A Static Approach for Series Fault Detection in Compensated Transmission Line Integrated with Wind Farm

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***Abstract*—An innovative approach for series fault detection (FD) in compensated power transmission lines with a wind integrated grid system has been proposed in this paper. The combination of distributed wind power generation in current power systems presents challenges in correct fault detection owing to fluctuating power flows and varying fault impedance, mostly in compensated transmission lines. The proposed methodology effects advanced signal processing and adjustable relay settings to accurately detection and classification of series faults while discriminating them from non-fault events. By employing parameters such as positive and zero-sequence mechanisms, as well as traditional fault directories, the method efficiently isolates fault conditions even underneath the variable load and power generation circumstances. Extensive simulations directed using MATLAB/Simulink authenticate the efficiency of this technique in both grid-connected and islanded wind DG circumstances. The result highlights the robustness of the projected method in enhancing fault detection accuracy and reliability, making it a valued device for certifying stability and resilience in wind-integrated power systems.**

***Keywords—* Compensated Transmission Line; Open conductor fault; Wind DG; Adaptive Protection, Utility Grid; Induction Generator; q components**

I. INTRODUCTION

The growth of renewable green energy (RGE), mainly wind distributed generation (WDG), has been an innovative strength in modern power systems, motivated by environmental concerns, energy security, and technical improvements. As wind and other renewable green energy resources release slight greenhouse gases (GHGs) as compared to fossil fuels, their acceptance has been seen as critical to talking about climate change. Many nations and regions have established determined renewable energy goals to decrease dependency on coal, oil, and natural gas, with wind energy emerging as one of the fastest-growing sources due to its accessibility and falling expenses. The Integration of wind DG (WDG) into the grid, produces various technical and operational challenges. The power output varies randomly as the wind speed varies because of unbalanced nature. To report this, modern grids are growing with advanced technologies like Smart Grids and Digitalization, Energy Storage System, Power Grid Compensation and Reactive Power Management. Wind distributed generation (WDG) system presented numerous difficulties in transmission systems, particularly in handling dynamic power flows and variations in fault impedance. Such challenges rise from wind energy's inherent intermittence and the changing nature of its generation, which effect the stability, reliability, and protection system arrangements of transmission systems. The integration of wind DG (WDG) into power transmission lines requests for advanced control, monitoring, and protection methods to manage the active power flows and fault impedance discrepancies efficiently. Adjustable protection, voltage regulation mechanisms, and dynamic relay synchronization are critical in handling these problems and verifying grid stability in wind-integrated systems.

In the modern power systems, series compensation acts as an important role in improving power transfer stability, that is significant for the reliable process of long transmission lines TLs, predominantly those that integrated with renewable sources like wind distributed generation (WDG). By purposefully inserting condensers in series with transmission lines, series compensation reduces the effective line reactance. Which leads to enhanced power transfer capacity and voltage stability across the system, as well as more effective operation of transmission system. This proposed work aims to address these challenges by offering fault detection FD techniques that account for the special behaviours adapted by both series compensation and the inconsistency of wind DG (WDG). By producing devices that exactly detect and locate faults, even in complex compensated systems, the proposed work helps to improve the safety, reliability, and resilience of power systems that are gradually dependent on renewable energy sources.

II. LITERATURE REVIEW

The work presented in [1] is a hierarchical, real-time work that effects phasor measurement unit (PMU) data and deep learning (DL) for FD, FC and FL in power transmission systems. The method comprises a multi-level erection where PMUs allow quick fault detection FD and classification FC, while deep learning DL models process enormous volumes of data for exact FL fault location. A fault location FL method for low-resistance earthing systems that effects multi-source data has been offered in [2] . By integrating information from numerous measurement positions, the technique recovers fault localization accuracy. The arrangement combines diverse signal types, with voltage and current, to accomplish the challenges shown by noise and various fault types. In [3] realize fault detection FD in transmission lines inside multi-machine power systems using deep learning DL techniques. The projected work designed a model that practices CNNs for fault FD and FC by analyzing the waveform data. Verified across various fault situations, the model validates robust performance in classifying fault types FT and locations FL in complex power system situations. The conclusions specify DL deep learning's potential for reliable, real-time fault detection FD, contributing to improved stability and flexibility in large-scale power systems.

The author discovered the efficiency of using M-Class PMUs for accurate fault location FL on transmission lines, presented real-world applications in [4]. A smart protection mechanism planned precisely for SCTL series-compensated transmission lines connected with extensive wind farms projected in [5]. The adaptive relaying arrangements has been used to recover fault detection FD reliability in systems where series compensation and wind energy incorporation pose tasks for conventional distance relays. An innovative fault location FL method based on traveling waves for such lines connected to DFIG wind farm proposed in [6]. The technique practices high-frequency voltage measures and is renowned for improving fault detection FD speed and accuracy under flexible grid circumstances, addressing real-world operation challenges exhibited by wind farm integration.

An adaptive distance relay arrangement for transmission systems with TCSC to better accommodate the dynamic response of wind farm-connected grids proposed in [7]. The study highlights the need for improved sampling and communication procedures to preserve relay accuracy across various fault scenarios and wind environments. In [8] proposed a FC procedure with the help of 'integrated moving sum method', which depends upon the current value only. The proposed process can accurately classify various types of faults, including high value of resistance at far away fault, near the load fault, and fault at diverse inception angle. The main conclusions of the paper include the expansion of an improved protective relaying method for quicker and precise exposure and FC in a TCSC compensated transmission line. The proposed process in [9] utilizes transient monitoring indices resulting from three-phase currents for FD and SVM method for classification of fault. The method was validated on a huge amount of fault states and equated with existing techniques, demonstrating its efficacy and the primary benefits of requiring only limited current data, small computational burden, and fast processing speed.

In [10] ,the research introduced a data-driven technique to analyze the various situations relating offshore wind farms (WFs) integrated with transmission lines affect differential relay behavior. The approach influences the STMP method for signal modernization to compute per-phase differential currents. In [11] presented a novel holdup defence procedure for distance relays that controls wide-area extents to report the complications introduced by offshore wind farms (WFs). Offshore WFs obscure traditional distance relay protection due to instable wind speeds, leading to variable voltage and current during faults. Various time-domain-based protection schemes, including R–L differential equations [12] and zero-sequence impedance [13], are presented for TLs coupled to wind farms. Additionally, [14] introduces a SVM based differential protection arrangement with 97.5% accuracy. In [15] – [16], a new impedance model scheme based on wavelet transform (WT) is presented for safeguarding Transmission Lines (TLs) coupled to DFIG based wind farms.

The whole work is systematized as given: In Segment 1 provides the brief introduction about various methods for compensation power transmission protection system, emphasizing the need for adaptive protection and the significance of q components in fault analysis. Section 2 describes the brief literature review about series fault analysis for compensated transmission lines. Section 3 introduces the proposed power transmission system module also outline's fault detection principles using q-component based adaptive protection approach for various power transmission system operational modes. Section 4 details the procedure for fault analysis , location identification, and classification. Section 5 discuss the implementation of the proposed procedure and analyse simulation outcomes. Finally, Section 6 and 7 summarizes the results and conclusions drawn from the study.

III. Description of proposed power transmission system prototype and principles of fault detection

The description of power transmission system model which is proposed in this paper explained here.The transmission model modelled according to the range and length of transmission line. The model consist of 9 buses, 3 machine with one WDG integrated power grid as shown in Fig. 1.

A. *Proposed power transmission system integrated with wind DG*

A 400 kV, 50 Hz, 3-phase SCTL is modelled and simulated in the MATLAB/Simulink environment to authenticate the effectiveness of the proposed arrangement for extensive variation under fault conditions. The transmission line between Bus 7 and Bus 8 is compensated via a series capacitor with 40% compensation. The types of faults tested include single open conductor, double open conductor and 3 open conductor faults across seven nodes. To Detect the open conductor faults in such system necessitates concentrating on variations in system

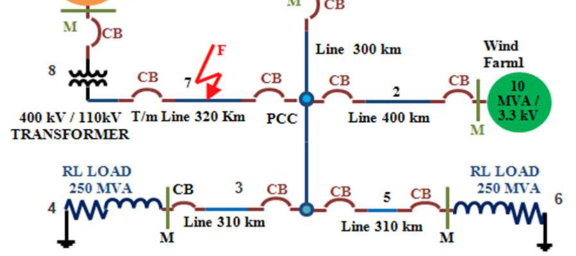

Fig. 1. Single line diagram of power transmission system integrated with wind DG

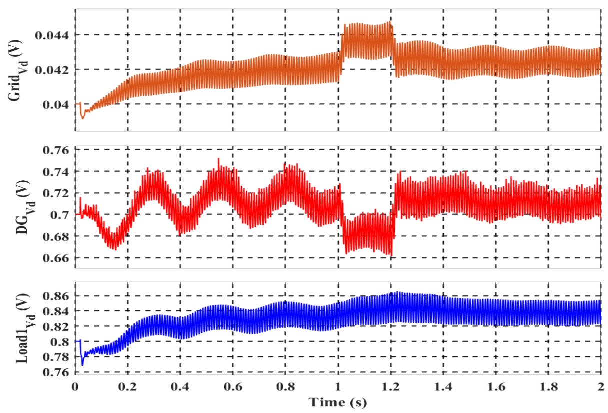

Fig. 2. Direct axis voltage characteristics with open conductor fault near the load1 side

parameters, predominantly in current and voltage profiles, using advanced systematic techniques.

To enhance the protection simplicity and efficiency, the accessibility of the utility and DGs is represented through grade signals: a power transmission system of 1 indicates availability,

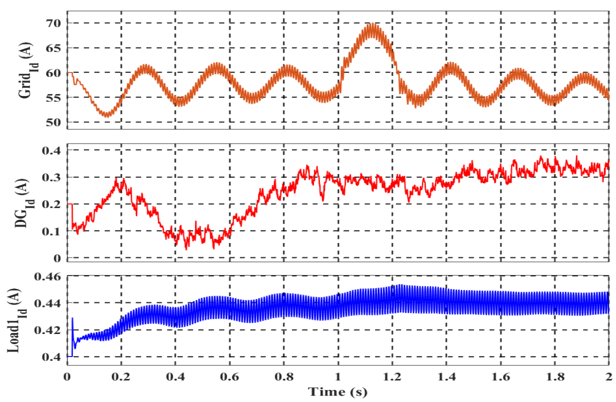

Fig. 3. D axis currents characteristics with open conductor fault near the load1 side

while 0 indicates unavailability. These grade signals determine the mode of action, whether grid-connected, islanded, or grid-only. The grid grade is set to 1 for both grid-connected and solely grid-connected modes, while it is set to 0 in island mode, where the DG grade is set to 1 as shown in table 1. For a fully

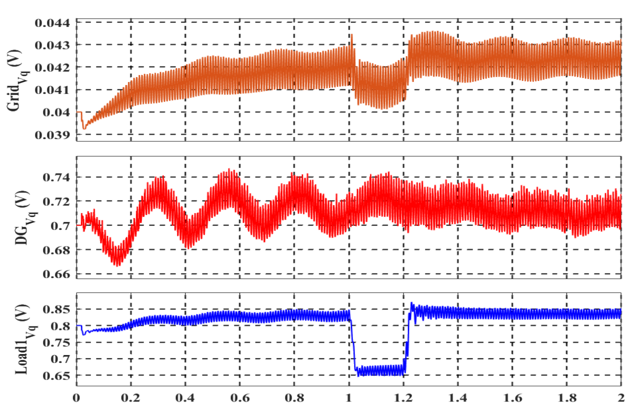

Fig. 4. Quadrature axis voltage for DG side with series fault near the load1 side

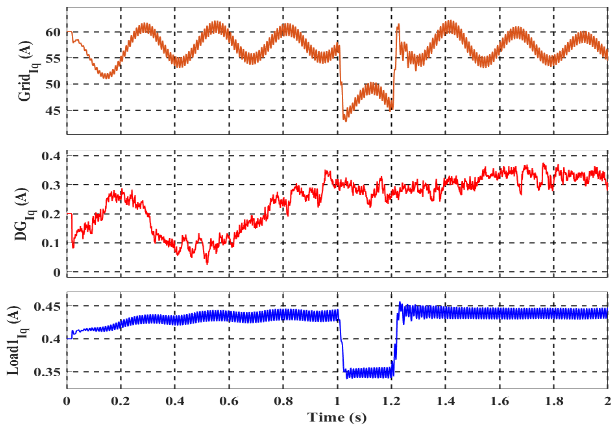

Fig. 5. Quadrature axis currents for DG side with series fault near the load1 side

grid-connected mode, the DG grade is adjust to 0. All the grade standards are assigned created on the current distribution configuration at the PCC. I_f 'Fault current' parameters are calculated by means of Simulink calculations block (S), which are placed at the grid, DG, and other load points, as illustrated in Fig 1.

B. Rationale of using q axis fault current components

The q-axis fault current Iq mechanisms are serious in fault detection FD and classification FC in systems with SCTL series-compensated transmission lines, predominantly in wind distributed generation (WDG) situations. The q-axis component, which links to the reactive power transfer in the system, delivers a strong information of system imbalance during fault conditions. Unlike direct-axis (d-axis) components, which primarily indicate active power flow, q-axis components are more sensitive to changes in fault conditions such as impedance, fault type, and location. This makes them particularly useful for identifying anomalies in systems with complex power flows introduced by compensation and renewable energy sources.

Additionally, the q-axis components allow for enhanced fault detection accuracy by capturing the transient characteristics of faults. In systems with WDG, these transients are influenced by the intermittent nature of renewable sources and the dynamic interaction between generation and compensation devices. By analysing these components, it is possible to distinguish between different fault scenarios, such as open conductor faults, and identify fault locations more effectively. This ensures improved protection and reliability of the grid, particularly in environments with high renewable energy dispersion.

TABLE I. GRADE OF WDG, UTILITY GRADE AND MODES OF OPERATION

Mode of operation	***WDG(grade)***	***Grid(utility grade)***
no	0	0
Island	1	0
Only grid connected	0	1
Grid connected	1	1

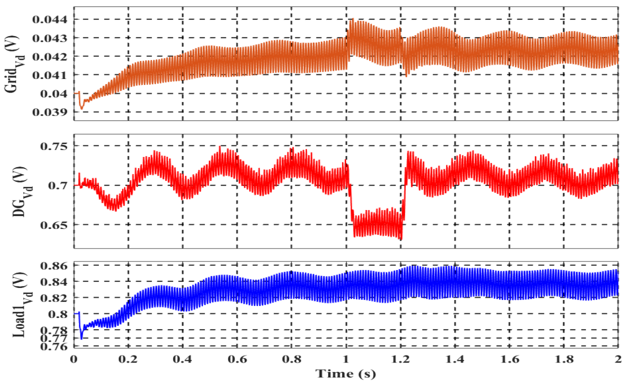

Fig. 6. Direct axis voltage characteristics with open conductor fault at the far end from the load1 side

C. Principles of fault detection

Fault detection in power systems is critical for keeping grid reliability and protection. It comprises monitoring electrical parameters like voltage and current to detect irregularities indicates about occurrence of faults. Important methods

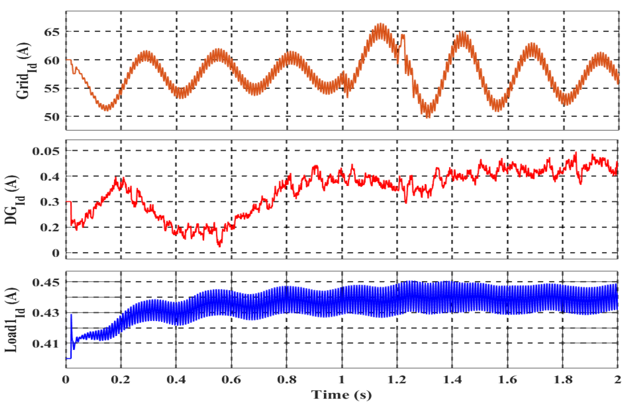

Fig. 7. D axis currents characteristics with open conductor fault at the far end from the load1 side

comprise analyzing sequence components for unbalanced circumstances, time and frequency-domain studies for transient signals, and impedance-based detection for investigative fault locations. Advanced methods leverage artificial intelligence AI and machine learning ML for improving the accuracy,

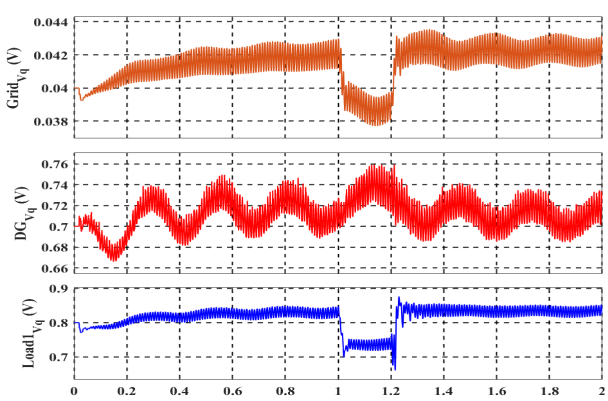

Fig. 8. Quadrature axis voltage characteristics with open conductor fault at the far end from the load1 side

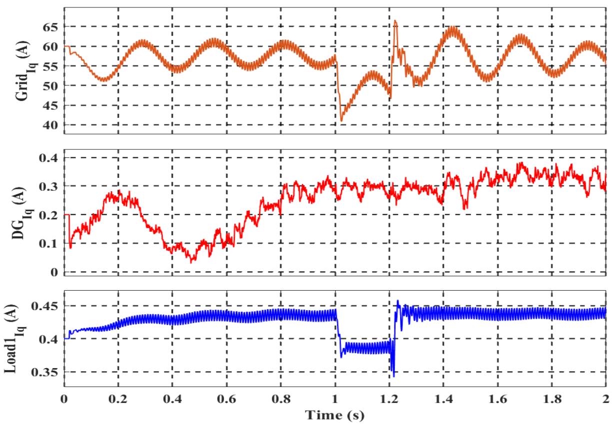

Fig. 9. Q axis currents characteristics with open conductor fault at the far end from the load1 side

particularly in integrated systems with renewable energy incorporation.

IV. PROPOSED METHODOLOGIES FOR FAULT DETECTION, LOCALISATION AND CLASSIFICATION

A novel adaptive protection mechanism based on q components is suggested, taking into account (1) and (2), in order to reduce the effect of small fault currents. This helps to diagnose the kind of fault and location of fault and detection as well.

A. Proposed methodology

Open conductor faults are specifically common in converter-collaborated and small-rating WDGs with small X/R ratios in low voltage power transmission networks. This is critical to detect the fault, localization and fault classification to operate the relays properly for synchronization between all protective devices for compensated transmission lines. The q transformation technique for fault location, fault detection, and fault classification could be used to make the protection system more consistent and modest. According to [14], the relationships for tripping action and mode of action recognition are realized using (1), (2).

$$I_{relay} = \left(I_{fG(q)} \times \text{Operating Mode}\right) + \sum_{k=1}^{n} (k_i \times I_{fDG(q)i} \times \text{GradeDGi}) \quad (1)$$

$$I_{fDG(q)i} = I_{ratedDG(q)I} \times G \quad (2)$$

The relay current I_{relay} is the threshold that triggers relay operation when it is exceeded during abnormal conditions. In this system, n represents the total number of distributed generators (DGs) within the power transmission system, and $I_{FG(dq)}$ is the utility grid's share of current during these conditions.

V. IMPLEMENTATION OF THE SUGGESTED METHODOLOGY

As elaborated in section III, Fig. 1 illustrates the grade signals indicating the accessibility of the power grid and distributed generators (DGs).

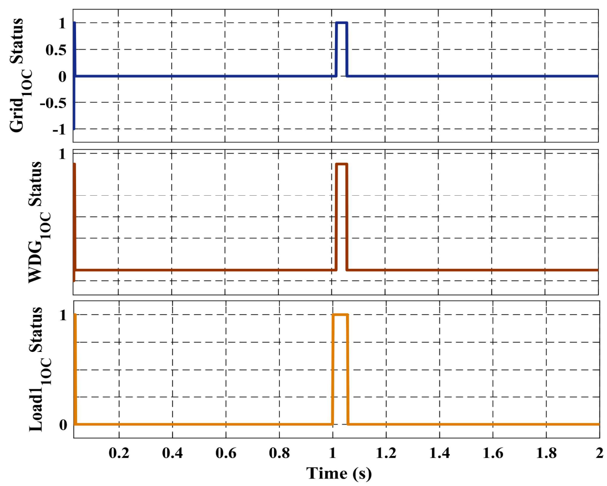

Fig. 10. Circuit breaker active status for one open conductor fault

A. Fault location and Fault classification in integrated WDG and grid- connected approach

In grid-connected schemes integrated with Wind Distributed Generation (WDG), open conductor faults (OCF) in series compensated TL transmission lines faces exceptional challenges owing to dynamic power transfer and nonlinear characteristics presented by compensation devices. As Open conductor faults cause unstable situations in the transmission line, it is essential to classify the faults and detect the fault. There is abrupt change in zero sequence and negative sequence currents due to open conductor fault. The integration of WDG introduces further variations which requires an adaptive model for accurate classification of fault. Direct, quadrature components of current and voltage at various locations with respect to load like near the load and at the far end from the load can be observed from waveforms provide insights into various fault types. Pattern recognition model can classify faults by analysing voltage and current signal patterns by means of supervised learning techniques. The fault classification system distinguishes between different fault types by comparing the characteristics of Id ,Iq,Vq and Vd . This comparison helps determine the fault type, whether one open conductor, 2 open conductor or 3 open conductor. At each node, specific conditions and logic are applied for each fault type. Nodes at the end of load has been done for fault classification as given open conductor fault founded on Iq and Id.

B. Change in q components with respect to time

The q-axis mechanism is essential to analysing the reactive power, voltage regulation, and dynamic behaviour of power systems. The variations over time are influenced by system conditions, control strategies, and disturbances. Due to transient imbalances the q-axis components shows abrupt changes during fault conditions. Open conductor or series fault make changes to voltage and current waveforms causes q-axis deviations. The magnitude and duration of q axis oscillations directly effects the location of fault.

To enhance the working of protection systems or to reduce complexity or dependency on a centralized adaptive protection mechanism, this paper proposes a distributed approach to power transmission system protection. This method focuses on detecting far end-side faults autonomously, using the d, q-axis quantities of current. The magnitude of Iq currents and Id current different for fault located near the load and at far end from the load. Fault 1OC,2OC and 3 OC as given in Table II here. However, the change to Id and Iq current during a fault is clearly distinct from its steady-state value. In the proposed far end side load at 1 position ,fault analysis technique, the pre-defined value of fault current components adapt based on the approach of operation, demanding three diverse set of values for reliable and correct detection. One set of such fault current values for the grid-connected mode has been represented in Table II. To classify other types of fault, the q component alone is enough for rapid fault detection on power transmission system side.

TABLE II. ID AND IQ PARAMETERS OF FAULT CURRENT ON LOAD SIDE

load	*Fault distance*	*Id pu*	*Iq pu*	*Vd pu*	*Vq pu*
load 1(near)	30 KM	0.43	0.42	0.83	0.82
load 1(far)	290 KM	0.41	0.42	0.78	0.79

VI. RESULTS AND DISCUSSION

The analysis of d-axis and q-axis components of current for series FD fault detection in a compensated TL with wind distributed generation (WDG), particularly when a fault is situated near the load at 30 km shown in Fig. 1. Some specific features appear due to the exclusive dynamics of the power system. The features of direct (d-axis) and quadrature (q-axis) current components are crucial for understanding series fault behaviour in compensated transmission lines, particularly with wind distributed generation (DG) as shown in Fig. 2 and Fig. 3. When a fault arises near the load, the d-axis current shows a substantial deviation from its steady pre-fault state owing to disturbances in active power transmission.

The q-axis current, associated to reactive power, also points sharply, reflecting the reactive power imbalance produced by the fault. Once a fault happens near the load (30 km) in a compensated transmission line TL with wind DG WDG, the voltage features of the d-axis and q-axis mechanisms show different forms due to the closeness to the fault and the effect of series compensation as shown in Fig. 4 and Fig. 5. Series compensation intensifies these discrepancies by dropping the line's reactance, leading to higher current peaks and fluctuations. The existence of wind DG further presents inconsistency and

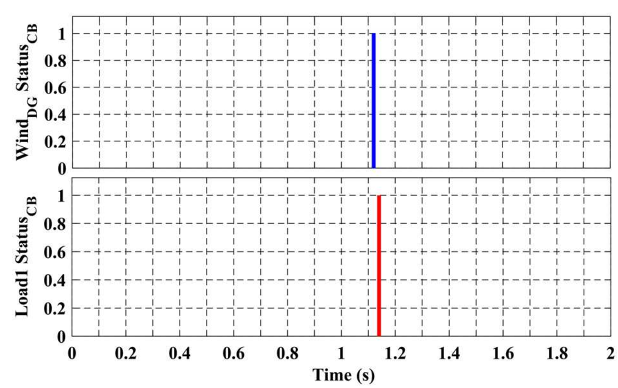

Fig. 11. Circuit breaker operation time

harmonics into the fault currents, complicating fault detection and fault analysis process. The drop is more noticeable because of the fault's closeness, which leads to negligible impedance defending the impact. The q-axis voltage Vq, represents reactive power, may display oscillations as it reproduces the dynamics of reactive power transfer between the compensation devices and the fault location.

The fault arises far away from the load about 290 km in a compensated TL transmission line with wind distributed generation (WDG), the d-axis current represents active power as shown in Fig. 6 and Fig. 7. It shows reduced peaks due to the indulgence of fault effects over the long distance. The q-axis current belongs to reactive power, shows reduced sensitivity and experiences fluctuations influenced by series compensation due to reactive power dynamics. The longer transmission line distance and compensation lessen the amplitude of fault-induced variations, which challenges FD fault detection. Wind DG (WDG) pays additional inconsistency, with its effect less visible as faults happen far away from the source. The fault located at the far end (290 km) of a compensated transmission line TL in a wind distributed generation (WDG) environment, the d-axis voltage shows a sensible fall upon fault inception due to the rise in fault impedance, which bounds the fault's effect on active power flow as shown in Fig. 8 and Fig. 9. The q axis voltage displays oscillations produced by disturbances in reactive power flow, which are enlarged by series compensation. While the d-axis voltage recovers more quickly, the q-axis voltage soothes more slowly due to reactive power dynamics. Far-end faults normally result in slighter voltage variations as compared to near-end faults, posing challenges for detection. Fig. 10 shows the circuit breaker active status for one open conductor fault at various locations w.r.t grid, load and WDG. The circuit breaker operating time characteristics shown in Fig. 11.

VII. CONCLUSION

The study of d and q axis mechanisms in series-compensated transmission lines SCTL integrated with wind distributed generation (WDG) shows the few complications produced by open conductor faults. The simulations results expose that the q-axis voltage features are highly sensitive to fault location FL, with different transient and steady-state conditions. When faults happen near the load (at 30 km), the q-axis mechanisms show an important deviation due to the interface of the series compensation and WDG contributions. These discrepancies are transient originally, followed by equilibrium phase influenced by the system's control devices and compensation approach. The study emphasizes the importance of precise fault location FL and classification FC mechanisms in modern power grids integrated with WDG.. The proposed work contributes to the development of robust protection systems for series-compensated transmission lines SCTL, highlighting the relationship of reactive power dynamics and compensation effects in fault situations.

REFERENCES

[1] H. Wang, C. Huang, H. Yu, J. Zhang, and F. Wei, “Method for fault location in a low-resistance grounded distribution network based on multi-source information fusion,” International Journal of Electrical Power & Energy Systems, vol. 125, pp. 106384–106384, Feb. 2021

[2] S. Belagoune, N. Bali, A. Bakdi, B. Baadji, and K. Atif, “Deep learning through LSTM classification and regression for transmission line fault detection, diagnosis and location in large-scale multi-machine power systems,” Measurement, vol. 177, p. 109330, Jun. 2021

[3] D. Akmaz, M. S. Mamiş, M. Arkan, and M. E. Tağluk, “Transmission line fault location using traveling wave frequencies and extreme learning machine,” Electric Power Systems Research, vol. 155, pp. 1–7, Feb. 2018

[4] M. Santhosh Prabhu, S. Biswas, Paresh Kumar Nayak, A. Y. Abdelaziz, and Adel El-Shahat, “An intelligent protection scheme for series-compensated transmission lines connecting large-scale wind farms,” Frontiers in Energy Research, vol. 11, Mar. 2023

[5] P. K. Mishra and A. Yadav, “Fault classification scheme for TCSC compensated transmission line using MODWPT-BTEC,” e-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 9, p. 100729, Sep. 2024

[6] A. A. R. Mohamed, H. M. Sharaf and D. K. Ibrahim, "Enhancing Distance Protection of Long Transmission Lines Compensated With TCSC and Connected With Wind Power," in IEEE Access, vol. 9, pp. 46717-46730, 2021

[7] S. K. Mohanty, P. K. Nayak, P. K. Bera and H. H. Alhelou, "An Enhanced Protective Relaying Scheme for TCSC Compensated Line Connecting DFIG-Based Wind Farm," in IEEE Transactions on Industrial Informatics, vol. 20, no. 3, pp. 3425-3435, March 2024

[8] M. Biswal, “Faulty phase selection for transmission line using integrated moving sum approach,” IET Science, Measurement & Technology, vol. 10, no. 7, pp. 761–767, Oct. 2016

[9] A. Panday, T. Ahmad, Sandeep Biswal, and R. Patidar, “An adaptive data-driven based pilot relaying scheme for protecting UPFC-compensated transmission line connected to wind farms,” Electrical Engineering, May 2024

[10] S. Biswal, S. D. Swain, R. D. Patidar, A. K. Bhoi, and O. P. Malik, “Integrated Wide-Area Backup Protection Algorithm During Stressed Power System Condition in Presence of Wind Farm,” Arabian Journal for Science and Engineering, vol. 46, no. 10, pp. 9363–9376, Jan. 2021

[11] N. Rezaei, M. N. Uddin, I. K. Amin, M. L. Othman, M. B. Marsadek and M. M. Hasan, "A Novel Hybrid Machine Learning Classifier-Based Digital Differential Protection Scheme for Intertie Zone of Large-Scale Centralized DFIG-Based Wind Farms," in IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 3453-3465, July-Aug. 2020

[12] Z. Yang, K. Jia, Y. Fang, Z. Zhu, B. Yang and T. Bi, "High-Frequency Fault Component-Based Distance Protection for Large Renewable Power Plants," in IEEE Transactions on Power Electronics, vol. 35, no. 10, pp. 10352-10362, Oct. 2020

[13] A. R. Adly and A. M. Abdel-Hamed, "A Novel Scheme for Fault Detection in a Series Compensated Line Based on Wavelet Transform," 2024 6th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), Moscow, Russian Federation, 2024, pp. 1-5

[14] S. K. Mohanty, S. B. Santra, and P. Siano, “Faulty phase identification and ground detection in TCSC compensated lines integrated with wind farms,” International Journal of Electrical Power & Energy Systems, vol. 153, p. 109383, Jul. 2023

[15] S. K. Mohanty, S. Mohapatra and P. Siano, "An Improved Protective Relaying Technique for Transmission Line Connected With UPFC and DFIG-Based Wind Farm," in IEEE Transactions on Industrial Informatics, doi: 10.1109/TII.2024.3463707.

[16] G. V. Raju and N. V. Srikanth, “A novel protection scheme for transmission lines connected to solar photovoltaic and wind turbine farms using fuzzy logic systems and bagged ensemble learning,” Electrical Engineering, May 2024.