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A reliable accelerated protection scheme for converter-dominated power networks.
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A Reliable Accelerated Protection Scheme for Converter-Dominated Power Networks

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***Abstract*—Communication assisted transfer trip schemes are generally preferred for transmission lines to provide reliable and accelerated protection from both ends. Dependability of such schemes on the performance of conventional distance and/or directional relays at both ends expresses a concern on their reliability in power systems with high penetration of converter-interfaced renewable sources. This work demonstrates the impact of converter-based sources on the available accelerated protection schemes and proposes a new transfer trip scheme mitigating the issue. The proposed method includes a new criteria to identify the fault direction in converter-dominated power networks using local voltage and current data. The scheme is tested for a modified WSCC 9-bus system with 100% converter-interfaced renewable penetration using PSCAD/ EMTDC and found to be reliable for different faults and system conditions.**

***Index Terms*—Accelerated protection, transfer trip scheme, distance relaying, directional relaying, power system faults, Converter-interfaced renewable sources.**

I. Introduction

Ambitious decarbonization target are enforcing power grids for large-scale integration of renewable energy sources [1]. Integration of such sources necessitates numerous control functions to be employed in the interfacing converters to ensure reliable power system operation [2]. Diversity in control schemes compels converter-interfaced renewable energy sources (CIRES) to behave differently (in terms of output voltage and current signatures during fault) when compared to conventional synchronous generators during fault, which results in a non-homogeneous situation in the grid [3]. With such increasing non-homogeneity in the power system, available local data-based protection schemes fail to derive correct decision at times [3]–[5]. Line differential scheme employing both end current data are recommended for such a situation. Cost associated with the high-bandwidth dedicated communication channel required for this purpose and the communication latency are two major concerns for wide-application of such a scheme in transmission network. Limited performance of current differential relays in converter-dominated power system also discourages for such a high investment [6]. Therefore, the transfer trip schemes requiring low-bandwidth communication channel are preferred for transmission network protection [7]. Such schemes communicate the trip decision derived by local distance or directional units to the other end for ensuring secure and dependable accelerated protection for the lines. Severe underreach and overreach issues with distance relays and inconsistent angular relation between voltage and current resulting directional relay maloperation impel to revisit the performance of available communication assisted tripping schemes for CIRES dominated power systems.

In this work, the limited performance of available communication assisted tripping schemes are demonstrated for converter-dominated power systems and a novel scheme is proposed mitigating the issue. A new criteria is defined using local voltage and current data to identify the fault direction in power networks in the presence of converter-based sources. The proposed scheme uses a low-bandwidth dedicated communication channel to transfer decisions derived at both ends and issues a trip command when the fault is detected in forward direction at both ends of the line. The scheme is tested for a modified WSCC 9-bus system with 100% converter-interfaced renewable penetration using PSCAD/ EMTDC. The performance is found to be independent of fault resistances, fault locations and different control operations associated with converters-based sources.

II. Problem Statement

This section first presents an overview of the available communication assisted transfer trip schemes commonly used for accelerated protection in transmission networks and later demonstrates the limited performance of those schemes for a converter-dominated power system. Fig. 1(a) represents a two-bus equivalent power network, where the tripping zones for each end distance relays are shown in Fig. 1(b). The operating principle of four commonly used tripping schemes are described below.

- **Direct Underreach Transfer Tripping (DUTT):** DUTT scheme, as shown in Fig. 1(c) issues a trip signal for both end circuit breakers when the fault is detected in Zone-1 by any of the relays (R_M and R_N) [8], [9].
- **Permissive Underreach Transfer Tripping (PUTT):** PUTT scheme employs Zone-1 decision at any end to trip the local breaker immediately and sends the decision to

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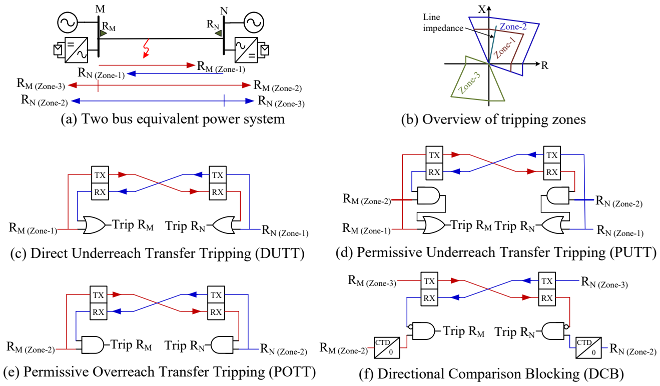


Fig. 1. Overview of common communication assisted transfer trip schemes.

remote end as a permissive trip command. The permissive signal confirm the tripping of remote end breaker only when the corresponding relay finds the fault in Zone-2 usinf local data, as shown in Fig. 1(d) [7], [10].

- **Permissive Overreach Transfer Tripping (POTT):** POTT scheme (shown in Fig. 1(e)) issues a trip signal for both end circuit breakers when the fault is detected in Zone-2 by both end relays [7].
- **Directional Comparison Blocking (DCB):** In this scheme, a trip command is generated when the fault is detected in Zone-2 by the local end relay and the remote end relay detects the fault outside of zone-3, as shown in Fig. 1(f) [7].

Now, the performance of the above mentioned schemes is tested for a 230 kV, 60 Hz modified WSCC 9-bus system with 100% converter-interfaced renewable sources, as shown in Fig. 2 [11], using PSCAD/ EMTDC simulation platform. Converter interfacing the solar plant at bus $2'$ follows grid-following control technique, whereas the converters interfacing the solar plants connected at bus 1 and 3 follow grid-forming control technique. The grid-following converter is controlled with balanced current controller, whereas the grid-forming converters are designed with dual-current controller mimicking synchronous generator negative sequence impedance angle characteristics. Line 2-7 is considered here as the protected line and the performance of relay R_2 and R_7 are tested for the purpose. Distance relays are set with quadrilateral characteristics as in [12] with a fault resistance coverage of 60Ω.

A phase-B-to-phase-C-to-ground (BCG) fault is created in line 2-7 at a distance of 0.25 pu from bus 2 with $R_F = 20\ \Omega$. Performance of the distance relays at bus 2 and bus 7 (R_2 and R_7) are demonstrated in Fig. 3. Results show that both the relays fail to identify the fault in corresponding Zone-1, which indicates a clear maloperation for DUTT and PUTT schemes. As shown in Fig. 3(a), the relay R_2 finds the fault even outside its Zone-2 boundary. This causes incorrect operation of PUTT and DCB schemes.

The decisions derived using distance relay Zone-2 setting can also be realized using directional relaying principles [7].

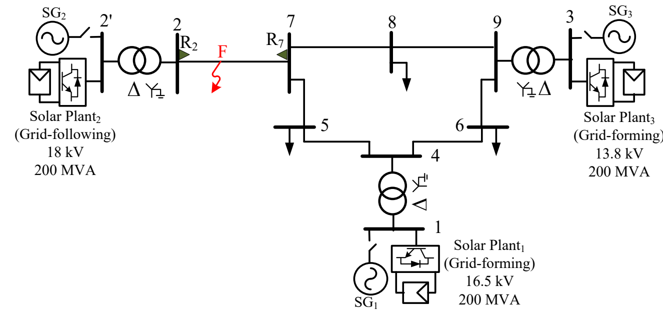
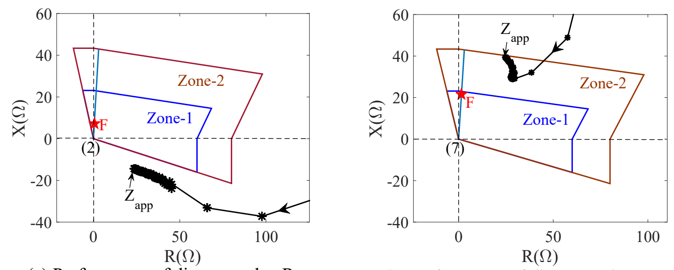


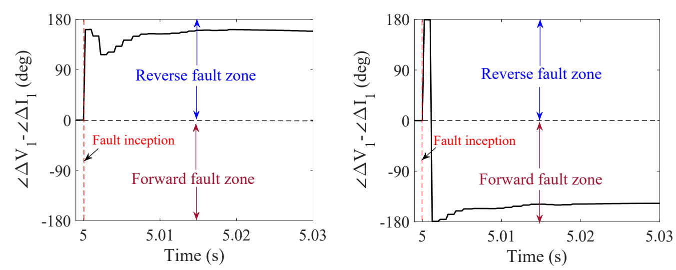
Fig. 2. Modified WSCC 9-bus power system with 100% CIRESs.



(a) Performance of distance relay R_2 (b) Performance of distance relay R_7

Fig. 3. Performance of both end distance relays leading to failure of available accelerated protection schemes.

Therefore, the performance of relay R_2 and R_7 are also tested after employing superimposed component based directional relaying principle, which is applicable for all types of faults [13]. Results are provided in Fig. 4. ΔV_1 and ΔI_1 are the positive sequence superimposed voltage and current obtained by subtracting 2-cycle memorized value from the fault data [14]. According to the principle, the relay identifies the fault in forward direction when ΔV_1 lags ΔI_1 i.e. the angle difference between ΔV_1 and ΔI_1 is negative. Results in Fig. 4 show that the relay R_7 finds the fault in forward direction correctly, whereas the relay R_2 detects the fault in reverse direction. This results in maloperation of PUTT, POTT and DCB schemes, even after applying directional principle. Thus, there is a need for a new scheme for reliable protection of transmission lines in the presence of converter-based sources.



(a) Performance of directional relay R_2 (b) Performance of directional relay R_7

Fig. 4. Performance of both end directional relays leading to failure of available accelerated protection schemes.

III. Proposed Method

This section introduces a new technique for reliable and accelerated protection of converter-dominated power networks.

For the two-bus equivalent system in Fig. 1(a), an AG fault is created at a distance of $x\ pu$ from bus M and with a fault resistance R_F. Distance relay at bus M calculates the apparent impedance (Z_{app}) as in (1) [15].

$$Z_{app} = \frac{V_{AM}}{I_{AM} + K_0 I_{0M}} = xZ_{1L} + \left(\frac{I_{AF}}{I_{AM} + K_0 I_{0M}}\right) R_F. \quad (1)$$

Where, subscripts 'M' represents the measurement at bus M and 'F' represents the the variables in faulted path. Z_L represents the impedance of line MN. The zero and positive sequence components are represented by the subscripts '0' and '1' respectively. Fig. 5 represents the sequence network of a system with converter-interfaced sources connected at both ends of the protected line (as shown in Fig. 1(a)) for AG faults. I_{1F}, I_{2F} and I_{0F} being equal, I_{AF} in (1) can be replaced by I_{0F}, as in (2).

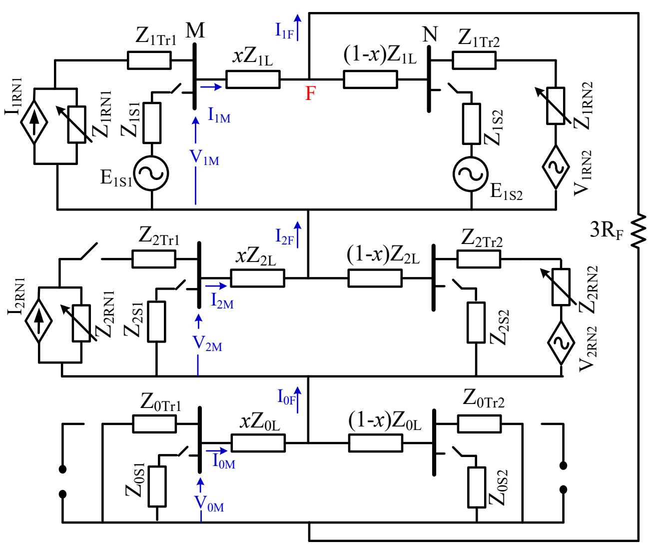


Fig. 5. Sequence networks of a renewable-dominated system for AG faults.

$$\frac{V_{AM}}{I_{AM} + K_0 I_{0M}} = xZ_{1L} + \left(\frac{3I_{0F}}{I_{AM} + K_0 I_{0M}}\right) R_F. \quad (2)$$

Applying the complex forms of the variables in (2), it is rewritten in (3).

$$\frac{|V_{AM}|}{|I_{AM}+K_0 I_{0M}|} e^{j(\alpha-\beta)} = x|Z_{1L}|e^{j\theta_{1L}} + \frac{|3I_{0F}|}{|I_{AM}+K_0 I_{0M}|} e^{j(\gamma-\beta)} R_F \quad (3)$$

Phases of V_{AM} and $(I_{AM} + K_0 I_{0M})$ are represented by α and β respectively. θ_{1L} is the impedance angle of the protected line. Phase angle of I_{0F} is represented by γ. (3) is rewritten in (4).

$$\frac{|V_{AM}|}{|I_{AM}+K_0 I_{0M}|} e^{j(\alpha-\gamma)} = x|Z_{1L}|e^{j(\theta_{1L}-\gamma+\beta)} + \frac{|3I_{0F}|}{|I_{AM}+K_0 I_{0M}|} R_F \quad (4)$$

Equating the imaginary components of each term in (4), it is rewritten in (5).

$$\frac{|V_{AM}|}{|I_{AM} + K_0 I_{0M}|} \sin(\alpha - \gamma) = x|Z_{1L}| \sin(\theta_{1L} - \gamma + \beta) \quad (5)$$

From (5), x can be computed as in (6).

$$x = \frac{S_{1M}}{S_{2M}} \quad (6)$$

Where,

$$S_{1M} = \frac{|V_{AM}|}{|I_{AM} + K_0 I_{0M}|} \sin(\alpha - \gamma)$$
$$S_{2M} = |Z_{1L}| \sin(\theta_{1L} - \gamma + \beta).$$

Converter-interfaced renewable sources are generally interfaced through a transformer of dYg type. Therefore, all the impedances in zero sequence network remain homogeneous as considered for a system with only synchronous generator based sources. Thus, γ is the angle of zero sequence current measured at bus M. γ for other faults is estimated using the sequence network corresponding to particular fault type, as available in [16]. x is also derived for other fault types in a similar way. x is always positive for any fault in forward direction. Thus, a new directional criteria for converter-dominated power network is proposed in (7).

$$\frac{S_{1M}}{S_{2M}} = \begin{cases} > 0; & for\ forward\ fault \\ < 0; & for\ reverse\ fault \end{cases} \quad (7)$$

Using this criteria, a new transfer trip scheme is proposed. The scheme issues trip command only when the fault is identified in forward direction at both ends, as shown in Fig. 6.

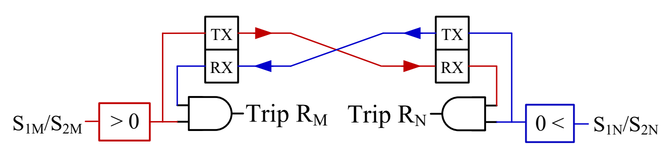
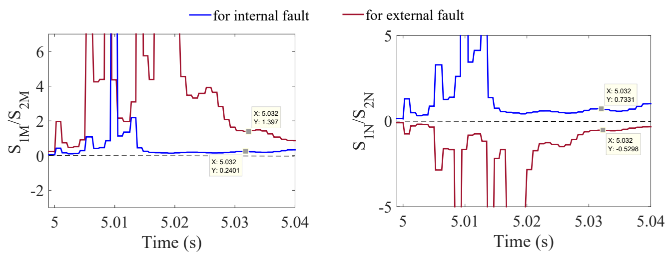


Fig. 6. Proposed transfer trip scheme logic implementation.

IV. Results

The 9-bus system in Fig. 2 is used for the performance evaluation of the proposed method. The method is tested for the relays at both ends of line 2-7 for different internal and external faults. Measured signals are sampled at a rate of 64 samples/ cycle and discrete Fourier transform is applied for phasor estimation. Results for two cases (one internal and one external) are demonstrated in Fig. 7 and the details are provided below.

In this first case, a BCG fault is created in line 2-7 at a distance of 0.25 pu from bus 2 with $R_F = 20\ \Omega$. Results in Fig. 7 show that the directional index calculated at both ends are positive (0.24 and 0.73). Thus, the method identifies the internal fault correctly and issues trip command for both end circuit breakers. In the second case, a BCG fault is created in line 7-8 at a distance of 0.5 pu from bus 7 with $R_F = 15\ \Omega$. From the results in Fig. 7, it is observed that the relay at bus 2 calculates x as positive (=1.40) using



(a) Performance of R_2 with proposed method (b) Performance of R_7 with proposed method

Fig. 7. Proposed transfer trip scheme logic implementation.

the proposed method, whereas the relay at bus 7 calculates x as negative (=0.53). Thus, the proposed scheme performs correctly even for external fault. The method is also tested for different types of faults created at different locations in different system conditions with variation in fault resistance, connected renewable sources and associated control operation. The method is found to derive a secure and dependable decision in each case.

V. Conclusion

Power grid is experiencing a noticeable change in fault characteristics with growing penetration of converter-based renewable sources. Conventional protection decisions derived in such a new grid scenario is found unreliable. This work demonstrates the impact of CIRESs on communication assisted accelerated protection schemes, where the trip decisions are generated and supervised by conventional distance and/ or directional relays. The work proposes a new criteria to identify the fault direction in converter-dominated power networks using local voltage and current data. The directional decisions derived at both ends are transferred mutually through a low-bandwidth dedicated communication channel to generate a secure and dependable trip command for the line end breakers. The method is tested for a 100% converter-interfaced renewable penetrated power system and found to be reliable for different types of faults created at different locations, with different fault resistances, change in converter-control operation and with different types of sources.

Acknowledgment

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