A New Non-communication Protection Scheme for Three-terminal Transmission Lines Based on Mathematical Morphology

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***Abstract*—In this paper a new non-communication based scheme is presented for protection of three-terminal transmission lines. Using this scheme, simultaneous operation of CBs at all terminals is provided for at least 92% of internal faults. This scheme can discriminate between external and internal fault using captured transients produced by fault and high-band stop filtering property of stray capacitance of busbars. The presented scheme uses Mathematical Morphology to analyze the captured transients. The presented scheme has been applied on one of three-terminal lines in Iran's transmission grid. The effects of fault resistance, fault inception angle, internal fault location, type of fault and sampling frequency on the performance of the proposed scheme are evaluated.**

Keywords-component; three-terminal transmission lines; mathematical morphology; non-communication protection;

I. INTRODUCTION

There are some cases where, for the reasons such as economical, technical or geographical views a new substation cannot be constructed to supply the energy for a new area. In these cases, one of the solutions is that the transmission lines become tapped. This construction is known as three-terminal transmission line [1].

When internal fault occurs in three-terminal lines, the performance of each relay is affected by infeed at each terminal, weak infeed at one or more terminals and any outfeed, if they exist. Due to these effective conditions and also the configuration of three-terminal line, stepped distance scheme cannot provide simultaneous fault clearing at all terminals of these lines. To eliminate this shortage, pilot protection which uses a communication channel as a means to compare the measuring results at the terminals of the line [2], is the most common solution. Moreover, in [3-4] applying differential protection, several new communication-based protection schemes are presented for these lines. Although both distance pilot and differential protection schemes prepare high-speed tripping for many of internal faults within the protected line, they have mis- or delayed operation in case of outfeed condition. Besides, the reliability of these solutions is further affected by the reliability of the costly installed communication devices (such as channel, transmitter, receiver and etc). Hence, complete protection of three-terminal transmission lines with non-communication schemes has obvious advantages.

In [5-7] non-communication based protections have been presented based on operation of circuit breaker at remote terminal. Thus, performance of these techniques is adventured in case of remote failure breaker and un-transposed lines. In other words, dependability of these protection schemes is affected by that of the circuit breaker. Specifically whenever CBs in one of the terminals are open, these schemes are failed. In [8] an accelerated distance protection scheme has been proposed, which has the same problem of mal-operation under outfeed conditions.

In this paper a new non-communication protection scheme employing Mathematical Morphology is presented for the three-terminal transmission lines. This scheme, by comparing an index with a pre-defined threshold, can discriminate between the internal and external faults. Although this scheme works at high frequency sampling (1 MHz), the proposed scheme excels both pilot protection schemes and other non-communication schemes due to higher reliability and dependability. Besides, speed of internal faults clearance by the proposed scheme is very high rather than other non-communication based schemes (comparing 5-10 μs in the proposed method with 100-120 ms in [5], 10-75 ms in [6], 300-700 ms in [7], 60-63 ms in [8] and 100-450 μs in [9]). It is worth noting that the required high sampling frequency is nowadays a common practice and commercially available on different hardwares.

In the rest of this paper, in section II the basic concepts of the proposed scheme are described. The structure of the Mathematical Morphology (MM) and its basic operators and a special proposed one, are introduced in section III. In section IV, the proposed protection scheme is described. Simulated power system and the results are explained in section V. At the end, conclusions are presented.

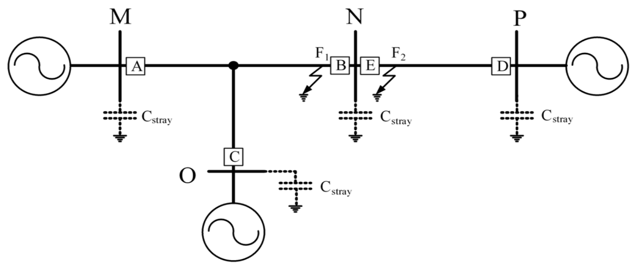

Figure 1. Multi-section Transmission System

II. BASIC CONCEPTS

When a fault occurs in power systems, high frequency transients are produced. These high frequency transients contain useful information about type of the fault (external or internal). In Fig. 1, when the external fault F2 occurs, the generated transients travel toward the busbars N and P. The arrival transient wave at busbar N is divided to three parts. One part reflects back, another part passes through the busbar and travel toward busbars M and O. The third one is shunted to earth through the stray capacitance of the busbar. Therefore, the stray capacitance of busbar N will act as a high-band stop filter.

In [9], it has been expressed that the filtering of the stray capacitance of the busbar can be considerable. For example, with C_{stray}=0.1 μF, it can be seen that 60% of transients with frequency of 100 kHz are shunted by the busbar stray capacitance; while only 10% of low frequency transients below 5 kHz are filtered. Hence, combination of frequency components in the transient wave reaching the relays A or C changes toward the low frequency components, but when internal fault F_1 occurs, the transients reaching the relays A and C have more high frequency components compared with those of the external fault. The proposed protection scheme is based on this fact for discrimination between these two types of faults.

III. MATHEMATICAL MORPHOLOGY

MM, as powerful tool to decompose a signal, is first introduced by two French researchers, Matheron and Serra, in 1964 [10]. MM can be defined as a theory for the analysis of spatial structures. It is mathematical in the sense that the analysis is based on the set theory, and it is called morphology because it concentrates on the form, shape, and size of structures. In sequel, some basic MM-based operations are presented.

A. Dilation and Erosion

Dilation and erosion are the basic words of the morphological literature in the sense that all other transformations in MM are based on these two elementary transformations. The dilation and erosion of a function *f* are defined as the following [10]:

$$\lfloor \delta_g(f) \rfloor (x) = \max\{ f(x-s) + g(s) \mid (x-s) \in D_f, s \in D_g \} \quad (1)$$

$$\lfloor \varepsilon_g(f) \rfloor (x) = \min\{ f(x+s) - g(s) \mid (x+s) \in D_f, s \in D_g \} \quad (2)$$

where the function *g* denotes *a* structuring element (conceptually similar to sample time in sampling of a signal) while its length should be considerably shorter than the irregularities of function *f* for better detection. Also, D_f and D_g are definition domains of the functions *f* and *g*, respectively.

B. The Proposed Operator

This operator has not been introduced ever. At each SE, first, the maximum and the minimum value of signal are determined. Then, the value of the following parameter is calculated by:

$$D = \frac{\max f \mid_{SE} - \min f \mid_{SE}}{s_{\max} - s_{\min}} \quad (3)$$

which s_{max} and s_{min} are the number of samples corresponding to the determined maximum and minimum value, respectively. It is assumed that SE is flat and all its values are zero (i.e. SE={0,0,0,…,0}).

At every data window, the maximum value of *D* is determined as the value of the proposed operator. This operator is very sensitive to irregularities of a signal.

C. Openenig and Closing

The opening of the discrete signal *f(n)* by *g(n)* is denoted by $(f \circ g)$ and defined as the dilation of the eroded signal:

$$(f \circ g)(n) = ((f \,\Theta\, g) \oplus g)(n) \quad (4)$$

Also, the closing of the discrete signal *f(n)* by *g(n)* is denoted by $(f \bullet g)$ and defined as the erosion of the dilated signal:

$$(f \bullet g)(n) = ((f \oplus g) \Theta g)(n) \quad (5)$$

The opening operator makes the sharp edges smooth, and the closing operator fills the narrow valleys and gaps. Combination of opening and closing operators can be used to derive the AVG filter as follows [10]:

$$AVG(f) = \frac{1}{2}(f \circ g + f \bullet g)(n) \quad (6)$$

The Detail filter can derive the sharp irregularities of a signal by:

$$Detail(f) = f - AVG(f) \quad (7)$$

IV. THE PROPOSED ALGORITHM

All protection schemes needs to discriminate external faults from internal ones for correct operation. In this paper, this discrimination is based on revealing the type of fault through inspecting the amount of high frequency components against low frequency ones. From this aspect, every fault can be categorized as high-transient, low-transient, and very low transient faults. In fact, every fault depending on its inception angle, resistance, and location can be categorized as one of these three types. For example, a single phase to ground fault, LG, occurring at peak of voltage, V_{max}, and fault resistance zero, R_{00}, is stamped as a high transient fault while another LG fault at V_{30} with R_{00} may be detected as a low transient fault.

Very low transient faults are the ones which usually occurred at small FIA (fault inception angle). Using this classification of faults, the discrimination of internal faults from external ones becomes possible.

Capturing the high frequency transient declares only internal fault has occurred. In other words, only and only if the internal fault occurs, the relay may detect the captured transient as high. In Fig. 1, when high transient external fault F2 occurs, due to high frequency components filtering by the stray capacitance of the busbar N, the relay A identifies that the extracted transient is not a high one. Using the pre-defined threshold, distinguishing between the high transients against others is possible.

On the other hand, when the relay detects non-high transient fault, the fault may be an external high transient which has become as non-high transient through passing a high-band stop filter (i.e. passing through a bus, modeled by its stray capacitances) or internal low transient. Once internal faults happen, irregularities and fractures in current waveform are sharper than ones related to external ones. Based on this feature, distinguishing between the above-mentioned faults is possible by applying a pre-defined threshold.

Faults, mostly, occur at large FIAs due to the fact that the probability of insulation breakdown increases as the voltage across it takes larger magnitude. Thus, faults are in the categories of high transient or low transient and a few of them may be seen as very low transient. Indeed, the proposed algorithm in this paper has not proper performance under very low transient faults.

The flowchart of the proposed protection scheme for the three-terminal transmission lines is shown in Fig. 2. As shown, the processes which the relay must perform at each time step contain the following steps:

First step: According to the selected data window (DW), the current signal at the relay location is sampled.

Second step: The proposed MM operator is applied to DW and the process is performed with SE_1=3 samples.

Third step: The first operation index, I_{op-1}, is defined as the maximum value of the output of the second step.

Fourth step: I_{op-1} is compared with the pre-defined threshold, $I_{threshold-1}$. If I_{op-1} exceeds $I_{threshold-1}$, a high transient internal fault has occurred and the tripping command is issued to circuit breaker. Otherwise, the relay detects a low transient event and the algorithm must go to the next step to do more process.

Fifth step: SE_2 is set at 5 samples, and Detail filter is applied to the output signal of the second step. Using this filter, the sharp part(s) of the signal is captured.

Sixth step: The second operating index, I_{op-2}, is determined as the maximum value of the Detail filter's outputs (output of the fifth step).

Seventh step: I_{op-2} is compared with pre-defined, $I_{threshold-2}$. If I_{op-2} is greater than $I_{threshold-2}$, an internal low transient fault has been occurred and consequently, the tripping command will be issued to the circuit breaker.

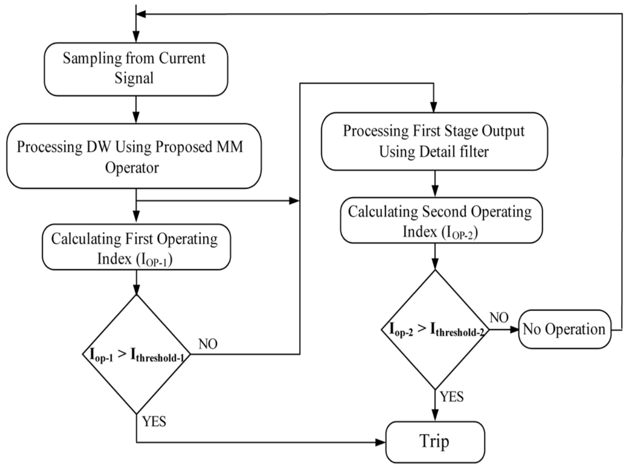

Figure 2. The flowchart of the proposed protection algorithm.

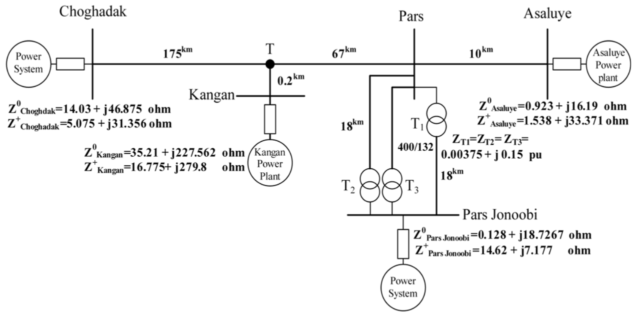

Figure 3. The simulated power system.

The performance of each protection scheme is evaluated from both dependability and security viewpoint. Investigations have shown that the security of the proposed algorithm is 100 % against external faults (not shown in this paper) while its dependability is discussed in the next section.

V. SIMULATION AND RESULTS

The proposed protection scheme has been applied on the three-terminal line of Choghadak-Kangan-Pars in Iran's Transmission Grid. Configuration and specification of this line have been shown in Fig. 3. The stray capacitance of each of main busbar (Choghadak, Kangan, and Pars) has been calculated based on [11]. The stray capacitances at Choghadak, Kangan, and Pars busbars have been calculated as 73.05, 11.91, and 61.53 nF respectively.

The zero and positive sequence impedance of all lines are Z_0=0.31933+j1.0652 ohm/km and Z_1=0.030217+j0.4228 ohm/km.

The performance of the proposed protection scheme is evaluated for both remote and near faults.

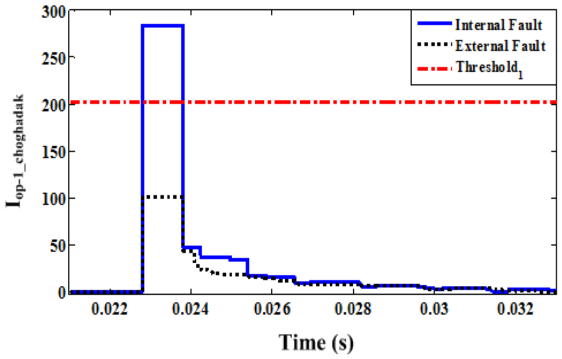

Figure 4. $I_{op\text{-}1\_choghadak}$ for remote internal and external LG fault at 0.5 km from Pars at V_{90} and R_{00}.

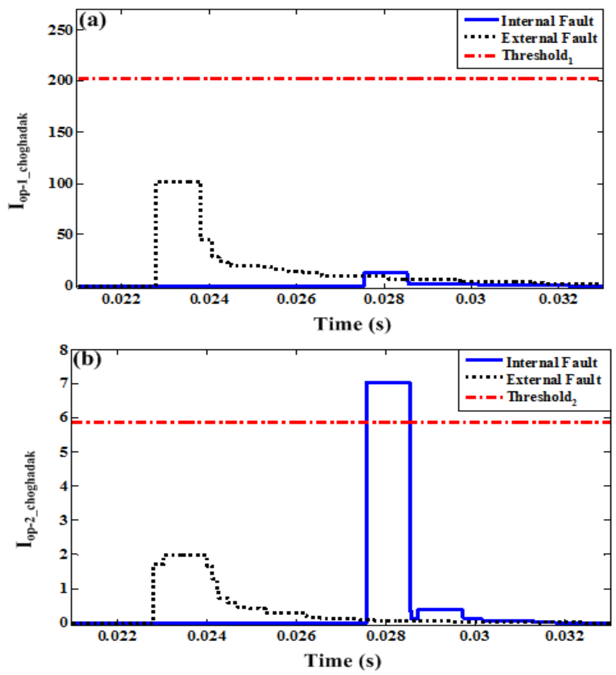

Figure 5. (a): $I_{op\text{-}1\_choghadak}$, (b): $I_{op\text{-}2\_choghadak}$ for remote internal and external LG fault at 0.5 km from Pars at V_{04} and R_{200} and V_{90} and R_{00} respectively

A. *Remote faults*

To study the performance of the algorithm, remote internal and external faults at 0.5 km inside and outside of Pars substation have been considered.

For single phase to ground (LG) at V_{90} and R_{00}, the first operating index, $I_{op\text{-}1}$, has been shown in Fig .4. According to this figure, $I_{op\text{-}1\_choghadak}$ has exceeded the pre-defined first threshold, $I_{threshold\text{-}1}$, thus, the relay at Choghadak detects it as a high transient fault deciding that an internal fault has happened and the trip command is issued for the local CB. The similar results are obtained by the relays at Pars and Kangan substaions. Furthermore, Fig. 5 has shown $I_{op\text{-}1\text{-}choghadak}$ and $I_{op\text{-}2\text{-}choghadak}$ for another LG at V_{04} and R_{200}. As shown, $I_{op\text{-}1\_choghadak}$ is lower than $I_{threshold\text{-}1}$, thus, the relay at Choghadak detects it as a low transient event, but as $I_{op\text{-}2\_choghadak}$ is more than $I_{thershold\text{-}2}$, this fault is identified as an internal low transient event; where again the trip command is issued for the local CB.

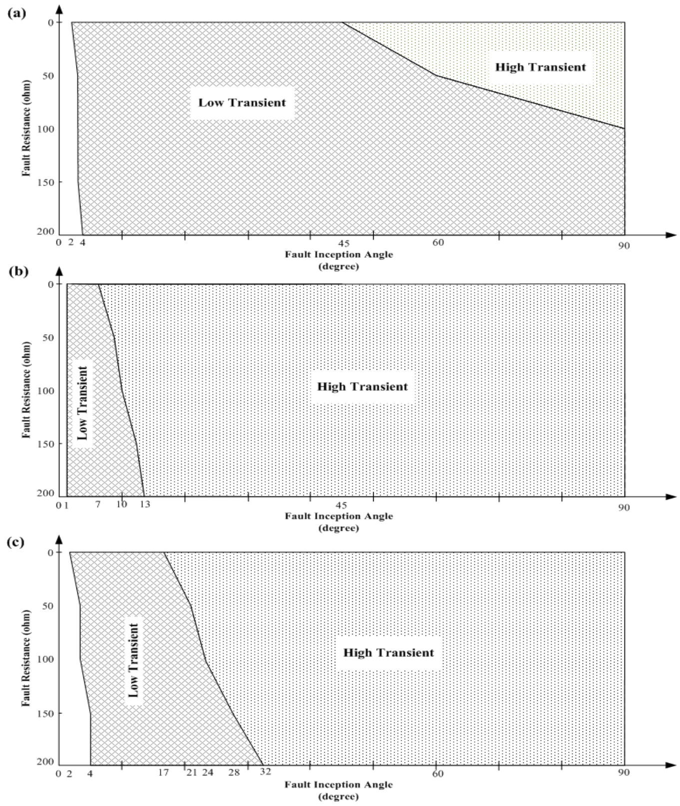

Figure 6. Operation characteristic of the (a): $Relay_{Choghadak}$, (b): $Relay_{Pars}$, (c): $Relay_{Kangan}$, for internal LG faults at 0.5km from Pars substation

The operation characteristics of the relays at all three terminals under LG faults at 0.5 km from Pars substation have been illustrated in Fig. 6. These figures have illustrated the dependability performance of the implemented algorithms at the three terminals in the plane of FIA versus fault resistance. It can be seen that there are very small areas that the proposed algorithm cannot distinguish internal faults due to the fact that they are very low transient ones.

Moreover, the performance of the proposed algorithm has been evaluated for remote internal and external LLG and LL faults at 0.5 km from Pars substation. Similar results have been obtained. The percentages of all internal faults at 0.5 km far from Pars substation that have been correctly and incorrectly identified by each relay have been given in Table I. As is shown, for the worst and/or farthest internal remote fault, the dependability of the proposed algorithm is more than 96% for all LG, LLG and LL faults.

B. *Near faults*

To investigate the performance of algorithm in distinguishing between close-in and close-out faults, different faults at 0.5 km far from Choghadak substation have been considered.

The $I_{op\text{-}1\_choghadak}$ for close-in and close-out LG fault at V_{90} and R_{00} (as the strongest close-in and close-out fault) are demonstrated in Fig. 7. As shown, because the $I_{op\text{-}1\_choghdak}$ has

TABLE I. THE PERFORMANCE OF THE PROPOSED ALGORITHM UNDER INTERNAL FAULTS NEAR PARS SUBSTATION

	Percentage (%)								
Type of fault	*LG*			*LLG*			*LL*		
Classification performance	*Correct*		*Incorrect*	*Correct*		*Incorrect*	*Correct*		*Incorrect*
Type of detected transient	*High*	*Low*	*Very low*	*High*	*Low*	*Very low*	*High*	*Low*	*Very low*
$Relay_{Choghadak}$	15.97	80.69	3.34	75.00	25.00	0.00	67.78	29.86	2.36
$Relay_{Pars}$	88.61	10.28	1.11	100	0.00	0.00	88.89	8.89	2.22
$Relay_{Kangan}$	72.92	23.47	3.61	92.5	7.50	0.00	85.69	10.97	3.34

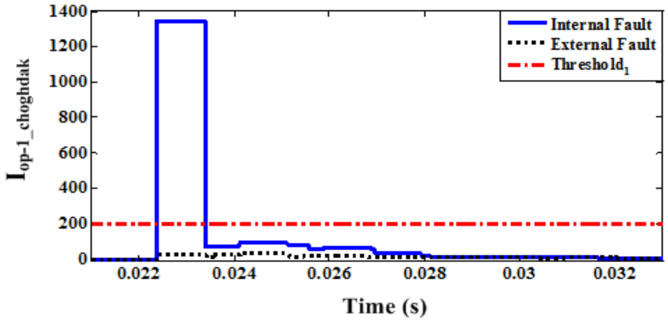

Figure 7. $I_{op-1\_choghadak}$ for close-in and close-out LG fault at 0.5 km from Pars at V_{90} and R_{00}

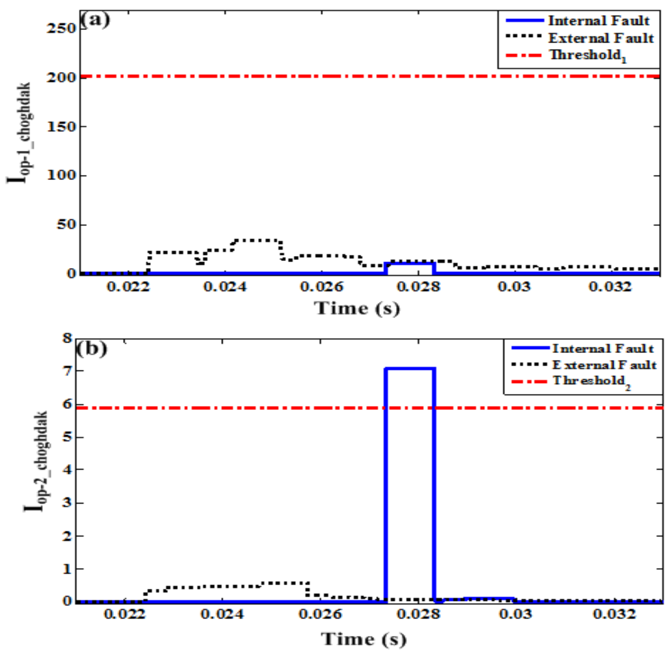

Figure 8. (a): $I_{op-1\_choghadak}$ (b): $I_{op-2\_choghadak}$, for the LG close-in fault at V_{01} and R_{200} and the strongest LG close-out fault at 0.5 km from Choghadak substation

gone over the $threshold_1$, the relay at Choghadak has identified the captured high transient event as internal fault and consequently has issued trip command to the local CB. For the relays at Kangan and Pars substations, the same results have been obtained which are not shown. Moreover, Fig. 8 has shown $I_{op-1\_choghadak}$ for LG close-in fault at V_{01} and R_{200}. It can be seen that although the relay at Choghadak has stamped the condition as low transient, the proposed procedure results finally in detecting this condition as an internal fault and consequently the trip command has been issued to the local CB.

Besides, the performance of the proposed algorithm has been evaluated for close-in and close-out LLG and LL faults at 0.5 km from Choghadak substation. Similar results have been obtained. The percentages of all internal faults at 0.5 km far from Choghadak substation that have been correctly and incorrectly identified by each relay have been given in Table II. As is shown, for the worst and/or nearest internal fault, the dependability of the proposed algorithm is more than 92% for all LG, LLG and LL fault.

C. *Sampling frequency effect*

According to Shannon's theorem, if a function $f(t)$ contains no frequencies higher than ω, it can be uniquely reconstructed by giving its ordinates at a series of points spaced $1/(2\omega)$ seconds apart [12]. In other words, the highest frequency component which can be reconstructed will be fs /2 if sampling frequency is fs. Therefore, the sampling frequency has an important role in transient-based protection schemes.

In this section, the effect of sampling frequency on the proposed scheme is revealed for faults close to Choghadak and Pars substations. For this purpose, with sampling frequency of 500 kHz, the percentage of identified fault at 0.5 km form Choghadak and Pars substation are shown in Table III. As shown, the performance of the proposed algorithm has decreased. This means that some useful frequency component have not been captured with this sampling frequency. It can be concluded that the proposed scheme cannot be used for low sampling frequencies such as 500 kHz.

It is worth to mention that although, nowadays, the digital/numeric protective devices mostly work at sampling frequency 1-10 kHz, digital signal processors (DSP) with high sampling frequency such as 1MHz are commercially exposed and will be employed, soon, for transient-based protection schemes.

TABLE II. THE PERFORMANCE OF THE PROPOSED ALGORITHM UNDER INTERNAL FAULTS NEAR CHOGHADAK SUBSTATION

	Percentage (%)								
Type of fault	***LG***			***LLG***			***LL***		
Classification performance	***Correct***		***Incorrect***	***Correct***		***Incorrect***	***Correct***		***Incorrect***
Type of detected transient	***High***	***Low***	***Very low***	***High***	***Low***	***Very low***	***High***	***Low***	***Very low***
$Relay_{Choghadak}$	85.56	13.33	1.11	100	0.00	0.00	87.78	11.11	1.11
$Relay_{Pars}$	25.86	66.36	7.78	79.44	20.56	0.00	73.61	22.92	3.47
$Relay_{Kangan}$	60.97	33.75	5.28	88.33	11.67	0.00	82.92	14.72	2.36

TABLE III. THE PERFORMANCE OF THE PROPOSED ALGORITHM UNDER INTERNAL FAULTS NEAR CHOGHADAK AND PARS SUBSTATIONS

	Percentage (%)					
Location of faults	***0.5 km from Choghadak***			***0.5 km from Pars***		
Type of fault	***LG***	***LLG***	***LL***	***LG***	***LLG***	***LL***
$Relay_{Choghadak}$	94.72	100	95.56	57.08	86.11	81.53
$Relay_{Pars}$	48.61	84.31	78.89	94.72	100	94.86
$Relay_{Kangan}$	74.44	94.17	88.89	79.31	95.83	87.64

VI. CONCLUSION

In this paper, a new non-communication protection scheme for three-terminal transmission lines is proposed which provides simultaneous operation of CBs at all terminals (according to worse time as 5-10 µs against the delay time of published methods including 100-120 ms in [5], 10-75 ms in [6], 300-700 ms in [7], 60-63 ms in [8] and 100-450 µs in [9]), for the worst case internal faults with more than 92% dependability and 100% security against external faults. This scheme, according to the concept of the busbars stray capacitances can discriminate internal faults and external ones. To perform the protection task, the captured transient is processed by the proposed Mathematical Morphology operator and Detail filter. This scheme needs two assigned threshold to fully discriminate the faults.

The performance of the proposed protection scheme is evaluated under different fault resistances, fault inception angles, fault locations, types of fault and sampling frequencies, and it has shown complete robustness against all of these parameters, whenever the sampling frequency is as high as 1 MHz.

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