

A New DC Fault Detector Scheme for Multi-terminal HVDC Transmission lines

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A In this paper, a novel selective DC fault detector approach based on the adaptive cumulative sum method (ACUSUM) is
B suggested for the protection of high voltage direct current (HVDC) transmission lines. Using a communication channel, the
S proposed method detects DC fault occurrence and determines faulty lines at a multi-terminal HVDC (MT-HVDC)
T transmission system in less than 2ms. The suggested approach works in the time domain and employs the ACUSUM method
R as a mathematical tool to detect abrupt variations in the magnitude of line currents for fault detection. Simulation results
A confirm the selectivity of the proposed algorithm at different DC fault situations, which enhances the reliability of the power
C system. Besides the low sampling rate, the ACUSUM calculation burden is very low and its implementation needs no special
T or complicated hardware. Adaptivity, independence from system parameters, robustness against fault resistance, fault
distance and noise are significant advantages of the proposed algorithm in comparison with other methods in addition to its
appropriate speed.

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I. INTRODUCTION

Nowadays, because of their undeniable benefits, HVDC systems play a vital role in enhancing power system capability and reliability [1]. It is more difficult to protect an HVDC system than an HVAC one [2]. When a fault occurs in a DC line, just correct DC breakers must be opened to isolate the faulty line. In this situation, opening any AC breaker or healthy DC line breakers will distort the selectivity of the protection scheme and notably decrease the reliability of the power system.

Various approaches have been proposed based-on different ideas for fault detection in multi-terminal HVDC transmission

systems. The first category employs the variation pattern of line currents and bus voltages for fault detection. The method introduced by [3] uses the superimposed theory and detects DC faults by monitoring the variation pattern of fault current at line terminals. An approach based on the magnitude and direction of line currents connected to the same bus has been suggested in [4] but it suffers from high sampling frequency (100 kHz). In [5], utilizing the ratio of the transient voltage indices and a fault-blocking converter (FBC), Relays have been coordinated to realize internal fault detection and faulty line location for hybrid MT-HVDC networks.

The approach suggested in [6] uses the voltage gradient and voltage derivative for fault detection and discrimination of AC from DC faults, respectively. Another method employs the monitoring of the calculated rate of change in the current-to-voltage ratio for fault detection. Consequently, the suggested method identifies the faulted section by checking the

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summation and direction of all branch currents at each busbar, individually [7].

Because of its capability in pattern recognition and classification, a fault detector based-on the artificial neural network (ANN) is proposed in [8], which uses the voltage waveform measured at the rectifier substation. Regarding the fact that there is no unique routine method for designing ANN layers, different structures may differ in performance.

The traveling wave theory is considered a strong tool in the field of fault detection. Detecting voltage waves at the terminal and comparing them with an appropriate threshold has been used in [9] for fault detection. In [10] a protection scheme based on the energy ratio between backward and forward traveling waves has been proposed which requires a logic signal from the remote end. A single-end protection method using the morphological gradient of DC voltage with predefined thresholds has been proposed in [11] to protect DC cables and overhead lines in voltage source converter-based MTDC grids. This method is based on the effect of series inductors attenuating high-frequency voltage traveling waves transmitted from the fault point to the grid line ends. A centralized protective scheme has been proposed in [12] in which the principles of busbar differential protection and traveling waves are employed. A non-unit line protection scheme is presented in [13], which is based on the initial line-mode voltage traveling waves (ILVTWs). Based on the analysis of the traveling wave (TW) propagation characteristics, the transfer functions of ILVTWs under typical internal and external faults have been derived. By comparing the differences of the transfer functions in the frequency domain, the corresponding protection principles have been developed.

Recently, protective algorithms based on harmonic analysis have been employed for fault diagnosis. Investigations show that monitoring the magnitude of the 12th harmonic of fault current can be useful for separating external faults from internal ones [14]. Another approach has used a specific frequency alternating current (SFAC) during fault transient [15]. Faulty zone selection based on harmonic content has been proposed in [16] too.

Presently, TW-based protection and voltage derivative protection are usually used as the main protection for HVDC transmission lines, while backup line protections are composed of DC under voltage and current differential protection [17]. Albeit their fast response (typically less than 1 ms), TW-based protections always suffer from not being supported by the capacitive voltage transformer (CVT) frequency responses, being affected by noise and fault resistance, and needing high sampling frequency devices while complexity and expensive implementation are major problems with TW-based fault detectors, too. On the other hand, voltage derivative protection is sensitive to fault transition impedance and noise. Under voltage protection is lowly reliable (i.e., separating internal

from external faults) and current differential protection operates with time delay up to hundreds of milliseconds [17].

Regarding these problems of the aforementioned protection principles, this paper proposes a new highly reliable DC fault detection algorithm based on the ACUSUM method for the protection of MT-HVDC transmission lines. This algorithm increases the detection time to less than 2 ms, which makes it appropriate for backup protection, not main protection. The suggested approach works in the time domain based on the variation patterns of the magnitude of line currents during DC faults. As a mathematical tool, the ACUSUM algorithm provides meaningful indices, which can detect DC faults and determine the faulty line. Appropriate speed (as backup protection), independence from system parameters, adaptivity, low sampling frequency, low computational burden, simplicity, no need for any complicated hardware, robustness against fault resistance, fault distance, and noise are the significant benefits of this method in comparison with others.

The rest of the paper is organized as follows. The proposed method is described in Section 2. Simulations and results are presented in Section 3. Finally, Section 4 concludes the paper.

II. PROPOSED ALGORITHM DESCRIPTION

The CUSUM test has been employed widely as a technique for detecting abrupt changes in various fields [18]. Considering the helpful variations in current signal amplitude during a fault, a fault detector based on the adaptive CUSUM (ACUSUM) algorithm for AC power transmission systems has been proposed in [19]. To detect and distinguish faults in an MT-HVDC transmission system, a new version of ACUSUM is proposed and used as the basis of the fault detector unit, which is explained below.

A. Main Idea

Fault inception in an HVDC transmission system, either in DC or AC zone, causes deviation of voltage and current signals from their original shapes. A detailed assessment of these variation patterns can be a valuable tool for fault diagnosis. Figure 1 shows a mono-polar meshed 150 kV four terminals VSC-HVDC network, where the points of measurement are on DC lines. The technical details of this simulated network have been explained in section 3, completely. Also, a DC and an AC fault have been shown on this system as F1 and F2 respectively.

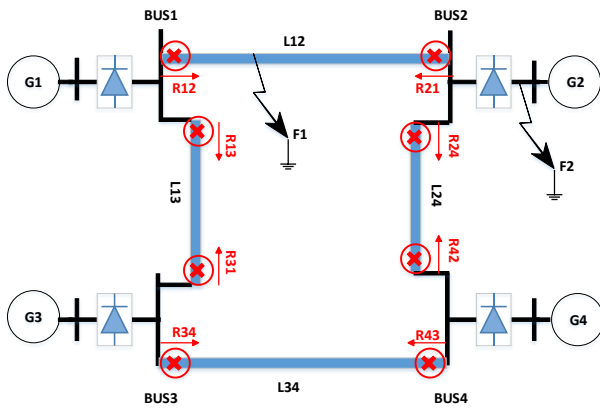


Fig.1. Simulated four-terminal meshed VSC-HVDC transmission system

- i) Figures 2 and 3 depict measurements by R12 and R21, respectively against fault occurrence on F1 (at the middle of the line at $t=0.5$ s). It can be seen that the incoming line currents at both ends of the faulted DC line experience an increment just after fault inception; while the bus voltages at both ends show decrements. Figure 4 shows the measurements by R31 for the same fault. It is observable from this figure that the control system of converters can retain line current and bus voltage without significant change. Regardless of voltage decrement at faulted line terminals, it is evident that relays installed at both ends of a faulted DC line experience incremental variations in measured current, simultaneously. This fact provides the basis for a selective protection scheme on the DC side, where an increase in the measured line current at both ends can be an indication of a fault on the DC line where these are observed.
- ii) For the fault at F2, Figures 5 to 8 illustrate measurements by R21, R12, R24, and R42, respectively. It can be seen that the bus voltage, with the fault on the AC side (V2), experiences a decrement after fault inception; while outgoing DC line currents from that bus (I21 and I24) show decrements. In this case, measurements by R12 and R42 at the remote ends of the DC lines connected to the bus (with the fault on behind) show an increment in the current signal with the remaining voltage in a controllable manner. These graphs confirm that regardless of voltage variations, based on the predefined positive direction for relays accruing an AC fault cannot lead to simultaneous incremental variation in the current signal of two adjacent buses connected with a line. This fact can make AC faults filterable from DC ones by the proposed method.

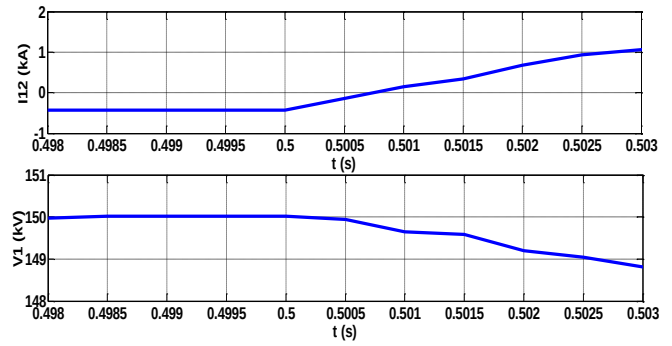


Fig.2. Current of L12 (top) and the voltage of bus 1 (bottom) against the fault at F1 seen by R12 (fault inception: $t=0.5$ s).

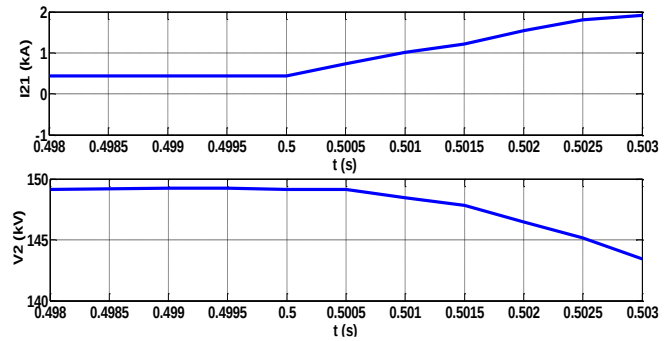


Fig.3. Current of L12 (top) and the voltage of bus 2 (bottom) against the fault at F1 seen by R21 (fault inception: $t=0.5$ s).

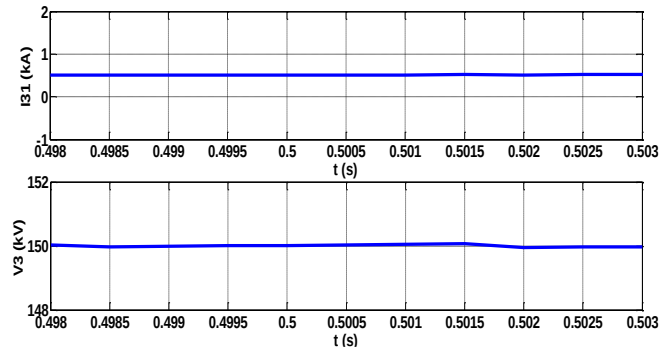


Fig.4. Current of L13 (top) and the voltage of bus 3 (bottom) against the fault at F1 seen by R31 (fault inception: $t=0.5$ s).

B. Fault Detection Procedure

The proposed protective scheme has four steps:

Step 1: Data Acquisition

In this step, the corresponding line current at each end of DC lines is sampled with an appropriate sampling frequency (2 kHz). Generally, two main concerns should be considered in selecting a sampling rate:

- Usually, fault detectors with a high sampling rate suffer from not being supported by CVT frequency responses and the need for high sampling frequency devices. Therefore, detector algorithms with low sampling rate are more practicable than other rivals with a high sampling frequency.
- Decreasing the sampling rate of the ACUSUM algorithm increases detection time, which is undesired. On the other hand, increasing the sampling rate can distort the security of the ACUSUM algorithm against the noise, which has been discussed in the next sections.

To sum up the above two factors, 2 kHz is employed as a sampling rate for ACUSUM to carry out the integration.

Step 2: Detection of Current Increment

In this step, the increment in current magnitude, as shown in Fig. 2, is detected by ACUSUM as:

$$P1_{(k)} = \max[(P1_{(k-1)} + i_{(k)} - \beta_1 I_{dyn,k}), 0] \quad (1)$$

where $i_{(k)}$ represents the k^{th} sample of the corresponding current signal, $P1_{(k)}$ represents output indices for k^{th} instants, and $\beta_1 I_{dyn,k}$ is an adaptive current setting of the relay at the k^{th} instant where $I_{dyn,k}$ is the average of the corresponding line current from the previous moments. β_1 is a setting parameter that can take any value. The values less than 1 will provide better dependability and larger than 1 will enhance the security of the proposed approach [19]. In fact, $\beta_1 I_{dyn,k}$ provides a low pass filtering effect. Regarding the max operation in (1), $P1_{(k)}$ is always zero or has a positive value. In other words, while the system is working in normal conditions, no current sample is larger than the adaptive setting of the relay ($\beta_1 I_{dyn,k}$) and the output index ($P1_{(k)}$) remains at zero. When a current increment happens, current samples become bigger than $\beta_1 I_{dyn,k}$ and $P1_{(k)}$ starts growing up. DC Trigger Signal will be switched if the following criterion is fulfilled at, for example, three consecutive samples:

$$DC\ Trigger\ Signal = DCTS = \begin{cases} 1, & \text{if } P1_{(k)} > h_1 \\ 0, & \text{else} \end{cases} \quad (2)$$

where h_1 is an arbitrary constant and should be ideally zero. In fact, h_1 determines the permitted increment in the output index of the algorithm when the magnitude of the current signal passes the adaptive setting of the relay.

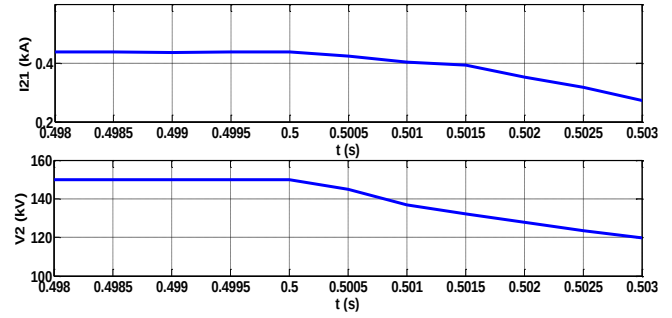


Fig.5. Current of L12 (top) and the voltage of bus 2 (bottom) against the fault at F2 seen by R21 (fault inception: $t=0.5$ s).

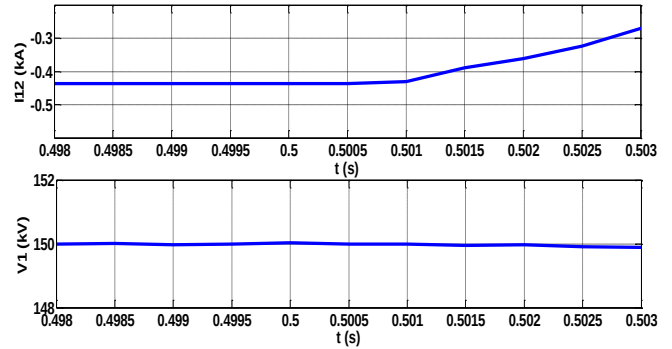


Fig.6. Current of L12 (top) and the voltage of bus 1 (bottom) against the fault at F2 seen by R12 (fault inception: $t=0.5$ s).

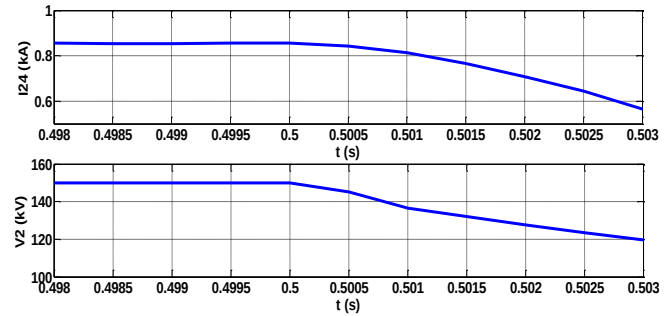


Fig.7. Current of L24 (top) and the voltage of bus 2 (bottom) against the fault at F2 seen by R24 (fault inception: $t=0.5$ s).

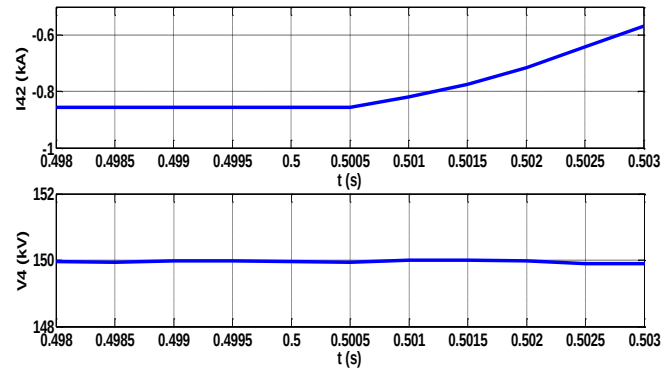


Fig.8. Current of L24 (top) and the voltage of bus 4 (bottom) against the fault at F2 seen by R42 (fault inception: $t=0.5$ s).

Step 3: State Announcement

DCTS (introduced in step 2) as a primary flag is attached to each installed relay at each terminal that addresses the primitive diagnosis of the relay whose high value proposes the corresponding DC line as a primitive candidate for the faulty line. Regarding what was described in section II-A, since the DC fault detection procedure needs the *DCTS* flag of both line terminals, a communication link should be employed. In other words, by using a communication channel, the adjacent relays share their *DCTS* flag values.

Step 4: Decision Making

Finally, the faulted DC line is detected as a connective line between two adjacent relays whose *DCTS* flags have become high, simultaneously. Regarding the proposed logic, *DCTS* changeover neither in one relay nor in two relays with no communication line in between leads to protective operation. After each fault detection, $P1_{(k)}$ is reset.

$$P1_{(k)} = 0, k = k_0 \quad (3)$$

Figure 9 shows the flowchart of the proposed algorithm.

C. Discussion

1) Determination of $I_{dyn,k}$

For the calculation of $I_{dyn,k}$, an appropriate data window should be employed. The length of the moving data window is a choice that may be affected by various parameters considering the fault detector's structure and features. Regardless of special issues, two facts are considered when determining data window length (DWL):

- DWL should be short enough to prevent the increase in the computational burden of the algorithm in each time step. This fact becomes essential for those detector algorithms with complicated structure and calculation. Luckily, because of the simplicity of computation and structure, ACUSAM is not affected by this fact.
- Considering the disturbance of extra short time constant phenomena like lightning, DWL should not be less than 3 ms to make these phenomena separable from faults [7].

To sum up the above two factors, a 5 ms moving window (containing 10 samples with 2 kHz sampling frequency) is employed to carry out the integration. In each step, I_k is the average of the current samples of the moving data window ended to k^{th} sample.

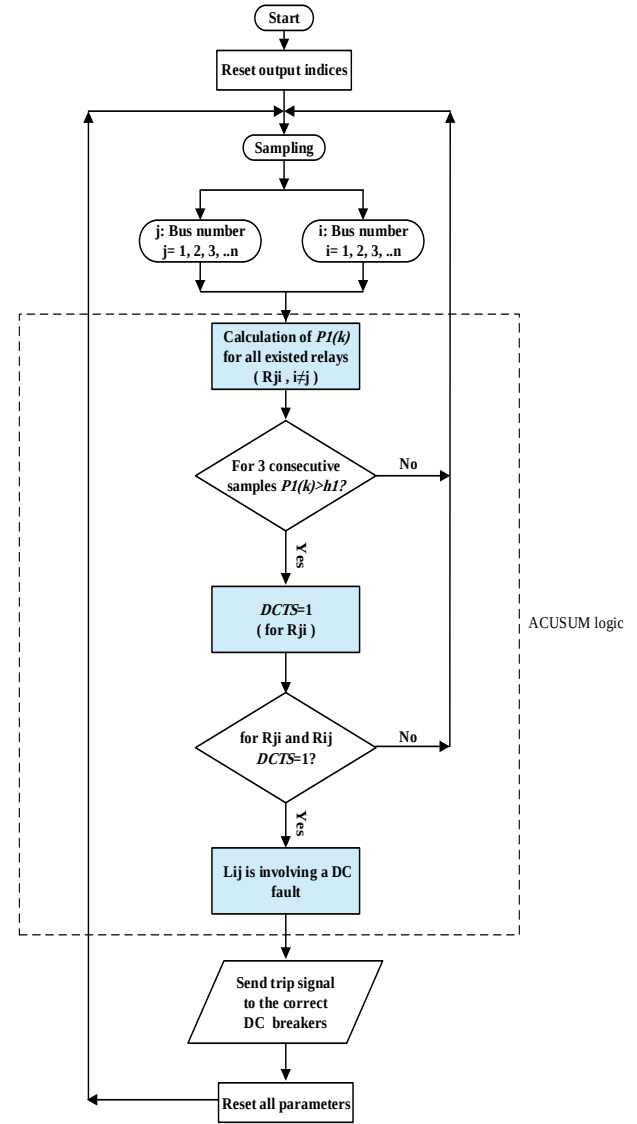


Fig.9. Flowchart of the proposed algorithm

$$I_k = \frac{1}{10} \sum_{j=k-9}^{j=k} i_{(j)} \quad (4)$$

While the system is working in a normal situation, extracted I_k has acceptable accuracy and can directly be used as $I_{dyn,k}$. But, by any sudden variation in the current signal caused by a fault or load switching, because the samples of the moving data window are not homogeneous, I_k does not correspond with the real line current. Luckily, since ACUSUM is capable of separating DC faults from load switching (which has been assessed completely in Subsection 3-B-1), there is no concern about this imprecise estimation, and $I_{dyn,k}$ in (1) can be simply substituted by I_k with an adjustable delay as follows [19]:

$$I_{dyn,k} = I_{(k-\gamma)} \quad (5)$$

where γ is a constant that has no effect on the magnitude and just shifts it by γ steps [19]. Regarding the fact that fault criteria should be satisfied for 3 consecutive samples, $\gamma=3$ is a good choice.

2) Determination of Setting Parameter (β_1)

To explain β_1 employed in *DCTS* calculation for DC fault detection, it should be noted that choosing values greater than 1 for this parameter makes currents with larger magnitudes than existing load current and less than $\beta_1 I_{dyn,k}$ not being detected by ACUSUM. This may be suitable for a forecasted increase in the load where it is desired that the fault detection unit (FDU) remains inactive upon that. But this choice makes high resistance faults (HRFs) with a similar condition on magnitude undetectable by ACUSUM as has been expatiated in [19].

The most important issue in a robust fault detection algorithm is high dependability, which must be 100% with acceptable security [19]. Therefore, no significant current variations should be ignored by FDU. Owing to what was mentioned above, in a DC fault situation, perfect dependability means that for any meaningful increment in the current level, *DCTS* must be issued. This is achievable by selecting $\beta_1 = 1$. It is clear that if this current increment is not related to a DC fault, the *DCTS* flag of the remote end will block FDU and support the security of the protective algorithm.

3) Determination of Threshold (h_1)

This parameter is arbitrary constant and should be ideally zero. Because of the inherent features of the real application such as noise, the security of the protection system necessitates replacing zero value with an appropriate threshold to prevent mall-operation of relays in normal conditions. Since remote terminal data transmission and setting parameter (β_1) are respectively assigned to mainly support the security and dependability requirements of FDU, the threshold should be defined to filter just small variations in input signals such as noise. In this study, h_1 is set at 0.05. It can be changed by the operator corresponding to the real field operation condition.

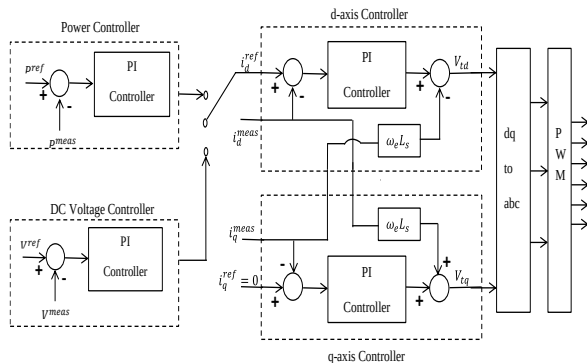


Fig.10. VSC control diagram

TABLE I
SIMULATED SYSTEM PARAMETERS

DC line parameters	L12	L13	L24	L34
Distance (km)	200	150	100	100
Resistance (Ω/km)	1.27×10^{-2}			
Inductance (H/km)	9.3×10^{-4}			
Capacitance (F/km)	12.74×10^{-9}			
VSC parameters	VSC1	VSC2	VSC3	VSC4
Terminal power situation	Receive	Send	Send	Receive
AC voltage (kV)	83	83	70	83
Converter type	Two-level converter			
AC frequency (Hz)	50			
DC voltage (kV)	150			
Series AC resistance (Ω)	0.92			
Series AC inductance (mH)	1			
DC link capacitor (mF)	0.4			

III. SIMULATION RESULTS

To evaluate the proposed algorithm, a 150 kV four-terminal meshed VSC-HVDC transmission system, which is an expanded example of the test network in [20] (shown in Fig. 1), was simulated in the Simulink environment of the MATLAB program whose details are summarized in Table 1. The mono-polar test network consists of four remote AC sources, four converter stations, and four transmission lines where both ends are equipped with two directional relays. Figure 10 shows the block diagram of VSC control. Terminals 2 and 3 are under constant active power control and terminals 1 and 4 are in the DC voltage regulator. V_q is considered $V_q = 0$. Additional details about the control system are available in [20]. Because of its more transient resolution than others, a distributed parameter model has been used for transmission lines [21]. Two convertor stations have been grounded solidly [22]. The sampling rate is 2 kHz. Data processing has been done in the MATLAB program. The incoming direction is considered the positive direction for lines current. Different DC faults at different locations with various fault resistances have been simulated and reported in the next section for the evaluation of the suggested algorithm.

A. Dependability Assessment

1) First Simulated Case

Consider a solid pole to ground (PG) fault at the middle of L12 as shown in Fig. 1 (point F1) at $t = 500\text{ms}$. Figs. 11 and 12 depict the line currents at buses 1 and 2, respectively. Output indices of the corresponding relays have been illustrated, too. According to Fig. 11, *DCTS* is issued by R12 at $t = 501.5\text{ms}$. Figure 12 confirms the same scenario for R21. R13 and R24 remain inactive correctly. It means that the proposed algorithm detects L12 as faulted line and the trip signal is sent to the related DC breakers to isolate L12 just 1.5ms after fault inception. As expected and shown in Figs. 13 and 14, the control system of VSCs retains other currents in an acceptable

controlled manner and no protective reactions are permitted for the installed relays at buses 3 and 4.

The effect of fault resistance on the performance of the suggested algorithm was inspected. The results are described in TABLE II. In these cases, the fault resistance for F1 has been varied from 0Ω to 100Ω . The results reveal that for all fault resistance values, the extracted indices are completely sufficient and meaningful to make a correct protective decision, so the algorithm can detect the faulted line in just 1.5ms after fault inception.

The performance of the algorithm in various fault locations has also been investigated. TABLE III presents the results of these simulations, supporting the robustness of the proposed algorithm against fault location. According to the detection time of the relays installed on both terminals of the faulted line, for all tested distances (from bus 1), the algorithm detects the faulty line in less than 2ms after fault initiation.

TABLE II

THE OUTPUT INDICES OF R12 AND R21 AND THE DETECTION TIME FOR DIFFERENT FAULT RESISTANCE OF F1

Fault resistance		R=0 Ω	R=10 Ω	R=50 Ω	R=100 Ω
R12	$P1_{(k)}$	2.05	1.89	1.4	0.99
Detection time		1.5 ms			
R21	$P1_{(k)}$	2.55	2.39	1.9	1.5
Detection time		1.5 ms			

TABLE III

THE OUTPUT INDICES OF R12 AND R21 AND THE DETECTION TIME FOR DIFFERENT FAULT DISTANCES (FROM BUS 1) OF F1

Fault distance		10%L	50%L	90%L
R12	$P1_{(k)}$	7.77	2.05	0.79
Detection time		1.5 ms	2 ms	2 ms
R21	$P1_{(k)}$	1.16	2.55	8.213
Detection time		2 ms	1.5 ms	1.5 ms

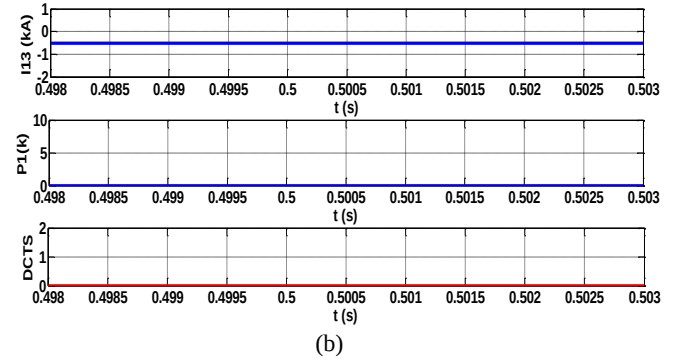
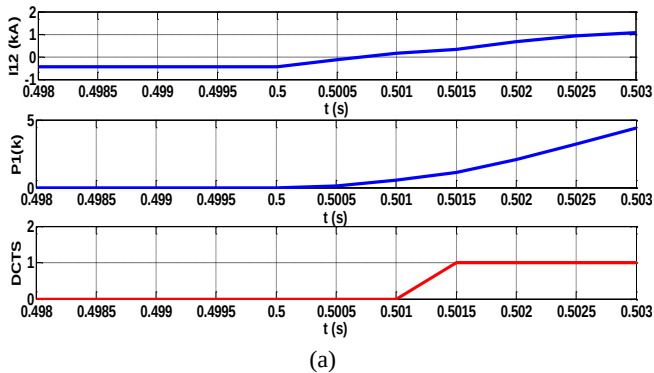


Fig.11. Current signals and detection indices at bus 1 against the fault at F1, (a) I12, (b) I13 (fault initiation: $t = 0.5$ s).

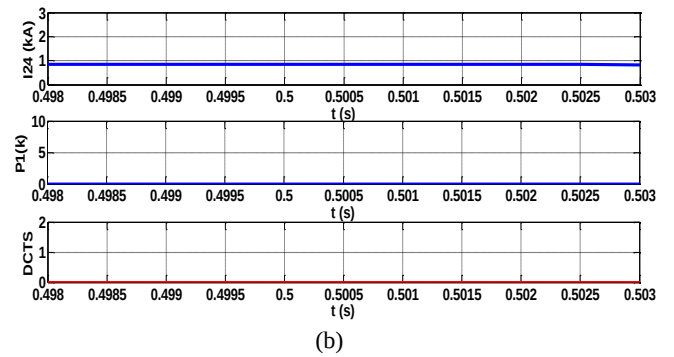
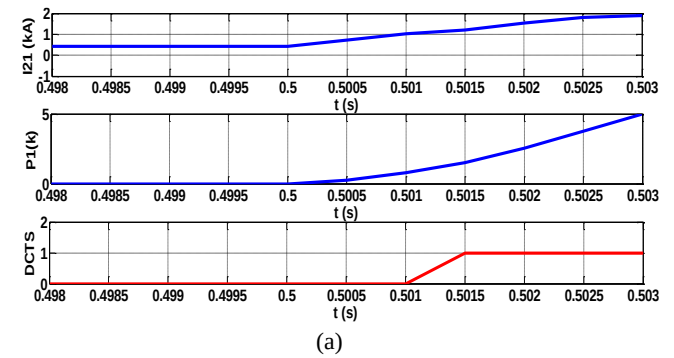


Fig.12. Current signals and detection indices at bus 2 against the fault at F1, (a) I21, (b) I24 (fault initiation: $t = 0.5$ s).

2) Second Simulated Case

An accurate selectivity assessment of the proposed method demands a close-up reverse fault simulation. For this study, F1 is placed at 2.5% of the length of L12 (5 km far from R12). In addition to R12 and R21, which must isolate the line, the correct operation of R13 and R31 are of importance and should be inspected. Evidently, this fault location replacement has no special effect on the measurements by R24, R42, R34, and R43, which have been depicted in Figures 11 to 14. On the other hand, regarding the former simulated case and Table 3, the DCTS flag surely becomes high for R12 and R21, so the related

figures are not shown again. The measurements by R13 and R31 are illustrated in Figures 15 and 16, respectively. Two valuable concepts are achievable from these graphs:

- First, there is no concern about R13 mall-operation in reverse close-up faults. Regarding Figure 16, *DCTS* becomes high for R31 at $t=503\text{ms}$, while R13 remains inactive in Figure 15. According to the predefined logic of the algorithm, these couple of flags are completely meaningless and do not start the protection of L13 correctly.
- Secondly, there is no concern about the overreaching of R31 for occurring a close-up/ low-impedance fault at an adjacent line, too. This robustness confirms the selectivity power of ACUSUM.

A question may be introduced as a relay could be designed to detect any increment in the current signal without needing the extra computational burden of ACUSAM. It should be noted that I_{setting} in a simple overcurrent relay is a static parameter that should be changed for different load conditions by the operator whereas I_{dyn} continuously adjusts itself by load conditions. The mall-operation of a simple overcurrent relay becomes worse when a decrease in the line current occurs followed by an HRF whose magnitude falls below I_{setting} . But, in ACUSUM, as I_{dyn} adjusts itself with the load decrease, it can detect HRF in this case as well as other types of faults [19]. Moreover, due to cumulative sum, ACUSUM provides bigger indices with more consistency than the simple over current approach, which is considered an important property in the detection of high-resistance or long-distance faults. Finally, it should not be ignored that all the aforementioned benefits are reachable without any notable extra computational burden regarding the present-day digital technology.

The results of the simulation for over 100 various cases have proven that the proposed algorithm can detect any DC fault in less than 2ms. Table 4 compares the vital features of the proposed method with those published in recent years.

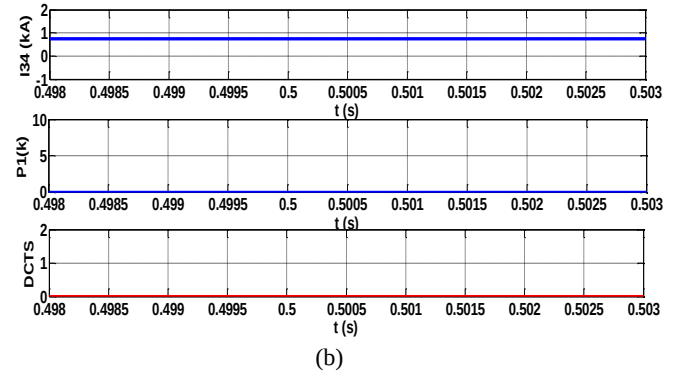
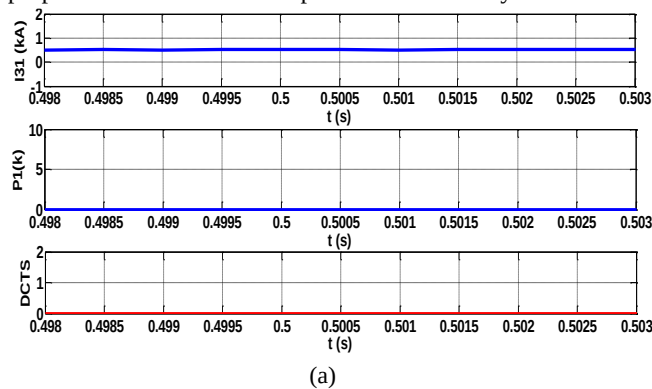


Fig.13. Current signals and detection indices at bus 3 against the fault at F1, (a) I31, (b) I34 (fault initiation: $t=0.5\text{ s}$).

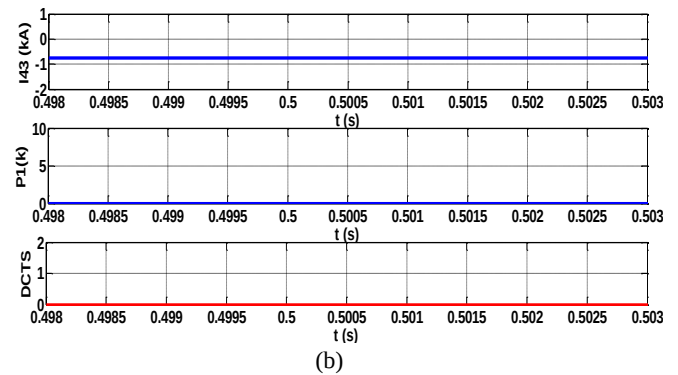
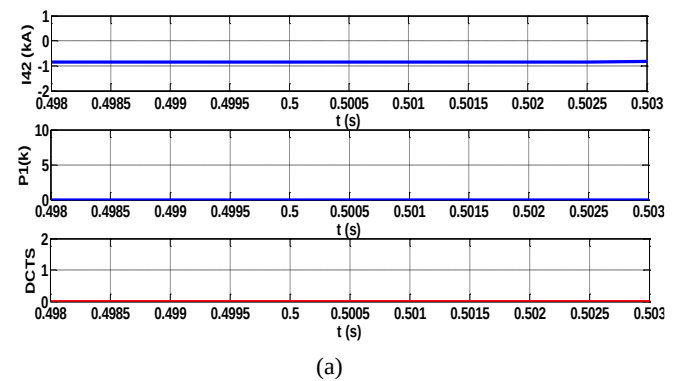


Fig.14. Current signals and detection indices at bus 4 against the fault at F1, (a) I42, (b) I43 (fault initiation: $t=0.5\text{ s}$).

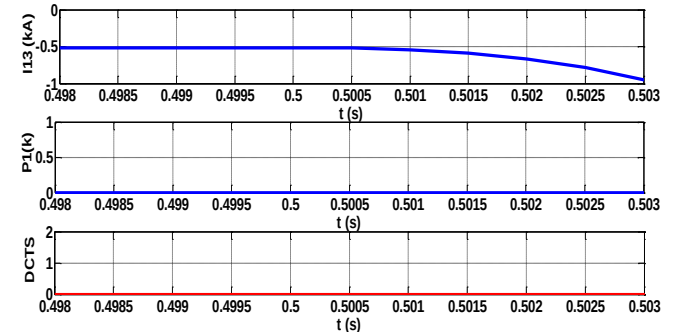


Fig.15. Signal and detection indices seen by R13 against the fault at F1 at the beginning of L12 (fault initiation: $t=0.5\text{ s}$).

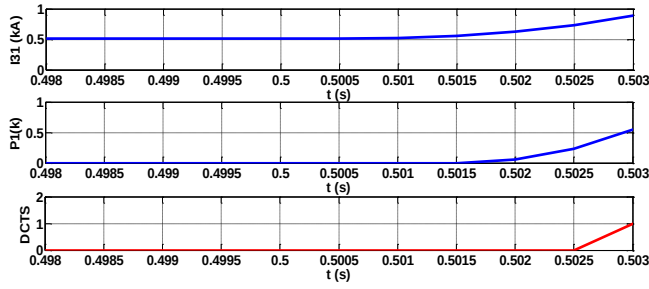


Fig.16. Signal and detection indices seen by R31 against the fault at F1 at the beginning of L12 (fault initiation: $t= 0.5$ s).

B. Security Assessment

1) Load changing

Since load changing at bus results in variations in the current magnitude of lines, a security assessment should be done to confirm that the proposed algorithm can filter load changing and separate it from DC fault occurrence. For more exact inspection, a load switching in bus 2 at $t=0.5$ s has been simulated. Figures 17 and 18 show the measurements at both ends of L12 and L24, respectively. The predefined positive direction for relays guarantees that the relays installed at both sides of a line cannot experience increment in measured current signal during a load switching. This fact is perceptible from Figures 17 and 18. According to Figure 17, although the current increment triggers *DCTS* for R12, R21 with remaining at $DCTS=0$ blocks any protection on L12 and does not permit the relay to react against this load switching. Figure 18 confirms the same scenario for the relays installed at both ends of L24. The results of the simulation illustrate the robustness of the proposed algorithm in the separation of DC faults from load changing.

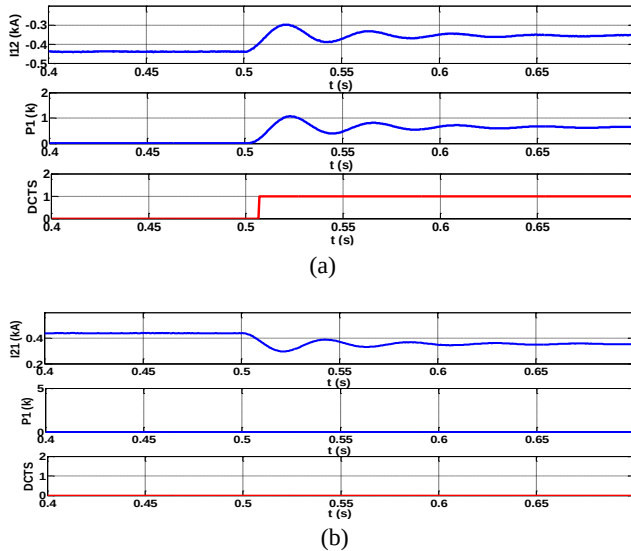


Fig. 17. Signals and detection indices at both sides of L12 against the load switching at bus2, (a) I12, (b) I21 (switching instant: $t=0.5$ s).

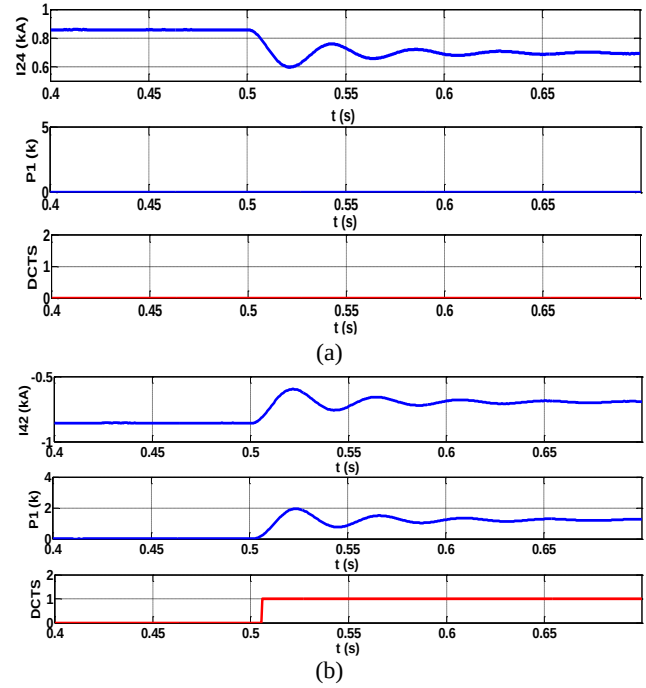


Fig. 18. Signals and detection indices at both sides of L24 against the load switching at bus2, (a) I24, (b) I42 (switching instant: $t=0.5$ s).

TABLE IV
THE COMPARISON OF VITAL FEATURES OF DIFFERENT APPROACHES

Reference	[4]	[23]	[17]	[24]	[25]	[26]	This paper
Sampling rate (kHz)	100	10	10	20	100	2	2
Detection time (ms)	Var	NI/R	≤ 6	≤ 1	≤ 2	≤ 10	≤ 2
Computation burden	L	H	VH	VH	H	VH	VL
Communication based	Yes	Yes	No	No	No	No	Yes
Maximum tested fault resistance (Ω)	350	300	200	0.01	50	300	100

Var: Variable with line length and communication speed.
NI/R: Not investigated or reported. L: Low H: High
VH: Very high. VL: Very low

2) Noise

This section investigates the performance of the ACUSUM algorithm in presence of noise. For this study, the fault simulated in Section 3.1.1 (F1 in the middle of L12 initiated at $t= 0.5$ s) is reconsidered while all of the measured signals are polluted with Gaussian noises with SNR=20 dB. Figures 19 to 22 illustrate the results of this part where the effect of noise is observable on the measured signals. In comparison with

Figures 11 to 14, the assessment results reveal that albeit signals have been polluted, the performance of the algorithm remains hale and the algorithm detects L12 as a faulty line in just 1.5 ms after fault initiation while other healthy parts of the system continue power transmission. These results confirm the robustness of the ACUSUM algorithm against noise. Four main points should be mentioned in this part:

- As is observable in Figures 19 to 22, low-magnitude disturbances caused by the noise have been filtered by the setting of an appropriate threshold as described in Subsection 2.3.C. In fact, h_1 does not permit $P1_{(k)}$ with values smaller than 0.05 to changeover the *DCTS* flag. Enlarging this threshold can lead to an increase in the security of the ACUSUM and its detection time.
- Applying a consistency check (checking for three consecutive samples) improves the performance of the algorithm against noise and does not permit the low-magnitude disturbances caused by the noise to start any protection. Increasing the number of consecutive samples for the consistency check enhances the security of the ACUSUM and its detection time.

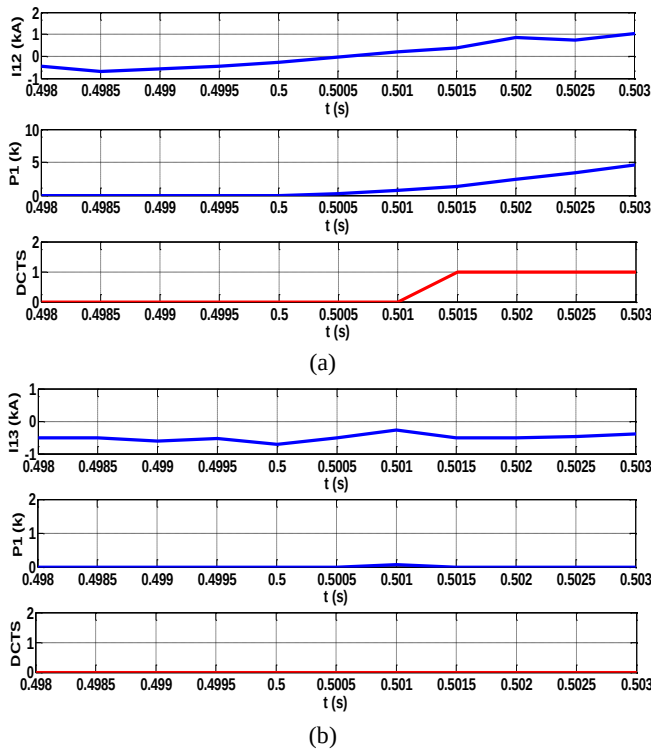


Fig. 19. Signals and detection indices at bus 1 against the fault at F1 in presence of Gaussian noise with SNR=20, (a) I_{12} , (b) I_{13} (fault initiation: $t = 0.5$ s).

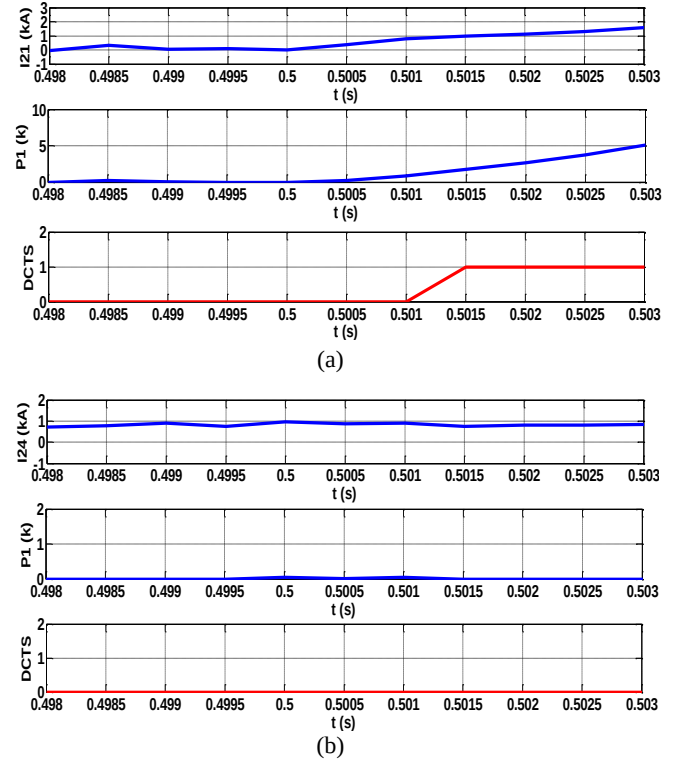


Fig. 20. Signals and detection indices at bus 2 against the fault at F1 in presence of Gaussian noise with SNR=20, (a) I_{21} , (b) I_{24} (fault initiation: $t = 0.5$ s).

- Regarding the former issue, increasing the sampling rate can reduce the security of the proposed detector in a noisy condition, unlike its detection time.
- In comparison with what was mentioned above, other parameters such as the length of the data window, β , and γ values have no significant effect on the ACUSUM performance in presence of noise.

C. Supplementary Augment

1) Communication

Currently, optical ground wires (OPGWs) are widely used in HVDC transmission systems [27]. The signal transfer delay in an optical fiber cable is approximately $4.9 \mu\text{s}/\text{km}$ [28]. In other words, even adding the communication time delay for transferring data between protective relays of the line, the proposed ACUSUM still belongs to the category of fast detectors (as backup protection). Furthermore, this protection can employ existing communication links without additional cost. Regarding the reliability concerns, OPGWs are immune to electromagnetic interference arising from corona on DC wires or faults in the transmission system [27], which ensures high communication reliability.

2) Independence of the Algorithm

The proposed algorithm uses the variations in current signal for fault detection, which is an inevitable phenomenon during

permanent faults. Moreover, the auxiliary parameters of the proposed algorithm are flexible and can change due to making the desired compromise between dependability and security (considering the network configuration and operation condition). Therefore, regardless of system parameters, different converter types and configurations, and different control systems, ACUSUM can be used as a fault detector algorithm. In other words, during a permanent fault, different converter types and control systems may result in different variation levels in the current signal, which cannot remain masked from ACUSUM. This sounds the independence of the proposed method performance from the system parameters and configuration.

IV. CONCLUSION

In this paper, a novel selective DC fault detector scheme based on the adaptive cumulative sum (ACUSUM) method has been proposed for MT-HVDC transmission lines, which can detect DC faults and discriminate faulted line in less than 2ms. This feature of the proposed algorithm ensures the selectivity of the protection system and enhances the reliability of the HVDC power transmission grid. The assessments have shown that noise, variations in fault location, and fault resistance cannot distort the performance of the algorithm. Appropriate

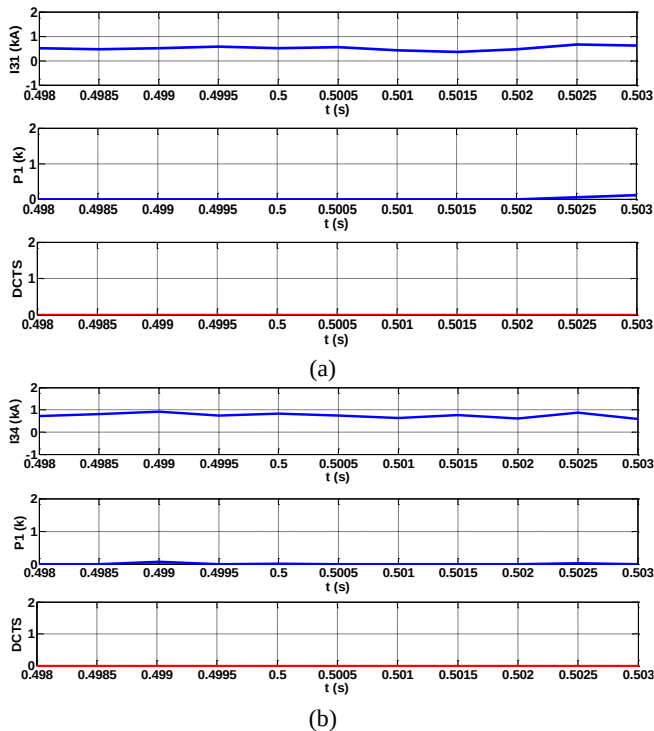


Fig. 21. Signals and detection indices at bus 3 against the fault at F1 in presence of Gaussian noise with SNR=20, (a) I31, (b) I34 (fault initiation: $t = 0.5$ s).

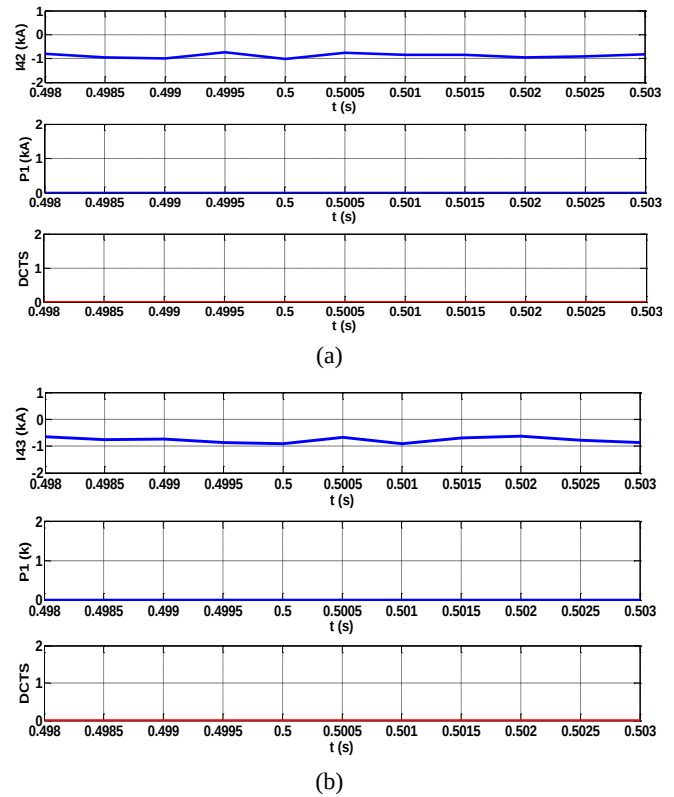


Fig. 22. Signals and detection indices at bus 4 against the fault at F1 in presence of Gaussian noise with SNR=20, (a) I42, (b) I43 (fault initiation: $t = 0.5$ s)

speed (as backup protection), adaptivity, low sampling frequency, low computational burden, independence from system parameters, and the need for no complicated equipment or hardware are notable advantages of the proposed method, which make it applicable for practical applications.

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