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Comparison of Current-Only Directional Protection in AC and DC Power Systems

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Abstract—Future distribution systems are conceived to be largely based on hybrid ac/dc power system architectures thus reaping the benefits of both ac and dc power systems. Directional protection is expected to play an important role for selective fault identification in such distribution systems. Traditionally, the directional protection comprises of a directional element working in conjunction with the overcurrent based fault detection algorithm. The selective operation is ensured by the definite mean-time operation of the overcurrent relays. For ac systems this directional element is based on the voltage polarisation techniques. In recent years, current-only directional element has been proposed which takes either pre-fault or the post-fault current as the polarising quantity. For the dc systems, directional protection is based on the operation only with the directional element which might maloperate during high-impedance faults. A new directional protection of dc power system is proposed in this paper which uses the time-domain based pre-fault current magnitude as the polarising quantity while frequency-domain of the fault current for fault detection. The proposed current-only directional protection of dc system is compared with that of ac systems. AC and dc power systems of similar topologies and power levels are considered and the faults of various impedances are tested to compare the current-only ac and dc directional protection. It is observed that the current-only ac directional protection has limitations at high-impedance faults while the proposed current-only dc directional protection can easily detect high-impedance faults.

Index Terms—DC Power System, Directional Protection, Fault Studies, Marine Vessels, Short-Time Fourier Transform.

NOMENCLATURE

$\mathcal{S}_{\mathcal{D}}$	Short-time Fourier Transform in discrete domain
f_u	Update frequency or zero-crossing frequency bin
$ \mathcal{S}_{\mathcal{D}} _{f_u}$	Magnitude of $\mathcal{S}_{\mathcal{D}}$ of frequency spectrum at f_u
$\mathbb{D}_{ac}$	Directional element in ac systems
$\mathbb{D}_{dc}$	Directional element in dc systems

I. INTRODUCTION

The advent of distributed generation and emerging renewable energy sources have fostered the development of the ac microgrids. Besides, efficient power electronic building blocks have enabled the implementation of dc power systems [1]–[5]. Although, the complete overhaul and replacement of the

existing ac system by the emerging dc is debatable, it is envisaged that the future power systems would comprise of hybrid ac/dc clusters thus taking the advantages of both ac and dc power systems [6]. Such systems could also find applications in more-electric aircraft [7] and marine vessels [8].

Protection of such systems would be carried out by the independent operation of ac and dc protection algorithms. Time-current graded non-unit protection has been a popular choice for ac systems [9]. This scheme is effective for larger ac systems where the close-in and far-end faults have significantly different magnitudes owing to longer line lengths. In ac distribution networks having smaller line impedance, definite mean-time (DMT) based protective relaying has been suggested. In such scenarios, the relays will trip after a fixed time when a current setpoint is exceeded. These methods are typically nondirectional and the operation of the multiple protective relays (R) (as shown in Fig. 1) would require complex coordination among them [9]. For such distribution systems with multiple generation and loads, directional protection system is found to be advantageous [9], [10]. Traditional directional protection in ac systems is the combination of $\mathbb{D}_{ac}$ and DMT based overcurrent (OC) protection [10]. $\mathbb{D}_{ac}$ determines the direction of fault, whereas the OC relay initiates the tripping command. The prime research thrust in directional protection in ac system has been in the selection of $\mathbb{D}_{ac}$. Voltage polarisation technique has been conventionally used where the current phasor is compared with the bus voltage phasor to determine the direction of fault in ac systems [9]. In recent years, determining $\mathbb{D}_{ac}$ using current-only methods have been proposed [11]–[18]. Such methods do not require expensive voltage measurement devices and are claimed to be robust while detecting the low-impedance faults.

The dc distribution bearing similar topology with that of ac systems (Fig. 1) is shown in Fig. 2. Similar to ac systems, directional protection is expected to be advantageous in such scenarios. As the transient responses of both systems are significantly different [19], it is expected that the working principle of the directional protection would also be different in nature. As compared to the ac systems, there have been limited advances in the directional protection for the dc systems [20]–[24]. Absence of phase and frequency makes the magnitude of dc current as the only parameter to devise the current-only directional protection. While the ac directional protection is

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Fig. 1. SLD of the representative ac system with radial distribution system.

based on the synergistic operation of $\mathbb{D}_{ac}$ and DMT based OC protection, directional protection in dc system is largely based on the operation of $\mathbb{D}_{dc}$. This works satisfactorily under the low-impedance faults, but might have limitations to detect the high-impedance faults. Thus, there is a need of additional fault detection to supplement the current-only $\mathbb{D}_{dc}$ in the dc power systems.

This paper aims a comparative analysis of the directional protection in ac and dc power systems. Fault of varying impedances are initiated on ac and dc power systems of similar topology and power rating for one-to-one comparison (Figs. 1 and 2). Current-only directional protection for ac systems is briefly reviewed and the time-domain based $\mathbb{D}_{ac}$ is compared with the time-domain based $\mathbb{D}_{dc}$. The limitations of the existing directional protection in dc systems are identified which are then modified by introducing new $\mathbb{D}_{dc}$ + STFT based current-only directional protection.

II. CURRENT-ONLY DIRECTIONAL PROTECTION IN AC SYSTEM

The time- and frequency-domain based deterministic approaches have been popular to compute the fault current direction. In ac systems, the current-only directional protection largely uses the pre-fault current as the polarizing quantity [11]–[17]. However, there are some approaches where the post-fault currents are taken as polarizing quantity [18]. Further, neural network based blackbox methods have also been proposed to compute the direction in ac systems [25]. However, for power system protection, the deterministic methods seems more suitable.

A. $\mathbb{D}_{ac}$ Based on Frequency Domain

Change in the phase angle is a popular approach to determine the direction of fault current. Recursive or nonrecursive discrete Fourier transform (DFT) can be used to compute the phase angle of the current signal [26]. It is computed every cycle and compared with the result obtained one cycle back. During normal condition, the difference in the phase angle of current and the previous current sample is not significant. For instance, by applying the recursive DFT, this difference would be zero, while the difference for nonrecursive DFT would be -1. For the forward faults, the difference becomes a large

Fig. 2. SLD of the representative dc system with radial distribution system.

Fig. 3. Illustration of $\mathbb{D}_{ac}$ based on comparing the phase angle.

negative magnitude while for the reverse faults the difference is a large positive value [11]–[15].

The possible algorithm structure of the directional element is shown in Fig. 3. It comprises the input current samples coming from current sensors which are transformed to the form of suitable feature vectors. DFT based phase computation is carried out, which determines the direction and thus decision logic. For three-phase operations, utilization of the positive phase sequence of sequential components has been proposed [14], [15]. The sequential components are known to be sensitive to changes in frequency, noise and amplitude. Thus, the construction of the current feature vector should be carried out with utmost care considering all the limitations [13]. The pre-fault current in such scenarios are assumed to be constant. The direction of pre-fault current is an important parameter to determine the direction of fault current. It is thus required to continuously update the status of pre-fault current depending on the direction of load flow [16].

Using only the post-fault current can be useful to determine the direction of power flow and hence the fault current [18]. The process involves the phasor estimation of the positive and negative derivative of the fault current. This is used for reference current generation and comparison with the post-fault current. The computed phases are needed to be expressed in the range of $[-\pi, +\pi]^{rad}$. It is observed that the change in phase (with respect to the generated reference current) for forward fault is $(+\pi/2)^{rad}$ while for negative fault is $(-\pi/2)^{rad}$. There is a difference of π^{rad} between the forward and reverse faults.

It is to be noted that the frequency-domain computation is primarily used for phase estimation which is then utilized to compute the direction of the fault current. NonDFT based methods such as Kalman filtering, recursive least squares, etc. might also be applied for phase estimation. However, such methods are found to be slow and not suitable for the protection algorithms [11]–[13].

B. $\mathbb{D}_{ac}$ Based on Time-Domain Analysis

Analogous to the phase estimation in frequency-domain, a zero-crossing time (ZCT) based method has been proposed to determine the direction of the fault current in time-domain [17]. This operation is depicted in Fig. 4. During normal operation (pre-fault current), the ZCT remains constant which is dependent on the system frequency. In this paper, the system frequency is chosen to be 50 Hz which makes the ZCT to be 10 ms. However, during the faults, the ZCT will change depending on the fault location in the forward or reverse direction. It is observed that the ZCT increases in forward faults, while it reduces under reverse faults, as shown in Fig. 4. Logic diagram of the ZCT based $\mathbb{D}_{ac}$ is shown in Fig 5 [13]. In real-systems, it is determined by counting the number of samples between the two zero-crossings. In

spite of the simpler operation, ZCT based $\mathbb{D}_{ac}$ is limited by the technical challenges such as dependence on sampling frequency, harmonics, frequency deviation, grounding systems and pre-fault current direction. Discussion of such challenges in determining ZCT along with the proposed solutions are elaborated in [13].

For directional protection in ac systems, the directional element $\mathbb{D}_{ac}$ is generally combined with an OC relay [9], [10]. For selective fault identification in distribution systems, DMT based time-current coordination in the OC relays is implemented. Such a combination should be able to effectively identify the fault currents of varying intensities. To study this, a range of fault impedances are initiated at point F of Fig. 1 and the ZCT based ac directional protection is applied. The peak rms fault current and maximum ZCT (Fig. 3) through R_4 and R_5 are indicated in Table I.

For fault F , R_4 will detect the forward fault while R_5 will detect the reverse fault condition. Thus, the ZCT width for R_4 will be larger than 10 ms while ZCT width for R_5 will be less than 10 ms. This can be seen in Table I for low-impedance faults from Case 1 to Case 8. For medium- to high-impedance faults, the ZCT for R_4 and R_5 is closer to 10 ms thus becoming difficult to detect the fault condition. Moreover, there is not so significant rise in the peak current of R_4 and R_5 . Thus, the $\mathbb{D}_{ac} + OC$ based directional protection is unable to detect

Fig. 4. ZCT for (a) fault in forward direction and (b) fault in reverse direction.

TABLE I
ZCT AND PEAK FAULT CURRENT FLOWING THROUGH R_4 AND R_5 FOR A RANGE OF FAULT IMPEDANCES AT 'F' IN FIG. 1

Case	Fault Resistance(Ω)	R_4		R_5	
		ZCT $_{R_4}$ (ms)	i_{R_4-rms} (pu)	ZCT $_{R_5}$ (ms)	i_{R_5-rms} (pu)
1	0.001	18.1	13.73	5.7	15.61
2	0.002	17.5	12.48	5.7	14.11
3	0.005	16.4	9.63	5.8	10.70
4	0.01	15.4	7.09	5.9	7.37
5	0.02	14.3	4.70	6.1	4.43
6	0.05	12.9	2.56	6.8	2.15
7	0.1	11.9	1.82	7.9	1.57
8	0.2	11.1	1.57	8.9	1.57
9	0.5	10.5	1.57	10	1.57
10	1	10.3	1.57	10	1.57
11	2	10.2	1.57	10	1.57
12	5	10.1	1.57	10	1.57
13	10	10	1.57	10	1.57
14	20	10	1.57	10	1.57
15	50	10	1.57	10	1.57

Base current: 1673 A.; Normal current flow: 1.57 pu

the fault conditions for high-impedance faults.

III. CURRENT-ONLY DIRECTIONAL PROTECTION IN DC SYSTEM

As compared to ac systems, directional protection in dc system is a relatively new area and is presently based only on the operation of the directional element $\mathbb{D}_{dc}$. Due to absence of phase and frequency in dc systems, magnitude remains the only parameter in time-domain to determine the direction [19]–[22]. In the existing approaches, the sign of the dc current has been used as a major indication of the direction change, which is illustrated as:

$$\mathbb{D}_{dc} = \begin{cases} 1, & \text{for } i[n] \geq 0 \\ 0, & \text{for } i[n] < 0. \end{cases} \quad (1)$$

The faulty segment is identified by comparing the $\mathbb{D}_{dc}$ output in all R . For instance, applying $\mathbb{D}_{dc}$ as per (1) for pre-fault and fault F in Fig. 2, gives the current direction in various relays as shown in Table II. It is seen that during the fault, the current through R_5 changes. By comparing the direction of R_5 with the nearest relays, it is seen that the direction is contradictory with R_4 . This infers that the fault has happened in between R_4 and R_5 .

Modeling $\mathbb{D}_{dc}$ as per (1) gives satisfactory results for low-impedance faults. However, for high-impedance faults, the current through R_5 might not reverse. To mitigate such limitations, $\mathbb{D}_{dc}$ could alternatively be modeled as:

Fig. 5. Illustration of ZCT algorithm.

TABLE II
RELAY DIRECTIONS FOR LOW-IMPEDANCE FAULT 'F' IN FIG. 2

Case	R1	R2	R3	R4	R5	R6
Pre-Fault Current	1	1	1	1	1	0
Fault Current	1	1	1	1	0	0

$$\mathbb{D}_{dc} = \begin{cases} 1, & \text{if } \Delta i \geq +\delta \text{ (Forward Direction)} \\ 0, & \text{if } \Delta i \leq -\delta \text{ (Reverse Direction)} \\ X, & \text{if } \Delta i < |\delta| \text{ (No Change)} \end{cases} \quad (2)$$

where, $\Delta i = i[n] - i[n-1]$, $i[n]$ is the present current sample whereas $i[n-1]$ is the past current sample. δ is a nonzero positive constant while $\mathbb{D}$ retains the previous operating value ($X = \{0, 1\}$) when the current difference lies between $\pm \delta$. δ must be greater than the ripple content of the dc current to avoid spurious directional output.

A. Overcurrent Based Directional Protection

The $\mathbb{D}_{dc}$ only determines the change in current direction, which apart from a faulty condition might also change during sudden load change, regenerative operation, change in system configuration etc. Thus, to confirm the fault condition, *OC* protection could be integrated with $\mathbb{D}_{dc}$ which is similar to the ac directional protection. To illustrate this $\mathbb{D}_{dc} + OC$ based dc directional protection, fault F is incepted in Fig. 2; the peak fault current and $\mathbb{D}_{dc}$ as per (2) is shown in Table III.

For low-impedance faults, the high-magnitude peak current is dominated by the dc-link capacitive discharge. Moreover, the current through R_5 reverses, which can be seen by the negative peak current during such conditions. However, for high impedance faults, the magnitude of peak current reduces. The current through R_5 stops reversing for high-impedance faults as inferred from Case 12 onwards. In such an scenario, computing $\mathbb{D}_{dc}$ using (1) would not detect the direction change. By using the proposed $\mathbb{D}_{dc}$ (2), direction change can be detected until Case 14 which is for a very high-impedance fault.

The *OC* based tripping of the relays depends on the DMT based tripping set-points. The peak current for high impedance faults has lower magnitude, hence this tripping operation might be limited to low-impedance faults. This is a major limitation of the $\mathbb{D}_{dc} + OC$ based dc directional protection. The rise time of the dc fault current is much faster than the rise time of the ac fault current due to lower inductance, and time constant of the system. Thus, the frequency-domain based approach could be used to compute the high-frequency components and hence confirming the fault condition. With this regard, short-time Fourier Transform (STFT) could be used as it allows for the quantitative analysis of high-frequency components [19], [23][27]–[30].

B. STFT Based Directional Protection

STFT is a frequency-domain analysis that helps in the quantitative analysis of the frequency components present in a signal. This is determined by computing the discrete Fourier transform of the signal over a pre-defined window function. In the discrete domain, it is expressed as follows:

$$\mathcal{S}_D[m, k] = \sum_{n=0}^{n=N-1} i[n]w[n-mH]e^{-j\frac{2\pi nk}{N}}, \quad (3)$$

where, $i[n]$ is the input signal, $w[n]$ is the window function, N is the number of FFT points, n is the time-domain index of $x[n]$, m is the position of $w[n]$ around which it is real and symmetric, H is the hop size between the successive windows

TABLE III
PEAK FAULT CURRENT AND $\mathbb{D}_{dc}$ IN R_4 AND R_5 FOR A RANGE OF FAULT IMPEDANCES AT 'F' IN FIG. 2

Case	Fault Resistance(Ω)	Current Through R_4 (i_{R_4})		Current Through R_5 (i_{R_5})	
		i_{peak} (kA)	$\mathbb{D}_{dc}$	i_{peak} (kA)	$\mathbb{D}_{dc}$
1	0.001	18.30	1	-20.74	0
2	0.002	17.75	1	-20.14	0
3	0.005	16.31	1	-18.48	0
4	0.01	14.38	1	-16.27	0
5	0.02	11.61	1	-13.09	0
6	0.05	7.35	1	-8.15	0
7	0.1	4.55	1	-4.89	0
8	0.2	2.71	1	-2.61	0
9	0.5	1.47	1	-0.95	0
10	1	0.88	1	-0.35	0
11	2	0.58	1	-0.04	0
12	5	0.40	1	0.14	0
13	10	0.33	1	0.21	0
14	20	0.30	1	0.24	0
15	50	0.28	1	0.26	1

Base current: 1300 A. $\delta = 20$ A.

Fig. 6. STFT operation to detect the high frequency components in a fault current.

TABLE IV
PARAMETERS USED IN STFT ALGORITHM

Sampling Frequency (f_s)	H	N	Time Res. ($=H/f_s$)	Freq. Res. ($=f_s/n$)
10 kHz	1	32	0.1 ms	312.5 Hz

TABLE V
UPDATE-FREQUENCY BINS FOR 32 SAMPLE HANNING WINDOW

Window Type	Win. Length [n]	Update Frequency Bins (f_u)		
		$2f_s/n$	$3f_s/n$	$4f_s/n$
Hanning Window	32	625 Hz	937.5 Hz	1250 Hz

and k is the frequency index. n is decided by the length of $w[n]$. The parameters used for computing $\mathcal{S}_D$ are listed in Table IV [27], [28]. The fault detection by $\mathcal{S}_D$ is illustrated in Fig. 6 where $w[n]$ is applied to $x[n]$. For the prefault current, the frequency spectrum has nearly zero magnitude at update frequency bins (f_u), which is shown in Fig. 6. The locations of f_u for given parameters are shown in Table V. During the faults in dc power system, the rapid discharge from the dc-link capacitor is expected to be comprised of high frequency components. This ingress of the high frequency components in the fault current is identified by the increased magnitude at f_u , i.e. $|\mathcal{S}_D|_{f_u}$, and is illustrated in the inset of Fig. 6. Along with $\mathbb{D}_{dc}$, this STFT algorithm will be embedded in the R and will operate according to:

$$\mathcal{S}_D = \begin{cases} 1, & \text{if } |\mathcal{S}_D|_{f_u} \geq \sigma \text{ dB} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where, σ is a fixed setpoint (in dB).

The operation of the STFT based dc directional protection for a range of fault impedances is shown in Table VI. It

TABLE VI

DECISION TIME OF STFT ALGORITHM AT R_4 AND R_5 FOR A RANGE OF FAULT IMPEDANCES AT 'F' IN FIG. 2

Case	Fault Resistance (Ω)	Current Through R_4 (i_{R_4})		Current Through R_5 (i_{R_5})	
		$ S_D _{f_u}$ (dB)	$t_{ S_D _{f_u}}$ (ms)	$ S_D _{f_u}$ (dB)	$t_{ S_D _{f_u}}$ (ms)
1	0.001	28.8605	0.20	30.8125	0.20
2	0.002	28.8462	0.20	30.7981	0.20
3	0.005	28.8035	0.20	30.7552	0.20
4	0.01	28.7326	0.20	30.684	0.20
5	0.02	28.5918	0.20	30.5427	0.20
6	0.05	28.1779	0.20	30.127	0.20
7	0.1	27.5149	0.20	29.461	0.20
8	0.2	26.2807	0.20	28.2212	0.20
9	0.5	23.1728	0.20	25.0951	0.20
10	1	30.7181	0.40	21.2195	0.20
11	2	25.3774	0.40	27.3136	0.40
12	5	24.5924	0.80	26.4906	0.80
13	10	23.3233	1.00	20.4584	0.80
14	20	20.5049	1.20	22.0975	1.20
15	50	15.5	—	16.4	—

$\sigma = 20$ dB, $f_u = 625$ Hz.

can be seen that the STFT algorithm can identify the high-frequency components for very high-impedance faults, which was difficult by using only OC relay. Thus $\mathbb{D}_{dc} + \text{STFT}$ based dc directional protection could be preferred over $\mathbb{D}_{dc} + OC$ based dc directional protection.

IV. DISCUSSIONS AND COMPARATIVE ANALYSIS

The comparison of the various aspects of the directional protection in the ac and dc power systems is depicted in Table VII. The following discussions are cited based on the comparative analysis of the directional protection in dc and ac systems:

- 1) Directional protection is the combined operation of the directional element and the fault detection algorithm. In traditional ac systems voltage-polarization based $\mathbb{D}_{ac}$ and OC based fault detection algorithm are used. In dc systems, directional protection with only directional element has been presented in the previous studies.
- 2) In the current-only directional protection, the directional element and fault detection algorithm is computed using only current elements. For ac systems $\mathbb{D}_{ac} + OC$ based directional protection is reviewed and compared. For dc systems, $\mathbb{D}_{dc} + \text{STFT}$ based directional protection is proposed which is supported by the limitation of the $\mathbb{D}_{dc} + OC$ based directional protection.
- 3) Directional element in ac systems i.e. $\mathbb{D}_{ac}$ can be computed in the time or frequency domain. The rms magnitude of the ac system is always positive thus becoming ineffective in computing the current direction. Frequency-domain based $\mathbb{D}_{ac}$ is based on the estimation of the current phase and comparing it with the previously computed value. Recursive or nonrecursive DFT can be used for this purpose. On the other hand, time-domain based $\mathbb{D}_{ac}$ computes the ZCT of the currents. The ZCT changes depending on the location of the fault.
- 4) It is seen that the time-domain based $\mathbb{D}_{ac}$ is ineffective for the medium- to high-impedance faults. However, it has been discussed in earlier works that the frequency-domain based $\mathbb{D}_{ac}$ could be better than the time-domain based $\mathbb{D}_{ac}$.
- 5) Apart from the ineffectiveness of $\mathbb{D}_{ac}$ for high-impedance faults, the magnitude of the fault current is

also not significant, which might not trigger the OC relay thus becoming ineffective in tripping the system. Hence, directional protection in ac systems could be chosen to mitigate low-impedance faults. The differential protection is expected to be the obvious choice for high-impedance faults.

- 6) On the contrary to ac systems, magnitude of the dc current is primarily used to compute $\mathbb{D}_{dc}$. The existing approaches are based on the sign of the dc current, which changes depending on the fault impedance and fault location. However, for high impedance faults this approach does not work properly. A new $\mathbb{D}_{dc}$ is proposed in this paper which is dependent on the present and past current magnitude.
- 7) Analogous to the ac directional protection, operation of the dc directional protection based on $\mathbb{D}_{dc} + OC$ is presented in this paper. The OC relay should be fast to cope up with the fast rising dc-link capacitor discharge. Like ac systems, the OC relay becomes ineffective for high-impedance faults. Moreover, for variable system configurations of applications in the aircrafts and marine vessels, the OC tripping setpoints must be altered accordingly. This may restrict the usage of OC for fault identification and tripping accordingly.
- 8) The rate of rise of fault current is faster in dc power systems as compared to the ac systems. Thus, it is expected that the STFT based fault detection is more suitable for dc power systems. It detects the high-frequency components in the rapidly rising dc fault current. With this regards, $\mathbb{D}_{dc} + \text{STFT}$ is able to detect high-impedance faults.
- 9) In ac systems, frequency-domain based $\mathbb{D}_{ac}$ (based on phase estimation) and time-domain based fault detection (OC relay) constitute the directional protection. However, for dc systems time-domain based $\mathbb{D}_{dc}$ (based on magnitude) and frequency-domain based fault detection (STFT) are more preferable. This is the major difference between directional protection in ac and dc systems.
- 10) Due to involvement of multiple relays, application of the directional protection to protect the lines and cables in ac and dc systems would require low-bandwidth communication infrastructure. This becomes similar in both systems.

V. CONCLUSION

This paper has presented a directional protection and a comparative studies of application to ac and dc power systems. It is seen that the $\mathbb{D}_{ac} + OC$ based directional protection in time-domain is suitable for low-impedance faults in ac systems. For high-impedance faults, the $\mathbb{D}_{ac}$ is unable to detect the current direction. For dc systems, a new directional element $\mathbb{D}_{dc}$ along with STFT based fault identification are proposed. This $\mathbb{D}_{dc} + \text{STFT}$ based dc directional protection is further compared with the $\mathbb{D}_{dc} + OC$ based dc directional protection. As compared to $\mathbb{D}_{dc} + OC$, $\mathbb{D}_{dc} + \text{STFT}$ based dc directional protection is able to identify the high-impedance faults. Although the magnitude of dc current is low, the rise time of the high-impedance fault is fast which is expected to be comprised of high-frequency components. Thus, the OC

TABLE VII
AC DIRECTIONAL PROTECTION V/S DC DIRECTIONAL PROTECTION

Comparison Metrics	AC Directional Protection	DC Directional Protection
Protection Philosophy	Directional Element + OC Relay [9], [10]	1) With only directional element [19]–[24]. 2) Directional element + OC tripping [24]. 3) Directional element + STFT tripping.*
Modeling Directional Element	1) Voltage polarising techniques [9]. 2) Current-only methods. a) ZCT based time-domain methods [13], [17]. b) Phase estimation based frequency-domain methods [14], [15].	1) Sign of the fault current [20]–[24]. 2) Comparison with pre-fault current.*
Polarising element for current-only protection	1) Polarising with pre-fault current [11]–[17]. 2) Polarising with post-fault current [18].	1) Polarising with pre-fault current.*
Fault Tripping Criteria	1) Fixed time and overcurrent settings [10]. 2) Time-current characteristics [9].	1) Comparison with the sign of the pre-fault current [20]–[24]. 2) OC protection. 3) Detection of high frequency components [19], [23], [27]–[30].
Tripping Setpoint Optimisation	Required if OC is used with variable system configuration [24].	1) Required if OC is used with variable system configuration [24]. 2) Not required if frequency-domain based protection such as STFT is used.*
Communication Requirements	Low-bandwidth communication [10]–[13].	Low-bandwidth communication [20]–[24].

*: Proposed in this paper.

relay may not reach the tripping setpoint but the STFT is able to detect such high-frequency components indicating fault in the system.

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