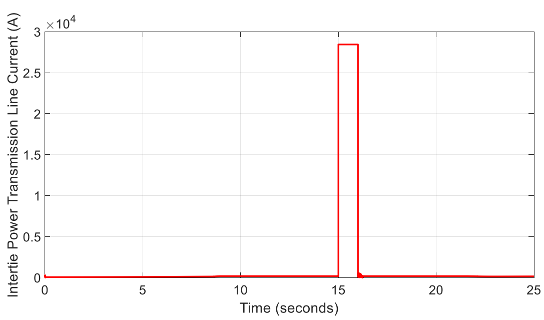

Fig. 16. Intertie power transmission line current flow during internal three phase fault on intertie power transmission line.

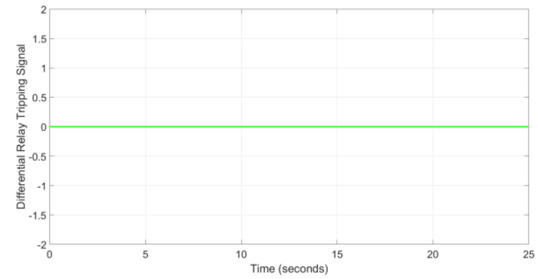

Fig. 17. Transformer differential relay successfully ignoring fault at the intertie power transmission line by considering it as an external fault.

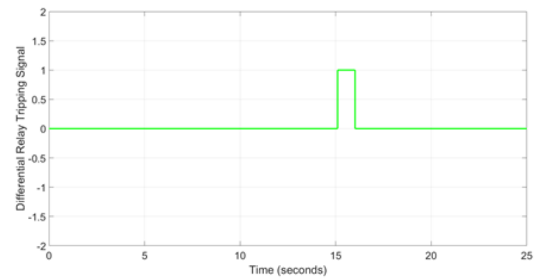

Fig. 18. Transmission line differential relay successful operation during internal fault at the intertie power transmission line.

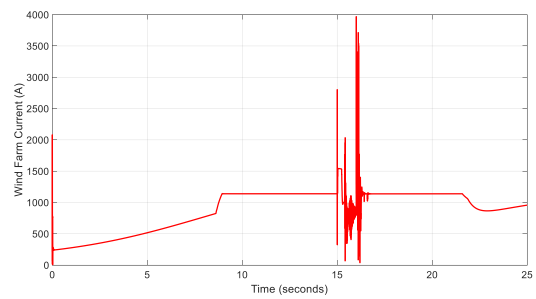

Fig. 19. Aggregated wind farm current flow during external three phase fault at the grid.

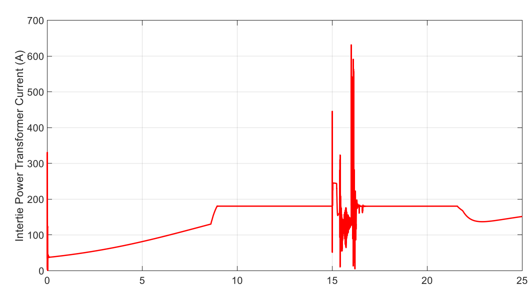

Fig. 20. Intertie power transformer current flow during external three phase fault at the grid.

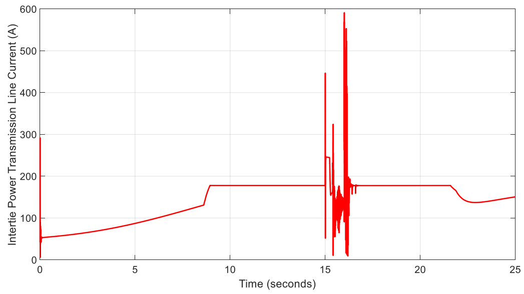

Fig. 21. Intertie power transmission line current flow during external three phase fault at the grid.

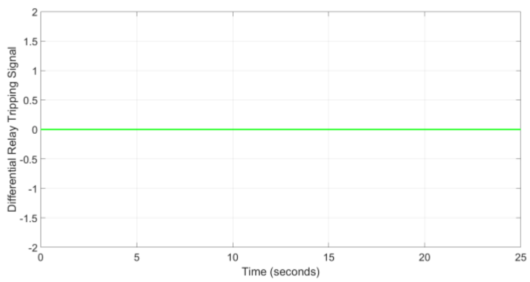

Fig. 22. Differential relays successfully ignoring to operate for external three phase fault at the grid.

VII. CONCLUSION

In this study, a novel differential-based relay protection scheme has been developed to provide a reliable protection for intertie zone of wind farm in order to overcome the limitations of distance relays due to their maloperation resulting from inaccurate impedance measurement during fault. Furthermore, a large-scale centralized DFIG-based wind farm was modelled as a test system to examine the effectiveness of the proposed protection scheme. Various faults have been imposed to the wind farm at different locations, where the wind farm current flow during normal operation and fault incidence were carried out to understand the adverse effect of fault on the wind farm behavior. The simulation results demonstrated that during internal fault on the intertie power transformer, the transformer differential relay successfully detected the fault and tripped accordingly while the power transmission line relay successfully ignored the fault by considering the fault as an external fault. Moreover, the opposite scenario was also tested by creating an internal fault on the power transmission line and the transmission line relay successfully detected the fault and tripped accordingly while the power transformer relay ignored the fault by considering it as an external fault. Therefore, the performance of the proposed DBPR scheme has been found reliable and fast against various faults at different locations. Thus, the proposed protection scheme could be a potential candidate to successfully replace the conventional distance relays that failed to operate reliably.

REFERENCES

[1] M. Aryanezhad, “An Iranian roadmap for special protection scheme with challenges of wind farms integration,” 21st Electr. Power Distrib. Netw. Conf. EPDC 2016, no. May, pp. 33–38, 2016.

[2] S. Gsänger, “World Wind Energy Association – Wind Power Capacity Worldwide Reaches 600 GW, 53,9 GW added in 2018,” 2019. [Online]. Available: https://wwindea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/. [Accessed: 09-Mar-2019].

[3] B. K. Sahu, “Wind energy developments and policies in China: A short review,” Renew. Sustain. Energy Rev., vol. 81, pp. 1393–1405, Jan. 2018.

[4] S. C. Jangam and H. T. Jadhav, “Protective systems for wind farms and its interconnection to grid- A review,” 2012 Int. Conf. Green Technol. ICGT 2012, pp. 263–267, 2012.

[5] N. Rezaei, M. N. Uddin, I. K. Amin, M. L. Othman, and I. Z. Abidin, “Grey Wolf Optimization based Improved Protection of Wind Power Generation Systems,” in 2018 IEEE Industry Applications Society Annual Meeting (IAS), 2018, pp. 1–8.

[6] H. Nguyen-duc, “Effect of DFIG Wind Farm Fault Currents on the Transformer Differential Relaying Performance,” 2018 IEEE Innov. Smart Grid Technol. - Asia (ISGT Asia), pp. 916–921, 2018.

[7] D. Jones and K. Bennett, “Wind farm collector protection using directional overcurrent elements,” Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf., pp. 1–8, 2012.

[8] A. Nateghi, H. K. Kargar, S. Bagheri, and S. H. Hashemi, “Voltage and current relays settings under reconnection of islanded wind farms,” Proc. 2nd Int. Conf. Dev. Renew. Energy Technol. ICDRET 2012, pp. 1–4, 2012.

[9] S. H. Horowitz and A. G. Phadke, Power system relaying. Wiley/Research Studies Press, 2008.

[10] E. Muljadi and V. Gevorgian, “Short-circuit modeling of a wind power plant,” 2011 IEEE Power Energy Soc. Gen. Meet., pp. 1–9, 2011.

[11] N. Rezaei, M. N. Uddin, I. K. Amin, M. L. Othman, and M. Marsadek, “Genetic Algorithm Based Optimization of Overcurrent Relay Coordination for Improved Protection of DFIG Operated Wind Farms,” in 2018 IEEE Industry Applications Society Annual Meeting (IAS), 2018, pp. 1–8.

[12] V. Phadke, S. Pathradkar, A. Rajput, S. Unde, and S. Dambhare, “Distance protection of lines connected to doubly fed induction generator based wind farms,” 2016 IEEE 7th Power India Int. Conf. PIICON 2016, pp. 1–6, 2017.

[13] G. H. Li et al., “Wind Farm Electromagnetic Dynamic Model and Outgoing Line Protection Relay RTDS Testing,” Univ. Power Eng. Conf. (UPEC), Proc. 2011 46th Int., no. September, pp. 1–6, 2011.

[14] A. Hooshyar, M. A. Azzouz, and E. F. El-Saadany, “Distance protection of lines connected to induction generator-based wind farms during balanced faults,” IEEE Trans. Sustain. Energy, vol. 5, no. 4, pp. 1193–1203, 2014.

[15] J. Ma, W. Zhang, J. Liu, and J. S. Thorp, “A novel adaptive distance protection scheme for DFIG wind farm collector lines,” Int. J. Electr. Power Energy Syst., vol. 94, pp. 234–244, 2018.

[16] M. Dewadasa, A. Ghosh, and G. Ledwich, “An inverse time admittance relay for fault detection in distribution networks containing DGs,” IEEE Reg. 10 Annu. Int. Conf. Proceedings/TENCON, pp. 1–6, 2009.

[17] B. J. Brearley and R. R. Prabu, “A review on issues and approaches for microgrid protection,” Renew. Sustain. Energy Rev., vol. 67, pp. 988–997, 2017.

[18] J. M. Dewadasa, A. Ghosh, and G. Ledwich, “Distance Protection Solution for a Converter Controlled Microgrid,” Power, no. December, pp. 586–591, 2008.

[19] H. Lin, C. Liu, J. M. Guerrero, and J. C. Vasquez, “Distance protection for microgrids in distribution system,” IECON 2015 - 41st Annu. Conf. IEEE Ind. Electron. Soc., pp. 731–736, 2015.

[20] A. M. Tsimtsios, G. N. Korres, and V. C. Nikolaidis, “A pilot-based distance protection scheme for meshed distribution systems with distributed generation,” Int. J. Electr. Power Energy Syst., vol. 105, pp. 454–469, Feb. 2019.