NTU Journal of Engineering and Technology (2025) 4 (3): 74-84
DOI: https://doi.org/10.56286/ntujet.v4i3

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

Developing Distance Protection Scheme for Double Circuit Transmission Lines Integrated Into Wind Energy System

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Article Information

Received: 04-06- 2025,
Revised: 26-06-2025,
Accepted: 28-06-2025,
Published online: 28-09-2025

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Key Words:
Distance protection relays,
developed scheme,
permissive underreaching,
transfer trip,
double-circuit transmission lines.

ABSTRACT

Wind energy integration into the grid presents a major challenge to the conventional Permissive Underreach Transfer Trip (PUTT) distance protection scheme. This technical challenge arises from variations in power generated by wind turbines connected to double-circuit transmission lines. This paper proposes an enhanced PUTT scheme to improve the accuracy of the Mho-type distance protection relay in such systems. The Developed PUTT (DPUTT) scheme incorporates compensation techniques for residual and mutual coupling currents in the zero-sequence network. Since variations in wind generation impact the security of conventional compensation methods, the DPUTT scheme compares earth current magnitudes at both ends of the system to distinguish between faulted and healthy circuits. Simulation results from a MATLAB model show the apparent impedance trajectories observed by the relays at both terminals. These results demonstrate the mechanism of the proposed tripping scheme across three protection zones and show improved performance over the traditional PUTT. The supervision signal generated by the DPUTT effectively blocks tripping of healthy terminals while correctly initiating trips for faulted circuits. The simulation confirms that the proposed DPUTT scheme reduces false tripping events by up to 99% compared to PUTT, significantly enhancing protection reliability and system stability under variable wind conditions.

1. Introduction

Integrating renewable energy into power grids imposes a significant challenge for the conventional distance protection relay scheme. This challenge is technically brought by variation in the generated power from wind energy systems under weather conditions. In particular, when the distance protection relays are intended to protect the double-circuit transmission line [1]. The variation in the generated power considerably influences the fault line impedance seen by these relays located at the transmission line ends [2]. Where extreme weather conditions, such as strong winds and storms, further compromise fault detection accuracy and relay operation. Thus, it is necessary to enhance protection system reliability with adaptive strategies during fault condition [3]. To improve the protection reliability of the double-circuit transmission line, they also introduce mutual coupling effects and series resistances, which interfere with residual currents, and the distance protection relay can release incorrectly tripping signal to circuit breakers [4]. Conventional distance protection relays tripping scheme would mis operate due to induced currents in the healthy circuit during earth faults, leading to unnecessary fault detection [5]. The zero-sequence mutual coupling meaningfully affects line fault impedance estimation, resulting in underreaching fault localization. Consequentially, it causes the distance relays to incorrectly locate fault and release tripping of the healthy circuit [6]. To overcome this mutual coupling issue, the compensation techniques were adopted to play an essential role in enhancing the accuracy of the distance protection relay scheme Adaptive fast protection techniques have been studied for compensated and uncompensated double-circuit transmission lines [7, 24]. This will be helpful to reduce false trip, which can improve relay response and help stability of system with time-varying wind power [8].

The methodology will provide a more accurate identification of faulted and healthy circuits, ensuring that network is not unnecessarily tripped. Afterward, few techniques that are utilized to block the distance relay by sending blocking signals when faults happen external to its protective zone are discussed which are essential in minimizing failure in the relay operation. This guarantees that the unfaulted circuits will operate [9]. Directional Comparison Blocking (DCB) is a mature and commercially-available communication-based scheme, which employs reverse-looking distance elements to refine relay operation and mitigate false tripping [10].

In contrast, (PUTT) schemes use blocking mechanisms to make sure that a trip command is issued only when a fault is detected in the protected zone by both terminals. By receiving a blocking signal from the remote terminal, the local terminal avoids tripping, enhancing the protection selectivity and reliability [2]. In addition, the advanced adaptive blocking methods based on mutual coupling and variations in fault resistances can improve the security by modifying the relay setting under suitable conditions [11].

In light of such complicated interactions, simulation tools like MATLAB/Simulink are of immense help in analyzing the effects of mutual coupling on the performance of the distance relay [23, 12].

These fault scenario-based simulations provide insight into system response and fault location under many different fault conditions, which facilitate engineering of effective compensation methodologies for a more precise fault location in a shorter time and for an effective protection coordination for better reliability [13]. Recent developments in the class of transient-based protection techniques, as opposed to traditional approaches, utilize high-frequency transient signals as a reference for the real time status of the system, resulting in precisely defined healthy system boundaries, thus achieving more effective fault separation especially for offshore wind farms [14]. Fault impedance trajectories were validated through MATLAB-based simulations, and the proposed scheme is shown to be well capable of significantly relieving maloperations triggered by mutual coupling and distributed wind energy generation fluctuations [15]. Besides, the proposed model is more selective and reliable than PUTT schemes [16].

This paper has proposed a DPUTT to improve the distance protection relays being operated in the wind energy connected to a double circuit transmission line. The DPUTT is brought to address maloperation of compensation techniques, which are used to mitigate the effects of zero sequence mutual coupling current in the double-circuit transmission lines. This is because the compensation techniques do not completely decouple the effect of mutual current in the health circuit of the double-circuit transmission line; therefore, PUTT would fail to initiate a correct tripping signal due to an error calculation in the line impedance and fault location eventually.

2. Materials and Methods

2.1 Wind energy connected double circuit

transmission lines model wind the investigated system in this study consists of the double circuit transmission line employed to integrate energy into the grid. The study considers the performance of the distance protection relays, which are located at each circuit end, in case that a single line to ground fault condition occurs in one circuit of the transmission line. The operation of full and low wind energy is considered to reveal the reliability of the distance relay under these operation and fault conditions. The distance relay scheme regards pilot protection mode, which ensures exchanging of voltages, currents and tripping signal at each circuit among the four distance relays as illustrated in Fig. 1. The pilot protection mode requires a telecommunication channel to facilitate the exchange of distance relays data, which are located at both ends of a transmission line. The communication technique among relays could be established through fibre optics, microwave transmission or power line carrier communication (PLCC) systems [17, 18].

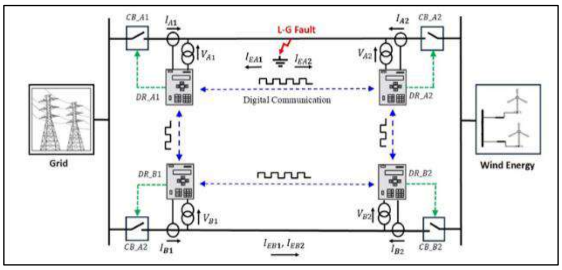

Fig. 1. Wind energy connected double circuit transmission lines with distance relay based on pilot protection mode

The investigated system is modeled and built with MATLAB Simulink environment as shown in Fig. 2, The modeled system represents the double circuit transmission tied with one terminal to the wind turbine located at the remote relay, while the other is tied to the grid placed at the local relay. The modeled system includes four distance protection relays DR_A1, DR_A2, DR_B1 and DR_B2, which are located at each circuit end. They protect the transmission line by detecting fault conditions and then tripping their circuit breakers and distance relay C.B._A1, DR_A2, C.B._B1, and C.B._B2, respectively. The voltage system of 220 kV has a grid power with 1250 MVA. The wind energy produces 1250 MVA, representing a full capacity which is equal to the grid power. With the worst case of the low generation, wind energy reduces to 1% of the full capacity. Hence, the model has been simulated with two scenarios according to the wind power generation and impact of mutual coupling of zero sequence current. The obtained results are analyzed under the line to ground fault occurring in the circuit A of the transmission line.

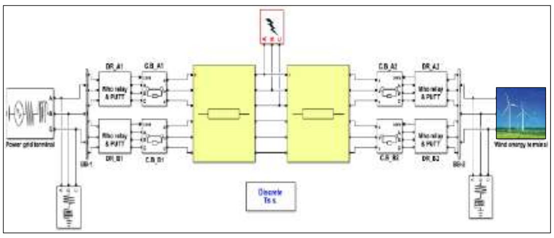

Fig. 2. Simulated model for wind energy-grid integrated double-circuit transmission line system protected by the Mho distance relay employing PUTT.

The modelling considers the system parameters listed in Table 1, which includes resistance, inductance, and capacitance of the positive, negative and zero systems, respectively. In addition, the resistance, inductance, and capacitance of mutual coupling in zero sequence system are taken into account as significant components for accurate fault location analysis. Because the transmission line length is directly proportional to its impedance value, the distance protection relay is used appropriately to estimate the impedance value of the transmission line up to the reach point at certain fault location. The impedance value results from the division of the measured phase voltage by the measured phase current at the relaying point. In the simulated model, the distance relay named DR_A1 instantaneously measures the phase voltage VA1 and the phase current IA1 at relaying point. The line impedance ZA1 seen by this distance relay is given by dividing the voltage and current. This impedance calculation is only adequate for the three-phase to ground fault (LLLG), and the resulting impedance represents the positive-sequence impedance Z1 of the transmission line.

The simulation was carried out using MATLAB/Simulink (version R2021b) and the Simscape Power Systems toolbox. Key blocks utilized in the model include: circuit breakers, three-phase voltage sources, fault blocks, and measurement components. The Mho-type distance relays were implemented using logical and mathematical blocks, including relational operators, delay blocks, logical operators, and switching logic. Scope and display blocks were used to monitor relay operation and signal behaviors. This configuration enabled accurate testing of relay response and tripping coordination under various fault and generation conditions.

Table 1. The parameters of the simulated model.

Parameter	Value	Unit
Positive-sequence resistance R_1	0.01840	Ω/Km
Zero-sequence resistance R_0	0.2188	Ω/Km
Zero-sequence mutual resistance R_{0m}	0.20052	Ω/Km
Positive-sequence inductance L_1	0.00092974	H/Km
Zero-sequence inductance L_0	0.0032829	H/Km
Zero-sequence mutual inductance L_{0m},	0.0020802	H/Km
Positive-sequence capacitance C_1	1.2571e-008	F/Km
Zero-sequence capacitance C_0	7.8555e-009	F/Km
Zero-sequence mutual capacitance C_{0m}	-2.0444e-009	F/ Km
Transmission line length	100	Km
Voltage source at $B.B_1$ and BB_2	220	KV
Short circuit level at BB_1 Grid side	1250	MVA

Short circuit level at BB_2 [Wind turbine side]	1250	MVA

However, this line impedance calculation experiences an under-reaching issue in the single to ground fault (LG). In this case, and the line impedance calculation appears higher than the actual value when the fault occurs inside the protected zone. The zero-sequence system produces additional impedance caused by the fault current which flows within the earth return path. Therefore, it is necessary to compensate an effect of the zero-sequence impedance Z0 for correcting distance protection relay setting. Over the distance relay used to protect a single circuit transmission line, this relay significantly suffers from under-reaching or over-reaching issues when used for the double circuit ones. The line impedance calculation is inadequate to meet the distance relay setting even though this calculation includes the earth current effect. Whereas the fault current flowing in the earth return path of the one circuit induces additional zero-sequence voltage in the adjacent circuit and vice versa. This leads to mutual coupling current in the zero-sequence system, which exists when the transmission line circuit shares the earth return path. For this case, the impedance calculation should take into account the effect of mutual coupling zero-sequence impedance Z_{0M} and earth current in the adjacent circuit, to satisfy the distance relay setting requirements.

The simulation model includes two compensation techniques to compute the line impedance when LG fault occurs in a double circuit transmission line. The first compensation considers a residual compensation current factor K_E, which is detailed in [2, 15, 19]. This factor mitigates the effects of earth faults in the zero-sequence system. While the second compensation is achieved by a zero-sequence mutual coupling compensation factor K0M in [2]. The line impedance calculation using these compensation techniques can be mathematically given as follows:

$$Z_R = \frac{V_{A1}}{I_{A1}+K_E I_{EA1}+K_{0M} I_{EB1}} \qquad (1)$$

Where $KE = Z0 - Z1 / 3Z1$, and $K0M = Z0M / 3Z1$.

For this calculation, it can be seen that the distance relay DR_A1 at its the relaying point measures the phase voltage V_{A1}, phase current I_{A1}, earth current I_{EA1} of the circuit A. In addition, the distance relay requires measuring the earth current I_{EB1} of the adjacent circuit B. The earth current in each circuit is a sum of its three phase currents. Similarly, the line impedance calculations are used for the distance relays named DR_A2, DR_B1 and DR_B2, which regard the voltage and current at the relay point, besides the current in their adjacent circuit.

2.2 Modelling of Mho-type distance protection relay

The double circuit transmission line used in this simulated model is a long overhead transmission line of 100 km. For this reason, this simulation model uses the distance relay based on a Mho type characteristic. This relay has a directional impedance behaviour, in contrast with other distance protection relay types. It operates when the calculated line impedance lies inside a circle on the R-X plane (relay impedance boundary). The Mho type relay is commonly set to operate only for faults that occur within three protective zones as the reach points. In this simulation, the first protective zone covers 80% of the positive sequence impedance of the transmission line with a quite small-time delay of 2 cycles. The second and third zones extend to 120% and 200% of the positive sequence impedance having proper delay time of 10 and 25 cycles, respectively. These protective zones are set to provide a backup protection for the first zone, and also to include the rest and beyond of the protected transmission line. The impedance setting using the mho type distance relay is coordinated with a grading factor GF. To achieve the zone impedance setting, it is obtained from the multiplication term of the line impedance Z1 and the grading factor for each protective zone. The impedance reaches for the three protective zones can be expressed as follows [2, 20, 21]

$$|Z_R| \leq |GF_n Z_1| \cos(\theta_1 - \theta_R) \qquad (2)$$

Where GF_n refer to the grading factor of the n protective zones in which n =1, 2 and 3. The θ_1 corresponds to an angle of the positive sequence impedance for the protected line. the magnitude Z_R and angle θ_R is relay measured impedance, which is determined from the line impedance calculation in Equation (1). The impedance magnitude $|Z_R|$ is compared with the protection zone impedance boundary of $|GF_n\, Z_1|\, cos(\theta_1 - \theta_R)$. When the relay measured impedance is less than or even equal to the protective zone impedance, it is supposed that a fault exists inside the n protective zones (i.e. faults occur between the relay location and its adjusting reach point). Consequently, the distance relay issues a tripping signal with a time-delayed release of the circuit breaker.

2.3 Developing the permissive underreach transfer trip scheme

The Mho type distance relay performing as the pilot protection scheme is also modeled in this simulation, in particular, it is built to achieve proper tripping scheme in the four distance relays located at both ends of the protected double circuit transmission line. The protection scheme model considers a permissible under reach transfer trip PUTT method as the communication channel among relays. In the PUTT used to protect the single circuit transmission line, the protection scheme commonly depends on detecting the fault on the 1st zone of the distance relay from at least one of the protected line ends [4, 9]. In this case, this relay commands a signal to trip the circuit breaker that follows the relay. At the same time, a permissive trip signal by the communication channel is sent to the remote relay requesting its circuit breaker to release. However, the received signal at this remote relay is supervised and delayed until the own confirms fault detection before the remote circuit breaker tripping. This PUTT scheme requires to be developed while employed in the double circuit transmission line as displayed in Fig. 3. Due to the mutual coupling of the zero-sequence system, the current in the faulted circuit induces currents in the healthy one. It causes incorrect line impedance calculation under fault occurrence and then leads to issuing unnecessary tripping signal to the circuit breakers of the healthy circuit. This study aims to DPUTT schemes in the distance relay protection to avoid tripping these circuit breakers by mitigating the effect of mutual coupling between earth circuit currents. An additional supervision signal is proposed to be integrated with PUTT as colored red block shown in Fig. 3. The supervision signal of DPUTT ensures to block tripping of the healthy circuit terminals, while it allows to initiate tripping of faulted ones. In the case relaying point at DR_A1, the earth current I_{EA1} of the circuit A is compared to that of the adjacent circuit B, which is I_{EB1}. When the fault occurs in the circuit A, $I_{EA1}$is superior to I_{EB1}, which means that the supervision signal of the DPUTT allows tripping signal to pass. For relaying point at DR-B1; however, $I_{EB1}$is less than the adjacent circuit earth current, which is here is I_{EA1}. Thereby, the supervision signal blocks the resultant tripping signal to release.

3. Results

To evaluate the accuracy of fault location detection using conventional distance relays, a simulation was conducted in MATLAB/Simulink. A ground fault was simulated on circuit A at various locations, ranging from 20% to 95% of the line length, with both voltage sources, BB1 and BB2, set to 1250 MVA.

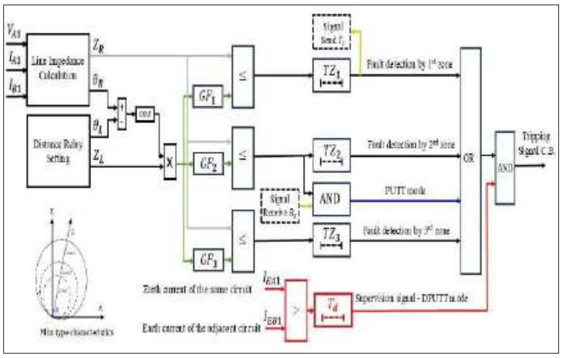

Fig. 3. Mho distance relay employing DPUTT scheme.

Table 2 presents the recorded relay measurements [DR_A1, DR_A2, DR_B1, DR_B2], revealing that all conventional relays failed to accurately determine the fault location, resulting in incorrect trip signals. This maloperation is primarily attributed to the influence of mutual coupling between the circuits, which distorts impedance calculations and compromises the reliability of protection decisions.

Table 2. Fault location errors for conventional relays at full generation.

Fault ocation	DR_A1	DR_A2	DR_B1	DR_B2
	F.Estimated	F.Estimated	F.Estimated	F.Estimated
20	36.8	150.2	184.7	351.6
50	93.5	91.58	496.6	483.4
75	165.9	27.16	320.5	131.5
95	190	9	157.6	40.5

The accuracy of relay measurements, Table 3 shows the measured impedances of the four relays as a function of reduced power of wind turbines. The results show that impedance measurement errors increase significantly, which results in a larger drop in the accuracy of fault location estimation. The implication drawn from this observation is that this issue is more pronounced with a generating source at one end of the transmission line where there is a power imbalance. The power fluctuations due to high penetration of renewable resources in a transmission network makes the determination of fault location more challenging and will mitigate the ability of the relay to perform effectively in both pre-fault and post-fault scenarios, which highlights the need of compensation techniques in enhancing performance of a relay working in these scenarios.

Table 3. Fault location errors for conventional relays in a double-circuit line under low generation at bb2.

Fault ocation	DR_A1	DR_A2	DR_B1	DR_B2
	F.Estimated	F.Estimated	F.Estimated	F.Estimated
20	39.38	140.6	368	135.7

50	104.3	74.3	319.2	75
75	169.5	36.2	284	36.4
95	234	7.9	289	7.9

In this analysis, the possible rested wind turbine power on the fault location estimation in double-circuit transmission lines is addressed. The findings show that as power diminishes, the error in estimation becomes larger, especially relative to the relays in the second circuit (B). Due to altered current flow and mutual coupling effects, this leads to wrong estimations causing erroneous line tripping or delayed isolation of the faulty line.

For the case where all relays transmit with equal power, relay estimates were also more accurate and consistent. Yet after cutting down the wind turbine power, the errors sharply increased, especially in DR_B1 and DR_B2, where the estimated fault locations were far deviated from the actual ones. Notably, both DR_A1 and DR_A2 also had distant fault location errors appearing more frequently (See Fig. 4, this gives more evidence to the fact that part paddig of the power variation takes place in both dc circuits).

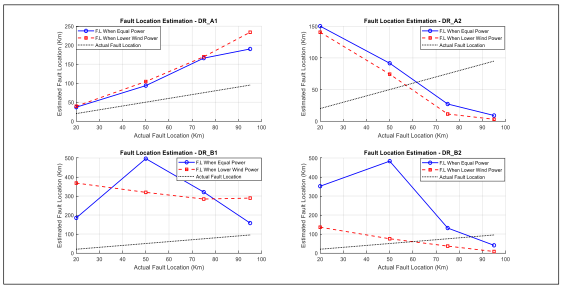

Fig. 4. The effect of wind power fluctuations on the accuracy of fault location in double-circuit T.L.

The relapsing errors which are witnessed in the fault location estimation of the distance protection schemes for the double-circuit transmission lines subjecting to changing growths of the wind power is an indication of the challenges faced while ensuring wide-area distance protection currently. Due to the mutual coupling effect in impedance including the effect of zero sequence currents the fault impedance will be misinterpreted by a much higher value giving the incorrect trip signal to healthy circuit and also delay the fault clearance. To tackle these issues, this paper introduces an innovative compensation strategy that improves the accuracy of relay decisions by reducing the influence of mutual coupling and residual currents. The method aims to improve fault impedance estimation under the power fluctuations condition, reduce the influence of the resultant induced currents on the relay operation, and thus, enhance the selectivity and dependability of PUTT-based distance protection. The motivation of this comprehensive model is to illustrate the potential roles of these compensation techniques when incorporated into the MATLAB/Simulink model to enhance the security (i.e., lessen the chance of false tripping) and robustness of transmission network protection schemes integrated with wind energy systems.

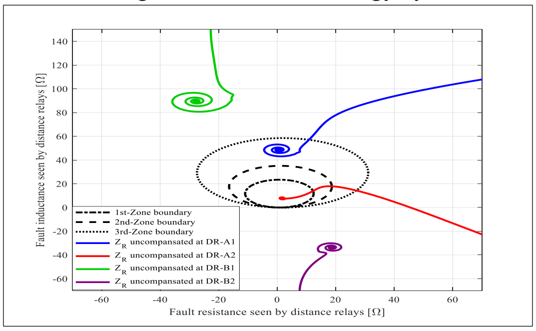

Fig. 5. Fault impedance error in Mho-type relays under mutual coupling without compensation (85% fault location).

Although the fault was located at 85% of the transmission line in length, as we see in Fig 5 only DR_A2 registered the correct fault distances from the location. On the other hand, the other relays, specifically DR_A1, DR_B1 and DR_B2 were not able to give correct estimations due to the presence of the zero-sequence mutual coupling between the incomings. This effect is wrong impedance calculation, also known as remnant effect, which indicates that wrong impedance value seen by the relays. As a result, the fault zone is dislocated significantly from its real situation.

The relays within circuit B experienced the most influence, with their estimations placed far from the actual location of the fault. This shows the requirement for mutual coupling compensation to improve accuracy of fault location. If these effects are not compensated, it may take time for the relay to respond to these effects, leading a delayed relay failure to isolate the fault or unnecessarily tripping the healthy circuit. In order to work more accurately on estimating the fault location, various compensation techniques including Residual Current Compensation and Mutual Coupling Compensation are needed for the accurate localization of the fault event.

These techniques enhance relay performance, reduce estimation errors, and improve the reliability of distance protection in double-circuit transmission lines. As demonstrated in Equations (1) and (2) these compensation processes help correct the impedance values perceived by the relays, mitigating the effects of mutual coupling and improving fault location accuracy.

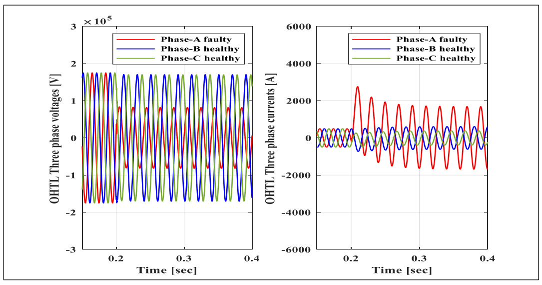

Fig. 6. Fault waveforms at DR_A1

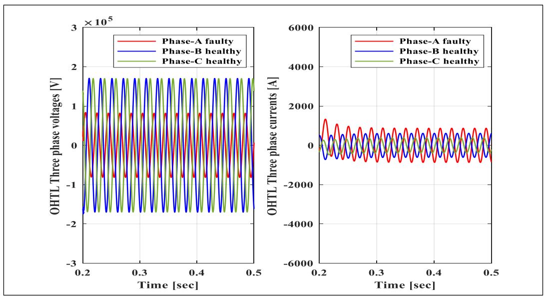

Fig. 7. Fault waveforms at DR_B1

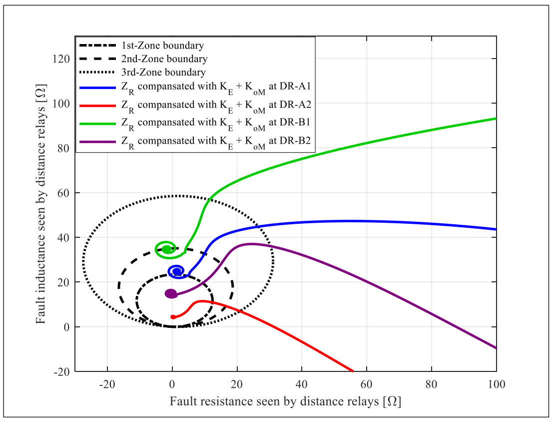

Fig. 8. Impact of residual and mutual coupling compensation on fault impedance estimation in distance relays (full generation)

As illustrated in Fig. 6, under full generation conditions, the current gradually increases as the fault location is approached, reflecting the expected response of the faulted phase. However, in Fig. 7, a noticeable rise in current is also observed in the healthy circuit (circuit B), despite the fault occurring in circuit A. This phenomenon is attributed to zero-sequence mutual coupling, which induces unwanted currents in the non-faulted circuit. In contrast, Fig. 8 demonstrates accurate impedance measurements, where each relay correctly identifies the fault within its designated protection zone highlighting the effectiveness of the proposed compensation scheme compared to the maloperation observed in Fig. 5.

Note: "Overhead Transmission Line (OHTL)" in Fig. 6 and Fig. 7 refers to Overhead Transmission Line, which represents the type of line These results, obtained under full generation conditions, indicate that mutual coupling compensation improves the accuracy of impedance calculations; however, it does not prevent relays from responding to induced currents. This necessitates the implementation of additional strategies to ensure that relays are not affected by these currents when making tripping decisions in double-circuit transmission lines.

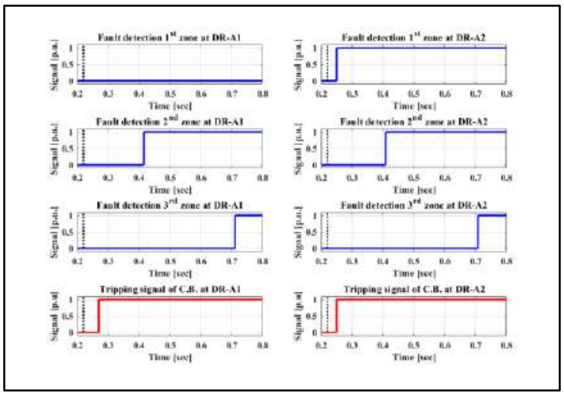

Fig. 9. Detection and tripping sequence of distance relays in circuit a using the PUTT under full generation.

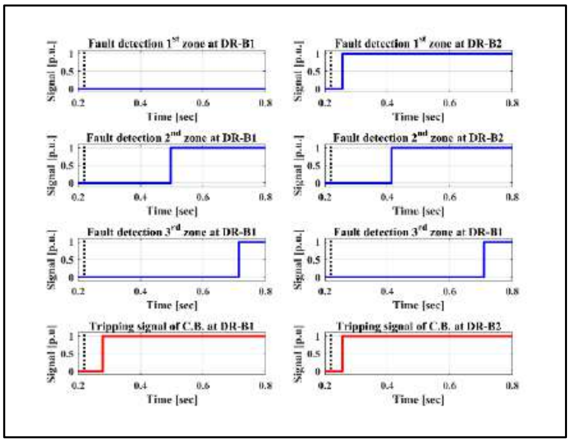

Fig. 10. Failure of distance relays in circuit b to detect and trip faults in putt under full generation.

Fig. 9 illustrates the response of DR_A1 and DR_A2 following a fault occurrence in circuit A. The results indicate that DR_A2 detected the fault within Zone 1 and subsequently transmitted a permissive trip signal to DR_A1, which identified the fault within Zone 2. Consequently, DR_A1 initiated the trip operation immediately, bypassing the typical time delay associated with Zone 2 operation, in accordance with the PUTT scheme. This coordination enabled the fault to be isolated rapidly and efficiently.

Conversely, Fig. 10 illustrates the response of DR_B1 and DR_B2 in circuit B, which, under ideal circumstances, should have remained operational to sustain power transfer while the fault in circuit A was being cleared. However, the relays in circuit B incorrectly issued trip signals, leading to the unnecessary disconnection of the healthy circuit. This maloperation is attributed to the influence of zero-sequence mutual coupling, which induced currents in circuit B, causing the distance relays to erroneously interpret these as fault currents. As a result, the key advantage of double-circuit transmission lines ensuring power transfer continuity via the unaffected circuit was compromised.

These results highlight the necessity of upgrading the PUTT method to be able to differentiate the fault currents from the mutually-coupled currents. The intent behind this was to improve this scheme so that healthy circuit should not trip unnecessarily and in the event of a fault, the power transfer should be sustained in the healthy circuit. This improvement is very important in such network to increase reliability and stability distance protection.

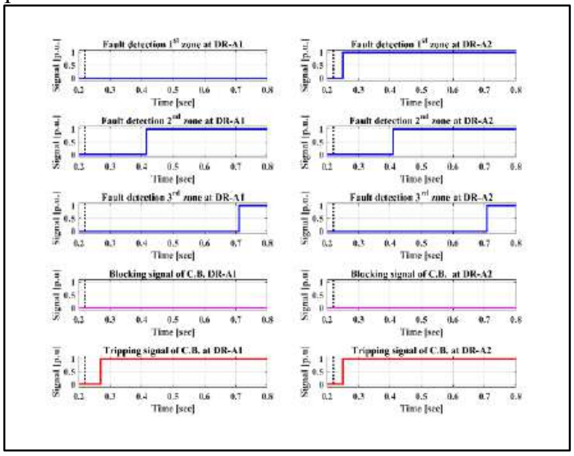

Fig. 11. Detection and tripping sequence of distance relays in circuit a using the DPUTT scheme

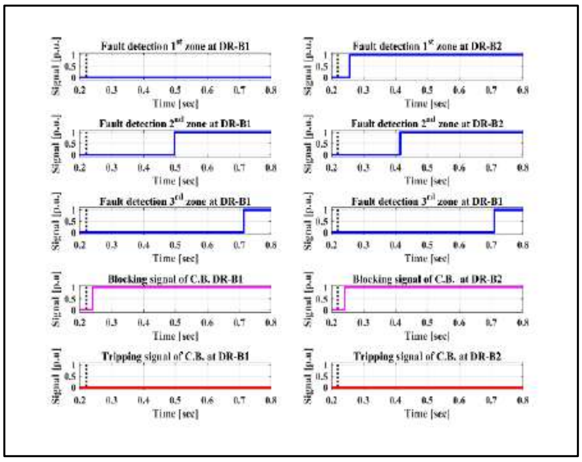

Fig. 12. Successful blocking of unnecessary tripping circuit B using the DPUTT scheme

The superior performance of the DPUTT scheme with respect to reducing mutual coupling effects and unwanted tripping under the full generation condition with grid-equal turbine generation is demonstrated in Fig. 11 and Fig. 12. By conventional mechanism, it will trip Circuit B incorrectly due to induced currents thereby preventing power transfer. On the other hand, by employing the blocking signals, the DPUTT scheme was able to prevent the Circuit B from tripping, and thus keep the Circuit B healthy during the fault in Circuit A.This demonstrates that the DPUTT scheme enhances distance protection reliability by distinguishing actual fault currents from induced currents, maintaining power continuity, and reducing errors caused by mutual coupling.

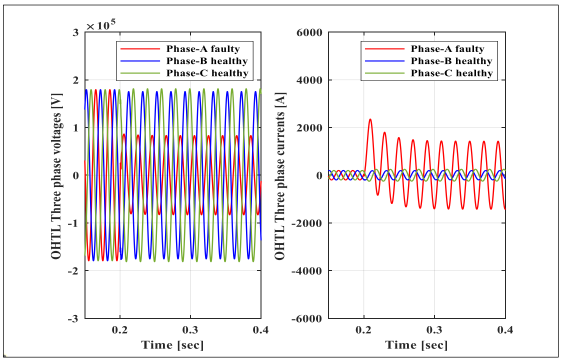

Fig. 13. Fault waveforms at DR_A1

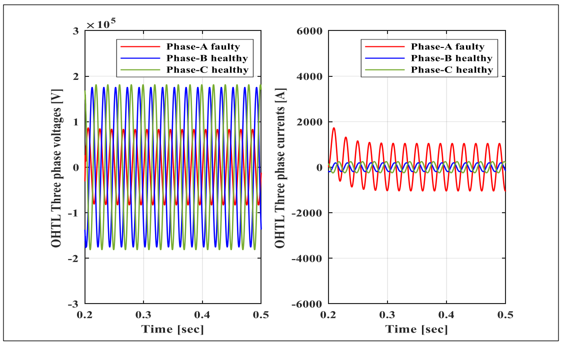

Fig. 14. Fault waveforms at DR_B1

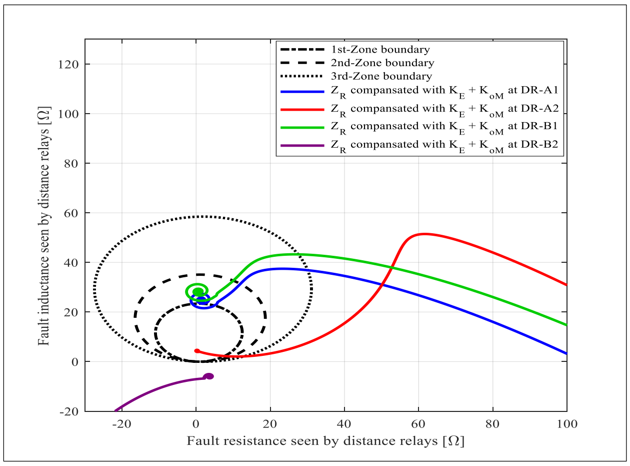

Fig. 15. Impact of residual and mutual coupling compensation on fault impedance estimation in distance relays (low generation)

The impact of reduced wind generation on the performance of distance relays is evident when comparing Fig. 13, Fig. 14, and Fig. 15. In Fig. 13 and Fig. 14, fault currents decrease due to the reduced contribution from the wind turbine, resulting in a less pronounced relay response. Although the influence of mutual coupling is lower compared to the full generation scenario, induced currents are still present, which may lead to incorrect tripping of the healthy circuit.

In Fig. 15, oscillations in impedance trajectories are observed, particularly at DR_A1 and DR_B1, indicating greater difficulty in accurately determining the fault location under reduced generation conditions. Despite the application of mutual coupling and residual current compensation, deviations in measured impedance values persist due to changes in power flow dynamics.

These findings suggest that relays may respond more slowly or fail to detect certain faults (under-reach), necessitating adaptive relay settings to ensure protection reliability under varying generation conditions. Since protection schemes optimized for full generation may not be effective under reduced generation, implementing dynamic compensation strategies is essential to maintain the accuracy and efficiency of distance protection.

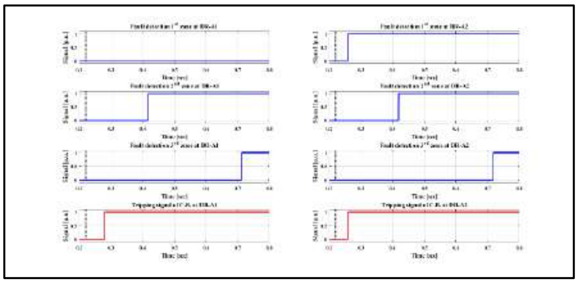

Fig. 16. Detection and tripping sequence of distance relays in A circuit using the PUTT scheme under low generation

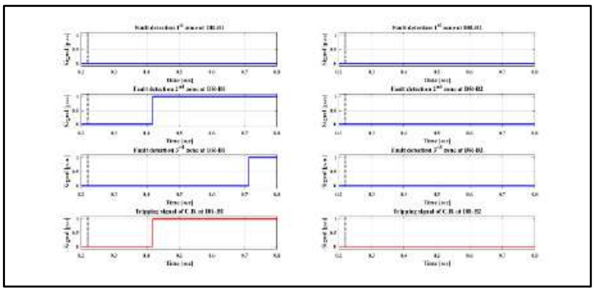

Fig. 17. Failure of distance relays in circuit B to detect and trip faults in PUTT under low generation

Under low wind generation conditions, the performance of the PUTT scheme is significantly impacted, as illustrated in Fig. 16 and Fig. 17. Ideally, the healthy circuit should remain in service while only the faulted circuit is isolated. However, the results in Fig. 17 indicate that the healthy circuit incorrectly issued a trip signal, an unintended and undesirable response.

This maloperation is primarily due to zero-sequence mutual coupling, which induces unwanted currents in the non-faulted circuit. As shown in Fig. 16, under low generation conditions, these induced currents become more significant relative to the total current, misleading the protection system. Consequently, distance relays in the healthy circuit (Circuit B) misinterpret these induced currents as actual fault currents, leading to unnecessary tripping of the fault-free transmission line.

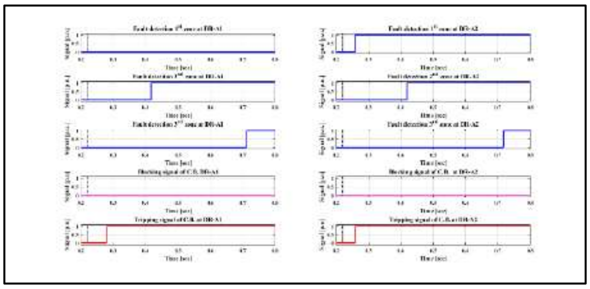

Fig. 18. Detection and tripping sequence of distance relays in circuit A using the DPUTT scheme

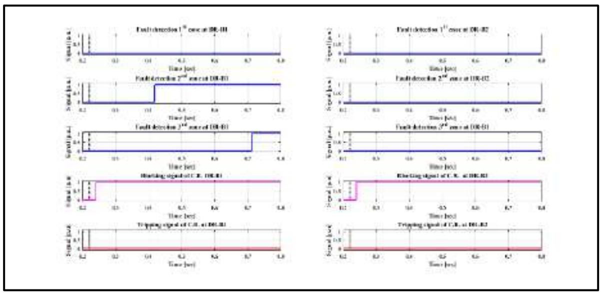

Fig. 19. Successful blocking of unnecessary tripping in circuit B using the DPUTT scheme

The DPUTT scheme in Fig. 18 and Fig. 19 demonstrates a significant improvement in relay response and the prevention of unnecessary tripping of the healthy circuit (B) compared to the conventional scheme, particularly under low generation conditions. As wind turbine power decreases, fault currents weaken, increasing relay sensitivity to induced currents and making false tripping more likely.

In the conventional scheme, low generation conditions caused induced currents to have a greater relative impact, leading relays in Circuit B to misinterpret these currents as actual fault currents, resulting in unnecessary tripping of the healthy circuit. However, in the DPUTT scheme shown in Fig. 18 and Fig. 19, blocking signals were effectively activated, preventing relays from issuing false tripping signals. As a result, only the faulty circuit A (where the fault actually occurred) was isolated, thus keeping Circuit B live and therefore improving protection dependability and power transfer continuity.

The results of this analysis highlight the adaptive nature of the proposed PUTT scheme to generation changes, which additionally enhances the reliability and efficiency of wind-integrated double-circuit transmission lines protection compared to the traditional scheme. Under changeable generation conditions, such as low power generation of wind turbines, it proves to be robust and enhances the stability and economic operation of dynamic systems.

4. Conclusion

This study presented an enhanced distance protection strategy for wind-integrated double-circuit transmission lines by improving the conventional PUTT scheme through adaptive directional supervision based on traditional fault current behavior in transitional zones. The findings revealed that the conventional scheme is significantly affected by mutual coupling often resulting in unintended tripping of the healthy circuit particularly under varying wind generation conditions.

To address this limitation the improved PUTT configuration incorporated a blocking logic based on zero-sequence ground current comparison. This enabled the relay to differentiate between genuine fault currents and induced components due to mutual coupling. The proposed method demonstrated a substantial reduction in false tripping incidents while maintaining uninterrupted operation of the healthy line.

The results also indicated that during periods of low wind generation the sensitivity of traditional relays to mutual coupling increases making them more vulnerable to incorrect operation. However the proposed DPUTT scheme exhibited strong adaptability to generation variability enhancing both fault detection accuracy and coordination between protective devices.

These outcomes underscore the necessity of implementing dynamic compensation techniques in distance protection systems for renewable-integrated networks. Future work may focus on exploring adaptive relay settings to further improve system stability and protection reliability under diverse operating scenarios.

A quantitative evaluation of the simulation results showed that the proposed DPUTT scheme achieved up to a 99% reduction in false tripping events compared to the conventional PUTT method. This remarkable improvement validates the effectiveness and robustness of the developed protection approach for wind-integrated double-circuit transmission systems.

While the proposed DPUTT scheme significantly improves relay selectivity, its performance under communication delays or failures in the pilot channel was not investigated. Future work should explore adaptive relay settings and redundancy strategies to enhance robustness under such conditions.

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