Current-Only Directional Overcurrent Protection for Distribution Automation: Challenges and Solutions

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Abstract—Overcurrent relays are widely used for power systems protection. Transmission side uses more directional type relays, while distribution systems, e.g., radial and ring-main subtransmission systems use non-directional types. The fault direction may be forward (between relay and grid), or reverse (between relay and source), the normal power flow being from source to the grid. Traditional directional overcurrent relays utilize the reference voltage phasor for estimating the direction of the fault. This requires measurement of both current and voltage using respective sensors. This makes the directional overcurrent relays more costly than the non-directional type. In this paper, a novel current-only directional detection possibility is highlighted along with theoretical, test signal analysis, challenges and associated solutions. Possible utilizations of the current-only directional relay in the distribution side protection are described, which is a key focus area for enabling the smart grid.

Index Terms—Distance protection, fault direction, fault isolation, fault location, medium voltage, MV, phase angle, radial network, relay, ring-main unit, voltage less direction, smart grid, subtransmission.

I. INTRODUCTION

Numerical feeder protection relays typically employ non-directional time overcurrent techniques, monitoring the overcurrent (from the set value) for a defined time to initiate the definite minimum time (DMT) or inverse definite minimum time (IDMT) type protection [11],[2]. Monitoring of overcurrent over time (typically 40–100 ms) is required to differentiate faults from load changes. This is typically governed by IEC standards like 60255 [3] for lowset, highset, very highset stages, depending on various overcurrent magnitude and duration for non-directional relays. Time relaying delays the operation of the relay for a remote fault, allowing relays and breakers closer to the fault to clear it. This requires a number of relays and complex coordination setting for effective distance protection [2].

Alternatively, directional overcurrent relays [4] rely on a reference voltage phasor, also known as “voltage polarization” [5], for estimating the direction of the fault, judging the current phase angle polarity relative to the voltage phasor [6]. This requires both current and voltage sensors, especially the latter (e.g., potential transformers) being expensive. The costly directional overcurrent relays thus cannot be considered for distribution side protection which then must use the non-directional ones.

Ukil et al. proposed current-only directional detection principle in [7]–[8]. In this paper, the technical challenges to the current-only directional protection principle and potential solutions are discussed in details. The remainder of the paper is organized as follows. In section II, the current-only principle is briefly mentioned followed by discussions on other relevant works. Frequency domain algorithm and signal analysis are briefly mentioned in section III. Time domain algorithm is described in section IV. Section V highlights the specific technical challenges, solutions of which are discussed in section VI. Discussions on the algorithm, challenges and solutions are described in section VII, followed by conclusions in section VIII.

II. CURRENT-ONLY DIRECTIONAL DETECTION

A. Principle

The current-only detection principle is introduced in [7], which is briefly mentioned here. As shown in Fig. 1, a power line connects an upstream power source (S) to a downstream power distribution system (grid, G) (with the normal power direction from the upstream source to the downstream grid).

The forward fault (F) happens between the relay and the line, and the backward or reverse (R) direction between the source and the relay. As the fault current in reverse case, \( I_{\text{res}} \), is directed reverse to the pre-fault current \( I_{\text{pre}} \) compared to the forward fault current, \( I_{\text{fwd}} \), one would see a phase angle difference in the post fault current due to Kirchoff’s current law [7]. This is also observed in the phasor diagrams which can be referred in [7]–[8], not repeated here.

![Fig. 1. Overcurrent relay: forward (F) and reverse (R) fault.](source)

B. Previous Works

Eissa [9] discussed about current-only directional detection, leveraging the difference in fault current directions. However, the work reported in [9] relies on time-domain method. Time-domain methods would be very much influenced by inherent noise, presence of harmonics, frequency deviations, etc.
Hence, it would be hard to achieve a robust implementation as required for power systems protection. Pradhan et al. [10] reported utilization of phase angle-based detection. This is a better approach. However, they used symmetrical components for three-phase operation, and Kalman filtering for the phase angle computation. It will be shown later that symmetrical components are very problematic when dealing with real-life current signals with inherent unbalances, frequency deviations. And Kalman filters might not be the optimal choice for harmonics issues, computational speed and complexity. Pradhan and Jena [11] also reported utilization of current-only directional protection algorithms for improving the ‘close-in’ faults, i.e., when the fault is in too close proximity to the relay.

### III. FREQUENCY DOMAIN ALGORITHM

#### A. Detection Method

The input to the directional device consists of only current samples from sensors like current transformers (CTs), Rogowski coils, etc. We propose to use the discrete Fourier transform (DFT)-based phase angle computation.

The basic idea is that under normal condition, there is not much change in the current phase angle, while that changes during fault. Let’s say, we continuously estimate the current phase angle via DFT at each cycle \( n, n+1, \ldots \) as \( \phi_n, \phi_{n+1}, \ldots \), and consider the difference \( \Delta \phi = \phi_{n+1} - \phi_n \). \( \Delta \phi \approx 0 \) under normal condition, while at forward or reverse fault, it will show big angle changes, with negative and positive polarity.

DFT is particularly suitable for tackling the total harmonic distortions (THD) [6]. Non-DFT based phase angle estimation, e.g., using Kalman filter [10], recursive least squares [6] might be too slow for online protection, which lies typically in the range of 20–100 ms [2]. Blackbox methods like neural networks (NN) [13] as decision logic might not be preferred over the deterministic methods like the DFT. Ensemble of decisions is also possible [7].

#### B. Fault Signal Analysis

Using the DFT-based algorithm, analysis of forward and reverse faults are discussed in [8], using signals from fault recorders with sampling frequency of 2.5 kHz in a 50 Hz system, i.e., 50 samples per cycle, sampling angle of \( \frac{\pi}{25} \) radian.

### IV. TIME DOMAIN ALGORITHM

#### A. Zero-Crossing Detection Method

Zero-crossing time (ZCT) in the time-domain could also be used for current-only directional detection [14]. The principle would be that, during normal operation, the ZCT width is fixed, determined by the nominal frequency. For example, for a 50 Hz supply frequency system, the ZCT width for half cycle would be 10 ms. From Fig. 2, we can see that for forward fault, the ZCT width would be increased, while that would typically decrease for the reverse case. The width between two ZCTs is determined by counting the number of samples lying between them with same polarity. The zero crossing detection (ZCD)-based algorithm is shown in Fig. 3.
B. Issues with ZCD-based Method

The ZCD-based time-domain method could be simple in implementation. However, being a time-domain method, it has several critical limitations [14], some of which are mentioned below. These also apply to other time-domain methods like the work reported in [9].

- The signal length between two consecutive zero crossovers highly depends on the fault inception angle. Therefore, if there is fault inception close to zero crossovers, there will be possibility of having two zero crossovers with small widths, giving erroneous directional decision. For the forward fault case shown in Fig. 4, we would expect an increased ZCT width. However, as the fault inception happens just after the signal crossed the zero, the reverse glitch (which causes increased ZCT width) itself crosses zero, indicating decreased ZCT width, i.e., reverse fault. To correct it, adjustments to the logic is needed, e.g., to handle two small consecutive ZCT widths, etc. These are not described further in details, as DFT-based method [8] is preferred.
- The processing is based on the digital samples of the input signal. In presence of harmonics or disturbances there are possibilities of false decision.
- No digital filtering techniques are used. Therefore, a constant DC can affect the ZCT width.

V. TECHNICAL CHALLENGES

The current-only directional algorithm(s), has several challenges. These are described in this section.

A. Three-Phase Operation

In real-life, one would need to incorporate current-only algorithms for three-phase operations. Pradhan et al. [10] proposed to use positive phase sequence (PPS) component using the symmetrical component analysis. However, the angle of the PPS is highly dependent on any frequency deviation, inherent unbalance in the phase currents, and noise [6].

From the theoretical analysis in [6], it is evident that due to frequency unbalance (e.g., in the range of ± 5 Hz), one can observe a slope and ripple in the PPS phase angle, as shown in Fig. 5 [6]. Furthermore, inherent unbalance amongst the three phases is typically present in real-life power systems operations. Analysis in [6] shows that due to the unbalance, an additional component gets superimposed on to the main phase components, resulting in a slope in the angle (e.g., like plot (b) in Fig. 5).

From previous discussions, it is evident that to apply the current-only concept, one would require the pre-fault current phase angle to be almost constant. However, due to the presence of harmonics and unbalances, the pre-fault angle could already have a slope. Due to the slope, the phase angle difference between two cycles would attain a finite value, erroneously indicating a fault. Thus, PPS component of the pre-fault current cannot be reliably used as a stable and robust polarizing quantity.

Fig. 5. Influence on frequency deviation on the (a) magnitude and (b) angle variation with time of phasor estimate.

B. Sampling Frequency Limitation

Depending on the sampling frequency, there might be limitation on the minimum fault angle change detection sensitivity. For example, if the sampling frequency is 1 kHz, then for 50 Hz system, the minimum angle change sensitivity (per cycle) would be \( \frac{360°}{1000/50} = 18° \) per sample. Any angle change below this limit cannot be recognized correctly. This is depicted in Fig. 6.

Thus, if the phase shift is smaller than about the sampling angle, one would expect that an approach based on the detection of the phase shift becomes unreliable. If, for example, a sample \((N − 1)\) is taken just before the fault inception (see Fig. 6), and if the fault angle change is less than about the sampling angle, then the next sample \(N\) will be taken after the change, resulting in a false directional estimation.

Fig. 6. Sampling frequency limitation.

C. Frequency Deviation

Typically, power systems are expected to operate at a nominal frequency, e.g., at 50 or 60 Hz. However, for many reasons, there are often frequency deviations. Typically, relays are certified for operations with a tolerance of ± 5 Hz [15]. As we propose to use the DFT for the phase angle computation, any frequency deviation has to be properly tackled.

D. Harmonics

As we are concerned with the current, harmonics (e.g., typically the odd ones like 150 Hz, 250 Hz, etc for a nominal frequency of 50 Hz) would in general be present, due to different reasons, e.g., non-linear loads like drives, power electronic devices, etc. As discussed above, presence of harmonics is quite a problem, and need to be tackled for a robust phase angle estimation.
E. Noise

Inherent measurement noise would be present, which would need to be handled for robust operation.

F. Grounding Systems

Phase-to-ground fault characteristics significantly depend on the type of the network neutral earthing (grounding). In medium voltage (MV, < 35 kV) networks, the neutral grounding can be directly or solidly grounded, grounded through impedance (e.g., Petersen coils), or isolated (unearthed) [17]. The effect of the different grounding systems, (typical ones shown in Fig. 7) need to be taken into account.

G. Coordination with Fault Inception Detection

The current-only directional detection module in general would not be used as fault inception detector. In practice, there are separate overcurrent fault inception detection modules, which leverage IEC standards like 60255 [3] for lowset, highset, very highset stages, depending on various overcurrent magnitude and duration. Therefore, the current-only directional detection module would need to coordinate with the fault inception detection module.

H. Valid Pre-fault Current

To judge the direction, as baseline information, the current-only relay has to see valid pre-fault current for certain duration. This is in general not any imposing condition, as the pre-fault current flows, and the relay sees that before fault inception [7].

I. Pre-fault Direction Change

The direction information estimated during fault, is judged with respect to the pre-fault current according to basic theory. If the direction of the pre-fault current changes during normal condition, the direction definitions (forward or reverse) would be vice versa. From the theory, the relay would not be able to judge that automatically [7].

J. Computation Time

In typical power systems protection relays [15], the sampling frequency is about 2–3 kHz, resulting in about 500–333 µs between arrival of two samples. Usually, all the protection function computations have to be performed before the next sample arrives.

VI. SOLUTIONS TO TECHNICAL CHALLENGES

In this section, we discuss about the potential solutions to the technical challenges mentioned in section V.

A. Three-Phase Operation

In order to solve the problem with the PPS for three-phase operation, we choose the algorithm as shown in Fig. 8.

In the first part of the algorithm in Fig. 8, we compute separately the phase angles of the three single phases using the DFT method, which is very stable. For the required accuracy, not a single value, rather a buffer of phase angle difference is accumulated for certain duration. For example, Fig. 8 shows accumulation of phase angle differences over the last twenty samples, which is equivalent to 1 cycle of 50 Hz system with a sampling frequency of 1 kHz. Then, we consider the maximum angle change and take this as the subsequent monitoring parameter for the next block which is aimed at addressing the sampling frequency limitation problem, explained later.

Computation of the phase angle for the three single phases does not suffer the issues of the phase angle drift using the PPS. This is because all the boundary conditions like noise, unbalance, etc remain same for all the three conditions, without any additional uncertainty coming through the joining of the phases, e.g., by using the symmetrical components. The shortcoming of this approach is that we have to compute the phase angles three times compared to only once in the PPS. However, the accurate operation has higher preference, and the computation time issue will be addressed in a later section. Also, the maximum operation ensures that we cover all types for fault, e.g., single to three-phase faults with and without involvement of earth.

B. Sampling Frequency Limitation

One possible solution to avoid the sampling frequency limitation would be to choose a threshold limit for the measured phase shift, the threshold limit being above about the sampling angle. Then, a fault direction is determined only if the phase shift is larger than the threshold, otherwise “neutral” should be the output, signalling that the fault direction could not be determined reliably. Then, to obtain a reliable prognosis for small angles, one would simply need to increase the sampling
rate in order to obtain a sufficiently small angular resolution (sampling angle). However, increasing the sampling rate would increase the cost because some higher-frequency equipment (e.g., sensors with higher sampling rate) and generally more powerful hardware (e.g., analog ADC, etc) and/or software would be required.

An alternative solution [16] is shown in the second part of the algorithm in Fig. 8, without the need of having higher sampling frequency.

At the moment of the fault or shortly thereafter, a ‘start’ (of overcurrent monitoring) command is issued. If the fault persists for some time, i.e., if the current still exceeds the threshold after a few AC cycles (e.g., two AC cycles until the end of or after the trip interval), a ‘trip’ command is issued causing a part of the power distribution system to be disconnected. The typical relay [15] should output the directional information at the time of the trip command, which is normally issued after the trip interval. The current values from the instant of the fault inception to the ‘trip’ command (typically about 2 cycles or more for distribution systems) are the post-fault current, and before the fault inception those are pre-fault values.

As shown in Fig. 8, from the post-fault current values, the decision logic section then determines a plurality of phase difference values, namely the phase difference values $\Delta \varphi(I_{\text{post}}(k), I_{\text{pre}}(k))$ between the $k$-th post-fault current values and the respective $k$-th pre-fault current values. Here, the $k$-th pre-fault current values $I_{\text{pre}}(k)$ are defined as the samples taken at an integer number $m$ of cycles previous to the corresponding $k$-th post-fault current values $I_{\text{post}}(k)$. Here, the parameter $m$ indicates how many cycles should lie between the $k$-th pre-fault and post-fault currents. Typically, $m = n = 2$ is chosen, where $n$ indicates number of cycles from the instant of the fault inception to the ‘trip’ command.

After having obtained the plurality of phase difference values $\Delta \varphi(I_{\text{post}}(k), I_{\text{pre}}(k))$, the decision logic section then accumulates them into an accumulated phase difference parameter $\Delta \varphi$. Then, the decision logic section determines a fault direction parameter by comparing the accumulated phase difference parameter to a threshold value. For example, a reverse fault will be determined if $\Delta \varphi < 0$. In practice, a small threshold number $\varepsilon$ is used as a threshold, and a forward fault will be determined if $\Delta \varphi > \varepsilon$, and a forward fault will be determined if $\Delta \varphi < -\varepsilon$. A neutral fault (indicating unknown fault direction) will be issued if $|\Delta \varphi| \leq \varepsilon$. This way, situations in which $\Delta \varphi$ is close to zero so that its sign cannot be determined reliably, the generation of a potentially unreliable signal is avoided. The determined fault direction (forward, backward or neutral) is then outputted [16]. It is to be noted that in case of ‘neutral’ decision, the proposed directional relay would act as a non-directional one, but still protection is invoked.

Figs. 9 and 10 show the angle difference trends for the forward and the reverse fault cases, for different phase angle changes at fault. These are obtained from different experiments, e.g., for different time-overcurrent values [3] at different fault phase angles for different types of fault, with embedded implementation of the DFT-based algorithm. Please note that positive and negative phase angle change at fault occurs during reverse and forward fault respectively. In Figs. 9 and 10, the Y-axis shows the angle difference value for each sampling instant (with respect to 2-cycles back) starting from the fault inception point. We monitor for 2 cycles at 20 samples/cycle rate (for a 50 Hz system, with a sampling frequency of 1 kHz). That is why, the X-axis shows 40 sample values. Then, we sum all the points, to indicate that the total sum is either positive or negative for forward (Fig. 9) or reverse (Fig. 10) cases respectively. We can also notice that, with this approach, we distinctively detect angle change sensitivity from about $\pm 5^\circ$, above which the curves in Figs. 9 and 10 show distinct trends, while below that there are confusability due to the equal oscillations of the trend curve about the X-axis [16].

Thus, with this approach, we are able to achieve for example an angle change sensitivity of $\pm 5^\circ$ with 1 kHz sampling frequency, which theoretically would only allow $\pm 18^\circ$. In other words, without this post-fault period monitoring approach [16], one would require e.g., a sampling frequency of 3.6 kHz to achieve the $\pm 5^\circ$ angle change sensitivity.
C. Frequency Deviation

Any frequency deviation is critical for the DFT. Because, if for example the actual nominal supply frequency is 50.5 Hz, however it is assumed to be 50 Hz in the DFT calculations, there will be leakage effects [6]. This will affect the accuracy of the phase angle computation. Even though it is not expected that supply frequency (for the grid) does not deviate from 50 or 60 Hz, it is common that due to different reasons the actual system frequency varies a bit. Typically, relays [15] are certified for operations with a tolerance of ±5 Hz. Of course, it is not expected that the system frequency varies every cycle.

Any such frequency deviation can be tackled by keeping the number of samples per period (over which the DFT is computed) constant. The first step is estimating the actual line frequency using frequency tracking methods [18]–[21]. Then one has to adjust the sampling frequency (by changing the ADC interrupt timings) to keep the samples/cycle ratio constant. For example, if the supply frequency is 50 Hz, and the sampling frequency is 1 kHz, the samples/cycle at the nominal frequency is 20 (=1000/50). Now, if the actual system frequency becomes 45 or 55 Hz, one would adjust the sampling frequency to be 900 or 1100 Hz respectively, in order to keep the samples/cycle constant.

D. Harmonics

DFT-based phase angle computation would be particularly helpful in tackling the harmonics problem. Knowing the actual fundamental frequency (as mentioned above), and utilizing the DFT, one can consider only the phase angle of the fundamental frequency. This is essentially harmonic filtering which would allow to discard higher harmonics.

E. Noise

To tackle noise, one would in general need low-noise, good accuracy sensors, electromagnetic interference (EMI) free electronics design, proper filters (typically high-pass) for offset, noise or jitter corrections.

F. Grounding Systems

Typically in power systems, the fault inception is detected by monitoring the neutral current $I_0$ [1],[2]. Under normal condition, which is a balanced three-phase operation, we have $I_0 = -(I_a + I_b + I_c) = 0$, where $I_a$, $I_b$, and $I_c$ indicate the phase currents. Due to fault inception, the power system becomes unbalanced and $I_0 = -(I_a + I_b + I_c) \neq 0$.

The different grounding schemes (see section V.F) influence the neutral current. Thus, if the neutral current, or the sum of the phase currents (and associated statistics like average, etc) are used in any protection parameter estimation, e.g., phase angle for direction, the influence of the different grounding schemes would be needed to be checked.

However, in the proposed algorithm (see Fig. 8), for three-phase operation, the maximum operation (of the three phase angles) is used not summation. Hence, the different grounding schemes would not have any explicit influence on the directional detection sensitivity (e.g., the angle change sensitivity).

G. Coordination with Fault Inception Detection

A typical overcurrent fault case is shown in Fig. 11. In Fig. 11, around the 80-th sample, the fault inception takes place. The fault identification module would employ DMT or IDMT type protection, typically monitoring the overcurrent for certain duration (e.g., one cycle shown in Fig. 11). Depending on the chosen lowset, highset, very highset stages [3], the fault inception module will provide a trigger in case of permanent fault, or issue no trip trigger in case of cleared faults or other temporary transient events.

The current-only directional module would not be used as a fault inception detection mechanism. Instead, the directional module would carry on its own computation, starting from the fault inception independently. Then, a coordination would be required with the fault inception module. This can be achieved checking whether the fault inception module has issued a trip trigger (in case of persistent fault) or not. If a trip trigger has been issued, the directional information module would be shown, otherwise it will be reset. The latter case would prevail for cases like load changes, for which there will be phase angle changes but no trip trigger.

H. Valid Pre-fault Current

In the proposed current-only algorithm, we are interested to consider the phase angles from the real and the imaginary values of the samples, out of the DFT (see Fig. 8). However,
one should consider the validity of the pre-fault values. This is illustrated by a simple example below.

Let us consider two imaginary numbers $a = 0.0005 + j0.0004$, and $b = 50 + j40$. This will give us $|a| = 0.0006403$, $\angle a = 0.6747$ rad, and $|b| = 64.03$, $\angle b = 0.6747$ rad. The key message is that the phase angle values of the two complex numbers are same, while the magnitudes are very different. In reality, the number $a$ might be synonymous to noise, while $b$ as valid measurement.

Therefore, before computing the phase angle, it is necessary to check whether the phase angle being computed is of noise samples (e.g., while the breaker is open so there is no current flow but the relay is still on), or of valid measured values. This can be done by considering the magnitude of the complex values. From our experiments, we consider typically about 10% of nominal values as a definition of valid pre-fault current.

I. Pre-fault Direction Change

To prevent the reversal of directional definition due to pre-fault current direction change (see section VI.I), on one hand the algorithm needs to see valid pre-fault current (like the abovementioned 10% of nominal values) for certain duration. From the discussions in section VI.B, we see that typically the algorithm needs to see about 2 cycles of pre-fault current.

If there is still direction change in the pre-fault current, it would need to be addressed at a logic level, which has been demonstrated via examples in [8]. Basically, then one would need to see the contradictory decisions amongst the contiguous relays in a collective way.

J. Computation Time

In order to overcome the PPS difficulty, three single phase angle computations are needed, resulting in three times more computation of the phase angle. For example, in typical protection relays [1],[15], the sampling frequency is about 2–3 kHz, resulting in about 500–333 $\mu$s between arrival of two samples. Usually, all the protection function computations have to be performed before the next sample arrives.

For the proposed current-only directional estimation, our experiments show that the major time consuming functions are the DFT operation and the phase angle computation. The recursive DFT computation [6] ensures optimized computation. For the phase angle computation, different schemes are comparatively evaluated, as reported in [22]. Out of the evaluation, look-up table based approach for arctangent function (for phase angle computation) is suggested as the fastest [22].

VII. DISCUSSIONS

The following comments are cited on the proposed algorithm, challenges and solutions.

1) The proposed current-only approach, along with the solutions for the different challenges, is intended for the non-directional relays which typically have no voltage sensors. Thus, any specific relay implementation is not mentioned. Based on the detection methods incorporating the various solutions of the different challenges, prototype development using ABB relays [15] are underway.

2) The current-only directional information is relative. The direction information estimated during fault, is judged with respect to the pre-fault current according to the basic theory. Hence, it will not be able to judge the change of power flow in a system in a normal situation, i.e., if the direction of the pre-fault current is changed. Under such circumstances, collective information of the relays would be required, as discussed in [8].

3) However, the current-only approach should not be perceived as a competitive alternative solution to the traditional voltage-based directional relays. Instead, one should consider that due to cost reasons, it is almost impossible to employ the voltage polarization-based traditional directional relays in the distribution side. Therefore, without the current-only approach there is no directional detection possibility for real-life utilization.

4) For the traditional directional relays, the voltage input is required for voltage polarization. Besides, the voltage is used for multitude of reasons, e.g., for estimating the power, power flow, power factor, voltage unbalance, power swing, frequency control, etc.

5) The current-only algorithm could also be implemented in the traditional directional relays, as an alternative and redundant method. And it would facilitate the ‘close-in’ faults [8].

6) From the discussion in section VI.B, we see that based on the detection sensitivity (even after best possible values), there might be some cases (at low values) where the relay would not achieve the sensitivity. Thus, it is very important to provide the ‘neutral’ output, ensuring protection even though it would be non-directional type.

7) The question of whether earth fault can be detected resorts to the angle change sensitivity. In the proposed solution, we achieved $\pm 5^\circ$ with 1 kHz sampling frequency. The angle change sensitivity is related to the ‘reach’ of the distance protection [1],[4].

8) The embedded implementation of the DFT-based current-only directional algorithm has been tested with different experiments, e.g., for different time-overcurrent values [3] at different fault phase angles for different types of fault. Each test configuration was repeated multiple times to check the robustness. With a typical 1 kHz sampling frequency for 50 Hz system, we achieved 100% correct classification accuracy above $\pm 5^\circ$, the angle change detection limit. For power systems protection algorithms, it is very important to achieve a 100% accuracy, in order not to compromise safe operation. The 100% accuracy might not be achievable over the full operational range, therefore, it is important to correctly mark the limit above which it can be attained, e.g., in our example implementation we had the limit of $\pm 5^\circ$.

9) The directional detection module is independent of the fault inception detection module. Both would need to crosstalk to effectively provide directional decision in case of persistent fault, as discussed in section V.I.G. The directional module is not used for fault inception
detection.

10) With the post-fault monitoring scheme, one would typically need 2 cycles (e.g., 40 ms for 50 Hz system) of post-fault current to provide the directional decision robustly. Therefore, e.g., for ‘very highest’ class [3] of protection, which is required for high magnitudes of overcurrent for short duration, the proposed algorithm would provide ‘neutral’ output, not seeing the required 2 cycles of pre-fault current. This is a trade-off condition for reliable detection in other cases. For distribution side application, it is generally ok.

11) Cost is an important factor for the distribution side operation. Therefore, things like naïve solution to the sampling frequency limitation problem by having hardware with higher sampling frequency, inherently faster computation platform might not be easy to implement. That is why the alternative cost-effective solutions are presented.

12) Utilization of the current-only directional relays for possible distribution side protection, like optimized fault localization using centralized breaking scheme, solutions to close-in faults can be referred to in [8].

VIII. CONCLUSION

We have presented in this paper a novel current-only directional relay concept, without utilizing the reference voltage as is done in the traditional directional relays. The current-only principle utilizes pre-fault current as the polarizing quantity. Under normal circumstances, the phase angle of the current from cycle to cycle would not differ much. Under fault conditions, there will be significant changes in the phase angle. The fault direction may be forward (between relay and grid), or reverse (between relay and source), influencing the phase angle polarity. Analysis of signals acquired during faults substantiate the feasibility of the proposed technique.

Different challenges to the current-only approach, e.g., for three-phase operation, limitation in angle change sensitivity, issues like frequency deviation, noise, presence of harmonics, etc are described. Cost-effective potential solutions to the challenges are discussed in details for robust implementation. The current-only directional relay can be used for intelligent directional protection, localization of fault section in the distribution systems [8].

REFERENCES