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# Adaptive Single-Phase Reclosing in Transmission Lines

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Graduate Program in Electrical and Computer Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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# ADAPTIVE SINGLE-PHASE RECLOSING IN TRANSMISSION LINES

(Thesis format: Monograph)

by

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Doctoral of Philosophy

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# Abstract

This research work is mainly concerned about dealing with temporary short circuit faults in power system transmission lines. In fact, there are two types of electrical faults in power systems, namely temporary and permanent. When a fault is permanent, the only way to clear it is to de-energize the transmission line by opening the associated circuit breakers. However, in many cases the fault is not solid and is caused by objects such as flying birds or broken branches of trees. For these cases, electrical arc plays a major role. For such fault cases, it is also possible to de-energize the faulted phase, temporarily, and re-energize it after a short delay by reclosing the opened circuit breakers. This operation is called single-phase reclosing. There is a chance that the fault becomes clear by natural extinction of the arc after the faulted phase isolation in case the fault is temporary.

There are two considerable challenges regarding traditional single-phase reclosing in transmission lines. The first challenge is the determination of the fault type, i.e., permanent or temporary, as there is no guarantee that the fault is temporary. This is crucially important as reclosing-on-fault, i.e., reclosing the opened breakers while the fault still stands, is harmful for both power system stability and power system equipment. The second challenge which is regarding temporary faults only, is that there is still no guarantee that the arc is extinguished by the moment of reclosing. In such cases, reclosing leads in re-striking of arc and therefore, an unsuccessful reclosing.

This research work is conducted in two phases. At the first phase, two adaptive methods are developed to improve the traditional reclosing method upon the two challenges mentioned in the second paragraph. The developed methods are capable of recognition of the fault type in a reasonable amount of time after single-phase isolation of the line. Therefore, the protection system will be able to block the reclosing function in case the fault is recognized as permanent and to issue three-phase-trip signal as the next action. For temporary faults, re-energizing of the isolated phase by reclosing the opened breakers is the next action which has to be performed after the arc extinction. The developed methods also have the capability of detection of the arc extinction and therefore, a better performance for temporary fault cases is guaranteed. This is the second feature required for an adaptive reclosing method.

The second phase of the research project is to estimate the arc extinction time well in advance in case the fault is temporary. The idea is that three-phase tripping could be the right action if the arc extinction time is too long as working under unbalanced conditions for an unnecessarily long time duration is harmful for the power system.

Both of the proposed adaptive single-phase reclosing methods in this research work employ local voltage information. Therefore, communication facilities are not needed for implementation of the proposed methods. It is shown in the thesis that the proposed methods are able to quickly detect the fault type and also the arc extinction if the fault is temporary. Also, the two proposed arc extinction time prediction methods are capable of prediction of the arc extinction time well in advance and with acceptable precision.

All four proposed methods are effective for various system configurations including ideally-transposed, untransposed and partially-transposed transmission lines and also for transmission lines with different compensation conditions including with and without shunt reactor. Superior performance of the proposed methods have been verified using 550 case studies simulated in PSCAD and Matlab, and also a field recorded temporary fault case associated with a 765 kV transmission line. The 550 simulated case studies include 100 ideally-transposed, 240 untransposed and 210 partially-transposed line cases. The performances of the two proposed reclosing methods are also compared with two of the existing adaptive reclosing methods where considerable improvements are observed.

**Keywords:** Adaptive protection, arc extinction, single-phase reclosing, tranmission line

*To my parents ...*

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# Chapter 1

# Introduction

Power system is one of the most important systems developed by humankind. Basic role of this system is to produce the electrical energy in power plants, etc., transfer it to the desired destinations and finally, distribute it among consumers. Each of these steps has its own importances and difficulties. In places in which locations of electrical energy production and consumption are far from each other, transferring the energy by means of transmission lines becomes extremely critical. One of the factors that can disturb the ideal performance of the transmission lines is short circuit fault inception against which the lines must be protected [1].

This research work is dedicated to adaptive single-phase reclosing in transmission lines. In the performed research, adaptive methods are proposed for fault type recognition purpose, i.e., permanent and/or temporary, at first, and then making a proper decision based on the detected fault type. The proper decision is always to initiate three-phase trip signal for permanent fault cases. For cases of temporary fault, normally, the correct decision is to reclose the breakers after the arc extinction detection. However, if the arc is being extinguished too slowly, it can be a better action to issue the three-phase trip signal and avoid reclosing as it is harmful for the system to be kept in unbalanced conditions for a long time. For this purpose, arc extinction time must be predicted in advance. This is also covered in the performed research work.

In this Chapter, at first, there is an introduction about single-phase reclosing followed by problem definition and literature survey sections. Finally, objectives, contributions and novelties of the performed research study are presented.

## 1.1 Single-Phase Reclosing

According to statistics, most of the faults happening in extra and ultra high voltage transmission lines are of temporary nature [1, 2]. When dealing with temporary faults, which are mostly accompanied by electric arcs, one interesting idea is to isolate the faulted line, temporarily, and re-energize it with or without a delay. This operation is called reclosing [1, 3].

The fastest way to extinguish an arc associated with a temporary fault is three-phase reclosing. This is because of the fact that after isolation of all three conductors, there would be no voltage source to feed the arc. However, this could be harmful for the stability of the system as two sides of the line will remain disconnected for a considerable amount of time. If the temporary fault type is single-phase-to-ground, a good trade off is single-phase reclosing [3, 4]. This technique can be very practical as faults are mostly single-phase-to-ground [1].

In single-phase reclosing, the two healthy phases are kept in circuit during the fault period while the faulted phase becomes de-energized, temporarily, by opening operation of the circuit breakers. In this technique, the faulted phase will be returned to service ideally when the fault is cleared [3]. Compared to three-phase reclosing, the problem with single-phase reclosing technique is that the arc can not be extinguished, immediately, as it will be fed through mutual coupling with the non-faulted phases [2].

The critical point about reclosing is to avoid reclosing-onto-fault, i.e., reclosing when the fault is not cleared yet. This can destroy the equipment and put the system stability at risk [1]. Therefore, the reclosing system has to wait for the arc to be extinguished in case the fault is temporary.

## 1.2 Problem Definition

In a traditional single-phase reclosing method, single-phase isolation of the faulted phase is performed as soon as the single-phase-to-ground fault is detected. The next step is to issue single-phase reclosing signal after a predetermined delay called dead-time [2]. There are two main problems with the traditional reclosing method. First, there is no guarantee that the fault type is temporary. In fact, traditional method recloses the faulted phase regardless of the fault type. Second, even if the fault type is temporary, there is no guarantee that the reclosing be performed after the arc extinction. This is a very big issue because reclosing prior to the arc extinction will lead to restriking of the arc which means the reclosing is not successful.

The next problem is regarding only temporary fault cases. For permanent fault cases, the proper decision is definitely to initiate the three-phase trip signal. But for temporary fault cases, the reclosing method must be able to detect the arc extinction time and the reclosing signal must be initiated after the arc extinction detection. However, arc extinction time can be too long for some temporary fault cases. Therefore, the proper decision can be to initiate the three-phase trip signal for such cases.

Also, regarding the proposed methods, the preference is that the methods utilize local voltage measurements information to perform reclosing as communication facilities are not available all the times. In addition, the proposed methods must be valid for transmission lines with any transposition and compensation conditions.

## 1.3 Literature Survey

According to statistics, more than 80% of faults in overhead transmission lines are temporary, mostly single-phase-to-ground faults [2]. There are different reasons for temporary fault inceptions including overvoltages as results of lightnings and temporary contacts between phase/ground wires, e.g., by broken branches of trees or flying birds. As these faults are not permanent and can be cleared by themselves, one practical solution is single-phase auto-reclosing, SPAR, of the faulted phase [5]. This way, there is a chance to bring the faulted phase back to operation shortly after the fault inception which leads to enhancement of reliability and stability of the system [6]. Even during single-phase opening of the faulted phase breaker, still 58% of the line capacity available due to presence of two non-faulted phases [7].

Traditionally, when SPAR function is considered, reclosing is performed after single-phase opening of the faulted phase by a predetermined time delay called dead-time [3, 8]. In such a condition, first, reclosing is performed regardless of the fault type, i.e., permanent or temporary. Second, there is no guaranty if the arc is extinguished at the moment of reclosing for temporary fault cases. Therefore, there is a danger of reclosing-onto-fault for permanent fault cases and restriking of the arc for temporary faults in which the arc is not extinguished at the time of reclosing. Both these scenarios which are considered as unsuccessful reclosing attempts,are dangerous for the power system and the system equipment [9]-[12]. Additionally, reclosing process is usually repeated after a short break in traditional SPAR if unsuccessful which makes the situation even worse [2], [13]-[15]. In [16]-[19] destructive effects of single-phase reclosing on torsional torques of turbine-generator shaft are analyzed and discussed.

There have been some methods proposed and implemented in practice to minimize the dead-time including installation of three-phase four-legged shunt reactor with inductively grounded neutral at both ends of transmission lines [2, 20, 21]. By properly selection of the neutral reactor, it is possible to limit the voltage across the arc and therefore, reduce the dead-time. This method is more effective for transposed transmission lines, although it has been applied to untransposed lines at very high voltage levels using switching scheme of shunt reactor at one end [2, 21, 22].

To overcome the mentioned problems regarding the traditional SPAR, several adaptive auto-reclosing methods are proposed. The main objectives of an adaptive single-phase reclosing technique is to quickly identify permanent fault and to detect the arc extinction in cases of temporary fault [2, 23, 24]. Most of the proposed adaptive SPAR methods in the literature use some features of the voltage/current waveforms [25]-[30]. In [25] 27 real temporary fault cases in 550 kV transmission lines are analyzed based on the voltage wave shapes. Zero-crossing point of the voltage is employed for enhancing the reclosing performance in [26]. In [27] and [28] frequency characteristics of the current are used for reducing the reclosing dead time. In [31], a method for arc extinction detection is proposed based on the behavior of the faulted phase voltage. The proposed method is also verified using test results from BC Hydro network. This paper in which information of only one side of the transmission line is employed for arc extinction detection, is a sample of contribution of Canadian researchers in the area of single-phase reclosing.

In the method presented in [32] which is registered as a US patent, the exact moment of arc extinction is detected by measuring the characteristics of the faulted phase voltage. In this method, depending on the compensation level of the line, one of the prepared algorithms is chosen for this purpose. Using this method, reclosing-on-fault will be prevented. In another patent, three-phase reclosing of shunt reactor is considered [33]. Three-phase voltages and currents are used for detection of the arc extinction time in the patent registered as [34].

Many researchers have investigated techniques for enhancing the effect of reclosing on system stability [36]. Recently, there have been major research activities to deal with this problem. As an example, artificial neural networks, ANNs, have been employed to detect the secondary arc extinction time after the breaker opening [37]-[39]. In [37] and [38], ANN is employed to extract appropriate features of frequency components of the voltage. Neuro-Prony and Taguchis methodology are used in [39] for a better reclosing performance. Also, wavelet analysis and neural network based SPAR schemes have been developed to recognize certain situations in order to decide if to reclose the circuit breakers [40]. However, the application of these techniques requires a broad data from the faulted system for the neural network training.

Fuzzy logic is employed in [30] and [41] for increasing the stability margin of the power system by enhancing the reclosing performance of the circuit breakers. In [42] a Fuzzy logic-based method is proposed for enhancing the single-phase reclosing in double-circuit transmission lines. This method identifies the fault type based on the angular difference between the positive and negative sequence components of the voltage. Reference [43] is specifically focused on secondary arc extinction in single-phase reclosing. In this paper, the role of neutral reactor as a tool for having a better arc extinction performance is of a high importance.

In paper [44] variable dead-time SPAR scheme has been presented based on stability margin. This scheme which is applicable only when the power system stability degree is sufficiently high, increases the reclosing dead-time [6]. In [45], voltage pattern is employed for reduction of the reclosing dead-time. Paper [46] proposes a method for decrement of the reclosing dead-time by reducing the mutual capacitive coupling effect. For this purpose, a capacitor in parallel to each pole of the circuit breakers must be considered.

One of the ways of categorizing adaptive SPAR methods is based on decision making method. In fact, all methods extract some features from waveforms or spectrum of the faulted system variables, including power, current or voltage [47]-[48]. These features are either compared to some thresholds or used independently for decision making.

There are many examples of methods use threshold for decision making. In [49, 50] zero sequence power as well as the faulted phase voltage are employed for arc extinction detection. In [52]-[54], spectrum of the faulted phase current is used for identification of the fault type. The method proposed in reference [6] uses rms value of the faulted phase voltage for the fault type recognition. For this purpose, rms value is calculated for different time periods and when the difference between rms values is larger than a predetermined threshold, arc extinction is detected. Arc extinction detection is performed in [54] using total harmonic distortion, THD, of the faulted phase voltage. This method works based on the fact that the amount of harmonic distortion of the voltage considerably decreases after the secondary arc extinction.

There are also few methods proposed based on the harmonic characteristics of the faulted phase voltage after single-phase opening of the breakers [55]. These methods are applicable only to uncompensated transmission lines. The reason is that the shunt reactor resonates with the line capacitances which leads to appearance of sub-synchronous oscillatory voltage waveforms in the faulted phase while the breaker is open. This can lead to inaccuracy in harmonic estimation and therefore, error in arc extinction detection [2]. There are more examples in [6], [56]-[61] in this order. However, the main problem with most of the methods of both groups is that these methods mostly depend on the under study system and the associated settings will change based on the parameters of the system [55].

Fourier transform, either fast Fourier transform, FFT, or discrete Fourier transform, DFT, is the most practical technique for analysis of the current and voltage waveforms [2], [58]. Other options can be few techniques such as wavelet [40], [59]. Although by using different mother wavelets, more data can be extracted, sampling rate and the level of complexity will also increase which is not appropriate and practical for protection and relaying. Therefore, Fourier based methods are more accepted, practically [5].

Another way of categorizing adaptive SPAR methods is the data type usage. In other words, generally there are two possible categories of reclosing methods available, namely local and communication-based. Local methods use only the information of one side of the transmission line while communication-based methods have access to data of both sides of the line. The method proposed in [56] is an example of communication based methods which predicts the faulted phase voltage after the arc extinction using the synchronized voltage phasor of the other healthy phases from both ends of the transmission line. Therefore, the instant of arc extinction can be detected when the faulted phase voltage magnitude and angle are close enough to their predicted values. However, this method is developed for arc extinction detection in ideally-transposed lines and is not applicable to untransposed or partially transposed lines.

Communication-based reclosing methods are faster and more accurate that local methods, but, they are not beneficial when communication facilities are not considered in that part of the power system. These methods are also dependent on the communication facilities which affects the reliability of the protection system. Therefore, local methods are more accepted in practice [5]. Reference [62] is an example of adaptive SPAR methods which is based on local voltage measurements. In this method, the faulted phase voltage magnitude is used for finding a reference time to start the required calculations. Then, the combination of the magnitude and phase angle is employed for detection of the fault type. Finally, arc extinction is detected based on behavior of the phase angle of the induced voltage for temporary fault cases.

Controlled switching of breakers for the purpose of reduction of surge overvoltages in shunt compensated transmission lines is proposed in [63]. In this method, unsuccessful reclosing is also prevented as the proposed method is designed to detect the arc extinction time as well. This method is also effective for both single-phase and double-phase-to-ground faults.

In [64], issues of single-phase and three-phase tripping of shunt reactor during reclosing are discussed. The main source of the problem is the resonance between the shunt reactor and the line capacitors. For solving the problem, it is proposed to switch off the shunt reactors before the arc extinction. Therefore, there will be no resonance after the arc extinction. However, this method can lead to some other issues and difficulties. The method proposed in the paper is to use power resistors in the neutral of shunt reactors for damping the resonance. However, what is missed in this analysis is the effect of neutral reactor which is usually used for a better arc extinction performance.

During single-phase reclosing of lines, the voltage condition is unbalanced as one of the conductors is isolated and only two phases are energized. In [65] application of Zig-Zag transformer for maintaining the balanced load voltages during single-phase reclosing is explained. In this method, for the purpose of reducing the negative-sequence and zero-sequence voltages of the load, application of a capacitor in the neutral of the Zig-Zag transformer is proposed.

At the end, there is a different idea for adaptive single-phase reclosing called hybrid reclosing scheme proposed in [7, 82]. In this method, the faulted phase is tripped, initially, thereafter, the remaining two phases are tripped with a short delay. After the three-phase opening, the residual energy in charged line capacitances and inductances feeds the arc until the energy is consumed and the arc is quenched. In this case, if the fault is temporary and arc is extinguished, a sinusoidal signal with a nonzero dc offset appears in the faulted phase voltage which can be considered as a sign of arc extinction, whereas if the fault is permanent, the faulted phase voltage becomes zero and a permanent fault can be differentiated from the temporary fault [2].

## 1.4 Objectives, Contributions and Novelties

In a traditional single-phase reclosing, the reclosing task is activated with a predetermined time delay after the single-phase isolation of the line called dead-time. There are two main issues about the traditional reclosing method. The first issue is that reclosing is performed regardless of the fault type, i.e., permanent or temporary. The second issue is that even if the fault is temporary, there is no guarantee that the secondary arc is extinguished before the reclosing. In this research work, both of the issues of the traditional reclosing method are covered. The third part of the research work is to propose a method for prediction of the arc extinction time in case the fault is temporary. This is important as in some temporary fault cases the arc extinction time is too long. Therefore, it can be reasonable to issue the three-phase trip signal instead of reclosing despite the fault type.

The first part of the research study is dedicated to adaptive single-phase reclosing. For this purpose, two reclosing methods are proposed. The first contribution of the proposed adaptive single-phase reclosing methods is to quickly identify the fault type, i.e., permanent or temporary. This is important as adaptive reclosing must be performed only if the fault type is identified as temporary. In fact, reclosing the open breakers when the fault is permanent is extremely dangerous for the power system equipment as well as the stability of the system.

The second contribution of the performed research study is to detect the arc extinction moment for temporary fault cases. In adaptive single-phase reclosing techniques, reclosing takes place only when there are evidences for the arc extinction. Therefore, in cases of temporary fault detection, the reclosing time delay is flexible depending on the situation [2].

There are some works done in the area of fault type recognition and arc extinction detection. The contribution of this research work is to develop faster and more reliable methods compared to the existing techniques. Also, the developed methods are effective for any kind of transmission line configurations, including ideally-transposed, untransposed and partially-transposed, and with and without shunt reactors. The developed methods utilize local voltage measurement data as communication facilities between the two sides of the transmission lines are not always available.

Finally, regarding the arc extinction time prediction, there are no publications presented in the literature in this area. In this research work, there are two adaptive methods proposed for the purpose of prediction of arc extinction time. Therefore, the proposed prediction methods are considered as novelty in single-phase reclosing research area.

# Chapter 2

# Reclosing in Transmission Lines

According to an IEEE Power Systems Relaying Committee report, auto-reclosing of circuit breakers in transmission lines has been considered as an applicable and beneficial function in power systems [5]. The main purpose of auto-reclosing is to keep the faulted transmission line in service as long as possible which makes the power system more reliable and economical. This concept works only when the fault is of temporary nature, i.e., faults in which the fault resistance is not solid and it can be cleared by itself. Faults occurred due to a broken branch of a tree is an example of temporary faults.

In reality, the idea of reclosing has been a very beneficial practice as according to statistics, 80% of faults in overhead transmission lines are of temporary nature [2]. The performance of auto-reclosing task can be confirmed during disturbances including abnormal weather conditions such as storms and heavy rains. In such conditions, the temporarily faulted system can go back to operation without any special interruption and any need for maintenance [2].

In this Chapter, history of reclosing is discussed to see how this concept has been adopted by power system utilities. Afterwards, application of single-phase reclosing in Canadian grids is considered. Then, various reclosing methods in terms of reclosing speed and number of shots and phases are described and the application of reclosing in various conditions are discussed.

Later, the operation sequence of protection system during single-phase reclosing is explained and at the end of this Chapter, IEEE guides for auto-reclosing including the settings and various operating modes are explained. It must be noted that in order to stay consistent, protective device in this Chapter means a device that performs the auto-reclosing task. This can be done either simply as a logical circuit in the same device or as a separate device.

## 2.1 History of Reclosing

Beginning of the twentieths century was when reclosing used for the first time in radial feeder circuits in which fuses and over-current relays had been employed for protection of the distribution system. Studies showed that the initial version of reclosing was successful in 73 to 88 percent of the cases [2].

Inverse-time relays with instantaneous trip elements were introduced to the power system in early 1930's. These relays helped coordination with fuse schemes. At those days, auto-reclosing techniques used for reclosing of the circuit following a predetermined delay for deionization of the arc path and mechanical reset of the relay, only one time, and if relay trips within 30 seconds after the first trip, lockout is considered. The Continuity of the service was the only purpose of the first reclosing techniques.

Later, transmission level circuit breaker were introduced to the power system with high-speed mechanical performances. Fault clearance time was reduced by faster operation of the newly developed breakers. The faster operating speeds of these new circuit breakers reduced clearing time, permitted high-speed reclosing by which system stability was also enhanced. Also, minimum reclosing time was determined by studying of the flash-over probability in insulators. This ensured the needed time for deionization of the arc path.

As the first, auto-reclosing applications for line with more than two terminals, in order to circuit completion, it was practiced to perform a delayed reclosing at all line terminals provided that the first reclosure be successful. Still the best reclosing practice from the continues serving point of view is multi-shot reclosure.

In recent years, transformer failures caused by reclosing of distribution substation feeders have concerned the system activists. Also, there is a chance of increasing stress on shafts between generators and turbines. It must be noted that this issue has been discussed in a paper at around 1940. It was concluded that despite transient power limits, single-pole switching might be dictated.

Considerable enhancements in mechanism, designs, operation reliability and speed of high voltage circuit breakers is been achieved, recently. Today, such achievements in addition to developments in protection devices have made high-speed reclosing a practical scheme.

Due to nowadays achievements in solid state and digital technologies, one reclosing Relay per Breaker has been considered again. e.g., one specified logic unit or reclosing processor can be used for programming for each of the breakers, differently. This processor can check the de-energized or energized status of all lines, buses, positions of all circuit breaker selector and control switches, closing control voltages, circuit breaker positions, etc. As various stations became available through communication, the condition knowledge at other substations can be more local than central.

Having access to fast communication systems and data acquisition, now it is possible to make control of the transmission line circuit breaker, central. But it seems that control of reclosing systems must stay local at the substation level.

## 2.2 Single-Phase Reclosing in Canada

Generally speaking, single-phase reclosing is in practice mostly in Europe and Asia [25]. In many North American provinces and states, single-phase reclosing is disabled due to the danger of unsuccessful operation of traditional reclosing methods.

Single-phase reclosing has been in practice in BC Hydro transmission lines with four-legged shunt reactors for the last 40 years [31]. Before 1970, high voltage transmission lines in BC were not equipped with four-legged shunt reactors. In mid 1970s, BC Hydro started to equip the new 500 kV lines with four-legged shunt reactors and applied single-phase reclosing to the lines. Currently, in BC Hydro grid, single-phase reclosing is disabled for 500 kV lines without shunt reactor [66].

According to Alberta interconnected electric system protection standard, all 240 kV and higher transmission lines shall be equipped with single-phase reclosers [67]. The minimum value for dead time setting is 0.75 s in Alberta. For longer dead time durations, appropriate system studies must be performed while shorter dead-time durations are not allowed [66]. In Quebec, 330 kV transmission lines are equipped with single-phase reclosers with dead time settings of 0.75 s and 1 s while this is not applicable to 735 kV lines [68]. Single-phase reclosing is applicable for 500 kV lines in Manitoba [69]. In Ontario, reclosing is applicable for distribution networks [70].

A different reclosing technique called single-phase switching obtained by combining single-phase reclosing and single-phase tripping was put in practice on 155 kV and 220 kV European transmission lines in 1950s [71]. The main reason of application of single-phase switching was to increase the power transfer capacity of the line and not the stability issues. This methods was applicable for transmission lines shorter than 40 km in length with no ground wires. This is because in such lines single-phase faults are very common while secondary arc extinction is not an issue. This technology was extended to 420 kV lines in 1960s [72].

In Canada, single-phase switching was employed by BC Hydro for two 230 kV lines in 1964 and 1971. Similar to European cases, the reason for application was to increase the line power capacity. This technology was used in Tennessee in 1970 for a 500 kV 150 km line [73]. Later in 1980s, single-phase switching was extended to 500 kV lines for transient stability enhancement purposes [72].

## 2.3 Various Reclosing Methods

There are various automatic reclosing systems in use today and they may be classified in different groups such as high-speed or time-delayed, single-shot or multiple-shot, and single-pole or three-pole. These reclosing methods will be discussed in the following.

### 2.3.1 High-speed vs. time-delayed

High-speed reclosing means reclosing of the breaker which is not delayed, intentionally. The only existing delay is the necessary time needed for deionization of the arc path.

However, most of reclosing schemes consider time-delay. In a time-delayed reclosure, the breaker is being closed after an intentional time-delay which is longer than what is considered for deionization of the arc path. The length of delay is mostly between one second and one minute depending on the situation [5].

**High-speed reclosing**

There are some benefits in application of high-speed reclosure including reduction in outage time, improvement in security and integrity of the system, higher probability of some recovery from multiple contingency outages and preserving machine stability.

When high-speed reclosure is considered, there are also some limitation considerations on system equipment, operating practices and configuration. Major limitations are as follows:

1) For permanent fault cases, stability of the system must be maintained after a high-speed reclosing.

2) High-speed protection must be considered to trip at all terminals of the line, simultaneously for all fault cases to provide enough time for deionization of the arc path.

3) Configuration of the system has to be able to hold the angle difference of two sides the opened breaker with a suitable variations.

4) Evaluation of any harm to rotational power devices connected to the system must be considered.

5) Voltages induced from circuits in parallel must not sustain the faults.

For a successful high-speed reclosing, the path of the arc must be sufficiently deionized so that the insulating properties can be re-established prior to re-energizing the transmission line.

There are some factors that are effective for a successful high-speed reclosing including:

- time of the fault clearance,
- construction and design of the transmission line,
- transmission line location compared to human-made or natural of any sources of danger,
- magnitude of the fault current,
- lightning stroke various components,
- weather condition,
- instantaneous voltage value at the moment of the line re-energization,
- inductive and capacitive coupling with the circuits in parallel connection,
- some other factors such as series capacitors, shunt reactors, tapped loads, etc.

**Time-delayed reclosing**

While time-delayed reclosure is applied, there are some factors to be considered including:

- Time-delayed reclosure can be beneficial provided that adequate protection system is not applicable for all of a transmission line terminals.
- Decrement of the fault arc re-establishment probability by increment in the predetermined time-delay.
- The desired minimum time for re-establishment of the system circuit, recognizing the number of terminals of the line, stability studies, requirements of the system, kinds of the loads and damping factors of the system.

Considering the time-delayed reclosure using the fastest reclosing schemes, usually only one of the line terminals is being reclosed each time for re-energizing the line. Also, relays for voltage monitoring are usually considered for determination of the system voltage presence on one of the breaker sides. Therefore, the user will be able to select the conditions of the system voltage that has to exist prior to issuing reclosing permission, in advance. Sometimes, users allow a delayed reclosing only when the phase difference between the contacts of the open breaker in a predefined range and stays synchronous with for a desired amount of time which is performed by sync-checks.

Load-flow and stability studies must also be performed in case sync-check for unusually long fault-clearance time is needed. Sometimes, double-checking of the phase difference and being synchronous before application of the reclosure function is unnecessary due to the number of parallel paths with the faulted line.

### 2.3.2 Single-shot vs. multiple-shot

Single-shot reclosure means either high-speed or time-delayed reclosing the breaker during a reclosing period, only for once. the other choice for reclosing, multiple-shot, is to reclose the circuit breaker during the considered duty cycle for more than one time.

A typical reclosure at a line terminal may include a high-speed reclosing which is not supervised by either sync-check or dead-line relaying, a time-delay reclosing which is supervised by dead line voltage protection. A successful reclosing would allow the other line terminals close by a time-delay, supervised by sync-check protection.

Generally speaking, modern high voltage and extra high voltage breakers are able to operate in any multiple-shot reclosure period, practically. Some special issues regarding the circuit breaker elements including opening or closing resistances, pressure of the available gas, air or fluid, or factor of derating based on the expected fault current and number of fault interruptions in a predefined time period in total can limit the effect on duty cycles or repetitive performances.

Before applying the multiple-shot reclosing, the user must make sure there would be no danger of system instability or other possible limitations in case the fault is permanent. As an example, multiple-shot reclosing is not practical when large motors or turbo-generators are danger of mechanical damage is probable. Also, it is more desirable to postpone the second reclosing shortly so that all transients of the previous reclosure are damped, properly.

Historically, single-shot reclosure of transmission lines has been in practice. But, later, multiple-shot reclosure also became desirable and practical. This is mostly due to the fact that most of the power system substations were not under supervisory control, traditionally. In such substations, it is not practical by the personnel to perform the second reclosure after one unsuccessful one. But, at substations where dispatching is performed by the personnel, an unsuccessful single-shot reclosing may lead to a later outage which is not necessary.

However, at those locations where an employee must be dispatched, a delayed outage may unnecessarily result if a single-shot reclosure is unsuccessful. About 25% and 10% of utilities have records of successful 2nd and 3rd reclosing functions, respectively. But at the same time, breaker constraints and reset time of the reclosing relays has to be taken into account not to have problems in the result of additional operations of the breakers in a predefined time duration. If there is no desire for single-shot reclosure schemes to be replace by multiple-shot methods, a considerable success may be achieved by single-shot reclosing schemes just by increasing the time-delay.

### 2.3.3 Single-phase vs. three-phase

The difference between single-phase and three-phase reclosing is that in single-phase reclosing, tripping and reclosing is performed only to the faulted phase. In single-phase reclosing, electrical power can be transfered through the non-faulted phases while the faulted phase is open. This leads to decrement is rotor-angle drift rate between the synchronous machines and increases the stability margin of the system. The only major problem is affection of the ground protection of the system due to circulation of the ground currents.

During fault clearance in a single-phase reclosing, due to capacitive an also inductive coupling of the phases, there is an induced voltage in the de-energized line. The magnitude of this voltage depends on the mentioned capacitance values and therefore, on the transmission line's configuration and physical dimensions. This voltage may causes the arc to stay on for a longer time period while the faulted line is isolated. In this case, the arc is called the secondary arc.

The main purpose of considering the reclosing time-delay is to give enough time to the secondary arc to be extinguished and therefore, to avoid reclosing-onto-fault and arc restriking. The amount of this time-delay, called the dead-time, is chosen based on the system analysis. One of the differences between single-phase and three-phase reclosing schemes is the difference in the dead-time which is considerably shorter in three-phase reclosing.

In some cases of single-phase reclosing, the amount of the induced voltage on the secondary arc is really huge which can make the arc extinction time very long or even infinity. In such cases, one practical method for decrement of the arc extinction time is to compensate the line capacitances and therefore, to reduce the amount of the induced voltage. This is basically done using for-legged shunt reactor, i.e., a three-phase reactor with a neutral reactor. Another possible method is to close and reopen the grounding switches installed on the faulted phase in a fast manner.

In some special power system substation designing methodologies, single-phase tripping/reclosing and three-phase tripping/reclosing are considered independent and non-related. In such designs, it is the role of the protection system ro recognize the fault type, i.e., single-phase or multi-phase and also to introduce the faulted phase(s). In general, three-phase tripping (with no reclosing) are applicable when:

- A single-phase-to-ground fault is followed by an unsuccessful reclosure,

- There is a multi-phase fault,

- There is an abnormal delay in performance of single-phase reclosure task while the fault is recognized as single-phase-to-ground,

- More phases become involved in the fault while the main faulted phase is isolated.

## 2.4 Protection System Operation During Reclosing

When the reclosing task is considered for the protection system, the sequence of operations can be listed as 1- single-phase isolation of the faulted phase and 2- reclosing of the open phase. If the reclosing process is successful, it means the isolated phase is back to operation, successfully, and the normal performance of the power system is expected afterwards. However, if the reclosing is not successful, the next action is either restarting the process by isolating the faulted phase for the second time or refusing the reclosing for the second time by three-phase tripping of the breakers.

Sequence of operation of the protection system during a successful reclosing is shown in Figure 2.1 [74]. As obsrved, there is a delay for operation after the fault instant, called operating time which represents the fault detection delay. Afterwards, another delay is considered, intentionally, called dead time. This time duration consists of 1- opening time, i.e., the time needed for the contacts of faulted phase to separate, 2- arcing time in which the secondary arc fed by the charge of the line and also by the non-faulted phases becomes extinguished and 3- waiting time for reclosing. After the dead time, reclosing command is issued and after a delay which is for the closing time of contacts, the system becomes energized and goes to normal operating mode. The typical value for the dead time setting varies between half a second to one second [3].

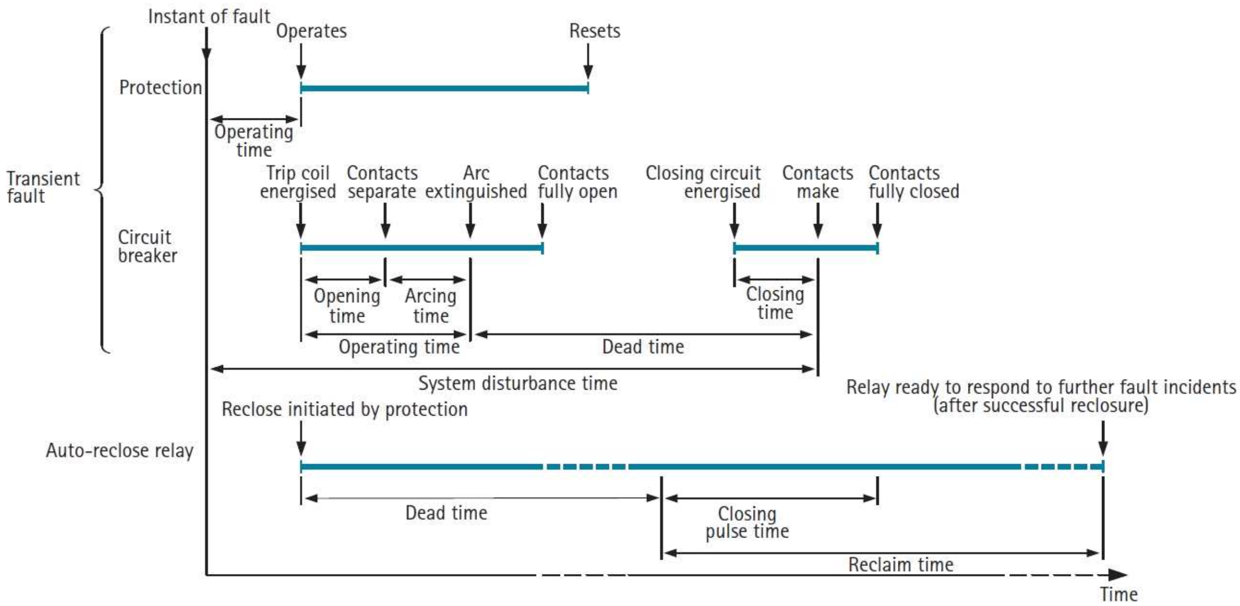

**Figure 2.1: Sequence of operation of the protective relay during a successful reclosing [74].**

Reclosing can be unsuccessful due to permanent fault inception of reclosing before the secondary arc extinction. If the reclosing is unsuccessful, the sequence of operations is more complicated. As shown in Figure 2.2, the sequence of an unsuccessful reclosing is similar to the successful one until the first reclosing. Then, as the fault is not cleared yet, the whole procedure may become reset by starting from the beginning and energizing the trip coil and trying the whole process for couple of times. If any of the reclosing trials are successful, the system can go back to normal operation. However, the number of trials is limited and finally, the last action will be to issue the three-phase trip signal and to de-energizing the whole line.

## 2.5 Application Conditions

### Lines with transformers and series/shunt compensation

In practice, necessary inspections and repairs must be performed for a faulted transformer and it is not a common practice to bring it back to service, immediately. Therefore, the line

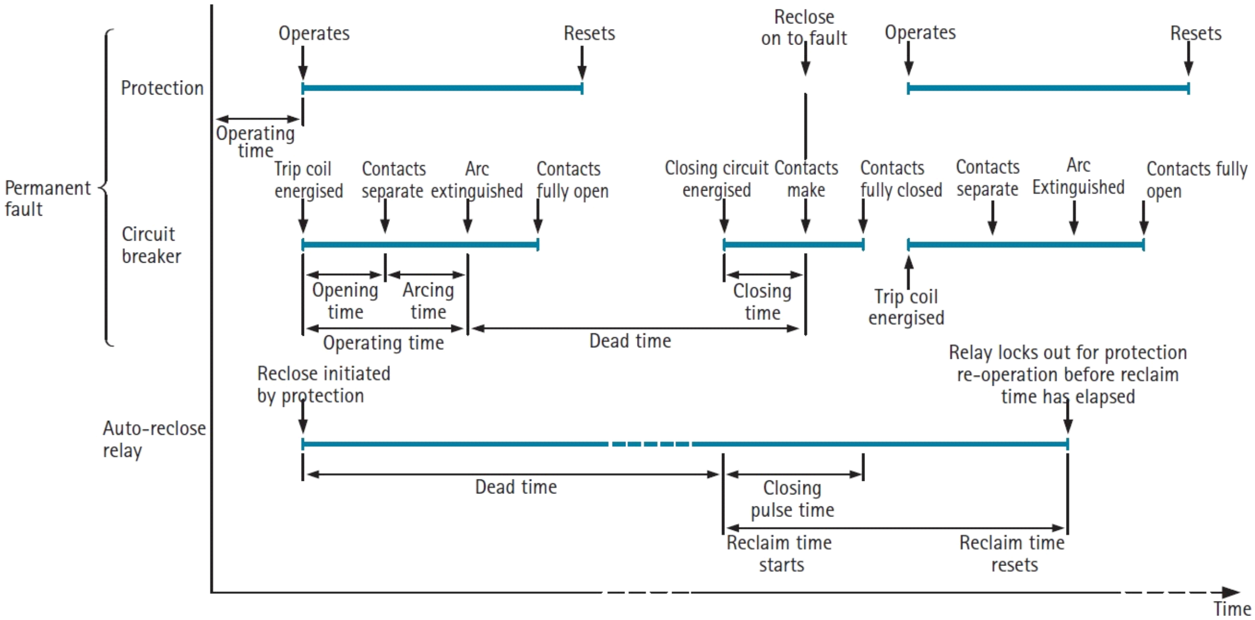

**Figure 2.2: Sequence of operation of the protective relay during an unsuccessful reclosing [74].**

breakers connected directly to a power transformer are not permitted to perform reclosing in case there is a fault inside the transformer. Therefore, by operation of the relays associated with the power transformer, reclosing task has to be blocked. In such cases, the pre-considered lockout relay will be initiated by the transformer relay and the transfer trip signal will be sent directly to the the part considered for reclosure tripping/blocking. In such a process, it is important to get the necessary permissions for terminal breakers' reclosure when fault happens.

For shunt compensated transmission lines, the same points mentioned for transformer-connected lines must be taken into account. In case a shunt reactor fault is detected, it is essential that the line breaker be tripped, remotely, by initiation of direct transfer trip signal. It is generally desired that these shunt rectors stay connected to line while being connected to the grid. In such cases, it is very important that the reclosing be prevented if any fault is detected in the reactor. The only practical solution is to isolate the faulted reactor in advance, provided that the line operation with no reactor is permitted by design of the system.

Another problem that may be arised is the voltage oscillations produced in the transmission lines due to the resonance between the line capacitances and the shunt reactors, following the line isolation. The problem is even more sever if the oscillation frequency reaches the frequency of the power system which will need much more time-delay for damping. Therefore, immediate line re-energization by high-speed reclosure with no delay consideration would not be applicable. At the other hand, the oscillations may cause errors in CVT output and also mall-operation of the relays, specially frequency and voltage.

When there is a fault in the line, series capacitors could be bypassed if they are controlled, automatically. Afterwards, the capacitor bank can be re-inserted, automatically, if the reclosure is performed, successfully. In such cases, reclosure is applicable as switching transients are mostly considered in design of the system.

### Transmission cables and gas-insulated buss

For transmission cables, auto-reclosing usually is not applicable. one exception is when the line is a combination of cable and overhead lines, provided that the overhead part is the major part. Sometimes, even the overhead line and cable have different protection systems and therefore, it is possible not to perform reclosing when the cable is faulted.

When dealing with gas-insulated buses, auto-reclosing is rarely applicable unless it is partially involved in the line relaying, e.g., part of the bus between breaker-and-a-half method breakers. However, the gas-insulated bus portion could have its own relaying system. In such conditions, the bus fault reclosure blocking will be possible.

### Multi-terminal/breaker lines

Regarding multi-terminal transmission lines, assuming that for all terminals, the stability of the system is not disturbed by reclosing on permanent fault and high-speed reclosing is considered for all terminals, It is possible to apply high-speed reclosing. Generally speaking, it is easier to apply high-speed reclosing to a two-terminal line than a multi-terminal one as at least a shorter dead-time will be required.

When applying reclosing to a multi-terminal line, the pilot relaying channel has to be considered. Also, relays must be set for each of the terminals to watch for all possible faults at that spot. This leads to more accurate performance as all terminals are being taken care all together. However, it could be more interesting to perform high-speed reclosing at one of the terminals and monitor other terminals for permanent fault detection.

Sometimes, it is practical to connect the line ends to more than one circuit breakers when dealing with extra high voltage systems. Breaker-and-a-half, double-breaker and ring-bus configurations are some examples for this purpose. For the fault clearance in such circuit arrangements, more than a breaker needs to be tripped.

However, applying the reclosure task to all breakers at the same time can lead to more fault duties. This means, the preference is to perform the line testing by applying reclosure to just one of the breakers and then move to the rest in case of success. This can be double-checked using sync-check and also by monitoring of the voltage. Sometime, the first reclosing is considered as high-speed.

#### Transformers

There have been vast studies performed on power transformer short circuit testing and even there were efforts to modify the standard test circuit to deal with the increasing rate of the power transformer failures due to the fault currents, specially for old transformers manufactured in 1960s. The major damages that fault currents arise in transformers can be mechanical and thermal which are interconnected. The mechanical stability of a transformer depends on factors such as the size of the clamping forces and the quality/dimensions of the materials used for manufacturing. It also depends on the instantaneous temperature of the transformer which is in a correlation with the density of the winding currents.

There are also some studies performed on transformer loading. If the currents in the windings are symmetrical, there would be less amount of stress compared to the asymmetrical cases. During a fault, different components of the transformer are under different stresses and tensions, and therefore, deformations of different types are expected for different parts, temporarily or permanently. In case of a permanent deformations, it means the amount of clamping forces have not been adequate and the transformer is subjected to failure due to future faults.

In the literature, short circuit studies are being performed mostly for the cases of small transformers and in distribution level. There are also similar problems for power transformers in transmission level. However, there are more complexities in studying the effect of reclosing on power/transmission transformers due to number of windings and components involved.

High-speed reclosing also affects the thermal capabilities of power transformers during short circuit. Although, thermal capability is not a very critical factor, it is essential to be studied when high-speed reclosing is considered. The last factor that can affect the transformer life is the loading habits. In some cases, power transformers are subjected to various overloading conditions that can decrease the short circuit capability of transformers and therefore, some restrictions in performing the reclosure must be considered.

### Generators

There could be considerable amount of stress in shafts and other parts of turbo-generators because of operation of switches which has been of research interest, recently. However, there are not that much documented reports showing that harms or damages are actually caused by switching or reclosing operations. But the fact is that, such stresses, even during an ordinary switching operation, have accumulative effects which means simple operations such as reclosing can damage the electrical machines by time even though not be the main reason.

Current and power oscillations/transients caused by opening/closing breaker operations can lead to damage and stress on the generator units close to that point. This will affect many turbo-generator components including stator components of the generator such as winding and core, all the rotary elements in the turbine, generator and exciter, and shaft. The main problem is when for a closed breaker, the average power changes. This leads to torsional stress production, specially in the rotary components of the turbo-generator

To prevent such damages, some limitations must be applied to rate of change of current and power depending on the power factor and the rated power, to be considered just for steady-state conditions. For damping of the oscillations, a delay as long as ten seconds seems adequate and by this assumption, a switching operation can be applied.

Another problem is what happens after clearance of a close-in fault close to generator buses if high-speed reclosure is considered. In such cases, the useful life of rotary components will be used which leads to the machine failure. If high-speed reclosing is considered, for any multi-phase fault cases, the level of stress will be less than thirty faults (which is the worst case scenario) but still the fault magnitude is enough for causing the life losses. High-speed reclosing onto single-phase-to-ground fault may provide less stress than multi-phase faults. Although, the chance of failure is not high for such a fault type, the suggestion is to do studies in any case, including high-speed reclosing effects on the geographically far but electrically near substations as huge amounts of stress might be applied to some possible remote generators.

The main studies for turbo-generator shaft failures caused by torsional oscillations is not easy at all. Such studies may include shaft and rotary system modeling, obtaining fatigue parameters from the torque time response and finally, extracting a considerable screening frame. Any of these steps could be a considerable topic for studying. However, the most essential part now might be the last part, i.e., to find some practical measures to be used in the process of design of power system substations. There are also some research works indicating that it is not feasible to study the shaft fatigue using very ordinary measurements like the rate of change of the current or the active power.

Considering all the mentioned parameters above, utilities have chosen very different strategies in different conditions. In some cases, they have ignored application of high-speed reclosing due to the possible harms, specially for power plant substations and instead, have employed some alternative reclosing schemes such as considering time-delayed reclosing, using sync-check and even not to perform reclosing. One other possible practice has been to apply time-delayed single-phase reclosing instead of high-speed three-phase reclosing.

In case auto-reclosing is not considered, the line will be tripped off and therefore, the parallel circuits will have to carry more loads which can lead to the over loading relay operation. Therefore, it might sometimes be better to accept the risk of the machine failure not to allow the phase angle to increase. In such cases, the reclosure method and the protection relay must be chosen, properly, to decrease the amount of the stress on the rotary parts of turbo-generators. This also needs more precisely selection of the relay/recloser settings as the situation can be extremely harmful and stressful.

**Motors**

Basically, there are considerably large similarities between generators and motors. Therefore, it is expected that most of the items mentioned for generators be valid for motors as well. Considering the rotary elements and the shaft, stresses similar to generators exist in induction and synchronous motors too. Motors in power systems are subjected to big stresses and damages caused by transients and other electric disturbances, and the amount of stress increases by increment of the motor and the associated drive systems. Switching operations in the power system can also cause such stresses on the drive systems by providing transient torques.

Also, similar to the generator issues, the level of stresses mostly depends on the system structure and configuration. The connected transformer impedances will act like buffers and will absorb the disturbances caused by switchings, considerably. When synchronizing with the power system, it is generally easier to perform the synchronization process for motors.

Another point to consider for isolation of disturbances is the protection speed. In fact, for making the reclosing more effective, it is very essential to use fast protection systems to clear the fault as fast as possible. During the reclosing time-delay, called the dead-time, it is also possible to isolate the motor form the rest of the grid, temporarily. In such cases, there is not that much limitations in the number of high-speed reclosing attempts and reclosing rates as large as twenty to thirty are also considerable. In such conditions, it is possible to reclose the breaker of a source, however, it is more desire to predict fast protective devices for the voltage, angle and frequency. Based on the connection of the primary side, it is better to separate the load from the motor by issuing the trip signal or by giving permission to the breakers to operate within a limited angle and voltage range.

Generally speaking, it is not easy to talk about the angle/voltage limits to be considered for re-energization of isolated motors, either automatic or manual. But, there had been some practical values in 1930's for both angle and voltage as $6\circ$ and 25%, respectively. Also in transmission lines, the rate of high-speed reclosing is considerably low and therefore, it will not affect motor loads and fast transfer when there is no supervisory device. In addition, it is fast enough not to allow the residual voltage decay reach toleration limits.

Regarding the design/application personnel, they may consider the factors mentioned above as each of them can cause permanent damages through transient torques, for example. To avoid this danger for motors, it is necessary to study these aspects of the system, precisely.

Larger motors, both induction and synchronous, can potentially cause problems in reclosing. But, in many processes in industry, when there are a huge number of small machines working at the same/close spot, high-speed reclosing can help improving the service offered by utilities. Therefore, they may advice the consumers about merits of this trick and also, in design it can be considered. Electrical energy providers and consumers both may know about the possible system transients during a switching process. In fact, the risk evaluation and possible solutions can be considered only if both sides are fully aware of the situation, in details.

## 2.6 IEEE Guides for Auto-Reclosing

### 2.6.1 Fundamentals and applications

In this subsection, basic ideas of auto-reclosing are described for distribution and transmission system circuit breakers. Usually, the preference is to reclose the breaker after the line protection system tripping operation. In case the fault is not permanent, the isolated line can be brought back to operation and therefore, the system will be able to carry full active/reactive power again, and the obvious results will be increment in the system stability margins as well as offering a more reliable service to the consumers. The same scenario is probable if there is a fault on the substation bus at which reclosing can help to restore the bus in case of a temporary fault.

For having a proper auto-reclosing, consideration of some items is essential including:

1) How successful is the reclosing?
2) How much is harmful to reclose onto a fault?
3) Is the any need for specialized interlocker to avoid reclosing under special conditions?
4) High-speed or time-delayed reclosing?
5) In case reclosing was not successful, how many attempts should be considered?
6) Is there any need for voltage supervision?
7) Is there any need for sync-check?
8) In what conditions, reclosing must be avoided?
9) In multi-terminal lines, which terminal must be chosen for the first reclosing attempt?
10) How to initiate auto-reclosing?

### Auto-reclosing task performed by a reclosure relay

Historically, auto-reclosing task has been done by reclosing relays which were reasonable for some special circuit breakers. But, it is possible to perform the reclosing task by any number of processes and devices which has an input to get if a breaker is closed or opened and even how the tripping signal is applied, either by a relay or manually.

Generally speaking, it is possible to perform auto-reclosing task in one of the following conditions:

1) Reset condition: In this condition, the breaker is closed at first. Then, the auto-reclosing task waits for receiving a signal for starting the timing for reclosing following the breaker's opening.

2) Cycle condition: In this condition, the breaker is open and the auto-reclosure task is timing to the set time for closing the breaker. The other case is when the breaker is closed after a successful auto-reclosure, timing to the set time for the purpose of returning to the reset condition.

3) Lockout condition: In such a condition, the auto-reclosure is in the close position and is locked in that condition. The reason is reclosing has happened at least once before, however, the relay has issued the trip signal again. In this condition, the breaker will stay at locked condition and the reclosing task can not be performed any more. The only way to reclose the breaker in this condition is manual operation, either locally or remotely (local-manual or remote-manual).

4) Power-up condition: In this condition, the associated relay reads the input signals and the breaker situation to determine the true condition and then will move to that condition. For example, in normal conditions when no special input signal is initiated, if the breaker is open, it will move to the lockout condition, and when it is closed, reset is the true condition.

If the auto-reclosure task is in the reset condition, this task may be performed in two possible ways for starting the timing to the first attempt which is based on the logic scheme or the design of the device:

- To detect the breaker's opening, which will start the first reclose/open interval timing,

or

- To Detect that the breaker has been tripped by the protection device, and to confirm the breaker opening afterwards, which will start the first reclose/open interval timing.

During opening of a breaker which is controlled, the reclosing protection device will start timing to the first auto-reclosure attempt. Such a transition from timing to the initial auto-reclosure attempt will change the reclosing task from the reset condition to the cycle condition. While completing this delay, the reclosing protective device will close the output contact to initiate breaker closing and will confirm that the breaker is been closed due to a condition change of the input of the breaker status. If the breaker could not perform the closing task during a preset time, the reclosure protection device might move to lockout condition, continue to assert the close output or release the close output, based on the design of the reclosure protection device and program.

During the closing of the breaker, the reclosure protective device will start the reset timer which is called reclaim timer too. When breaker stays closed, means a temporary fault was detected, the protective device will continue timing to reset. When the reset time-delay is completed, the auto-reclosure task will return to the reset condition and will remain there for the time the breaker stays closed.

For the cases of no fault clearance and the protection method shows the second tripping signal, the reset timer is stopped and reset, and the reclosure protective device starts timing to a second auto-reclosure attempt provided that the relay is set or programmed for more than one auto-reclosure attempt.

Following any of the attempts for auto-reclosing, in case the breaker stays closed for a time as long as the timer of the reset delay, the reclosure relay will return to the reset condition.

For the permanent fault cases, if number of the reset auto-reclosure attempts finishes, the next condition of the relay would be lockout while the breaker will stay open. This condition of the reclosure task will be kept until the breaker becomes closed by other methods, e.g., manual. Based on it's design, the protective device might reset right away of after a time-delay. The amount of the delay can be equal to the successful reclosing reset delay or can be different.

For permanent fault cases, if the breaker is closed, manually, but becomes open again, the manual reclosing must be blocked. Similarly, it will be reasonable to avoid the reclosure device from resetting provided that the breaker closure leads to the protection system pick up and starts timing to trip. In case the tripping time-delay be larger than the reset time-delay, a pumping condition of the breaker may happen which finally can cause the damage for the system equipment and breaker, and also some other hazards will be possible.

### 2.6.2 Auto-reclosing for transmission systems

#### Transmission systems overview

Loosing a transmission line in the power system will have a considerable effect on the system's reliability and economics. Auto-reclosure is been performed in a line for minimizing this effect. Time-delayed and high-speed reclosing methods are effectively and widely employed. The access to a huge amount of information using intelligent relaying system and SCADA will permit more selective reclosure tasks which can makes the reclosing a more successful operation at one hand and can reduce the rate of damage to the power system due to reclosing onto permanent fault at the other hand. By increasing rate of adaptive reclosing techniques, controlled breaker closing and single-phase trip application, the reliability of the system has improved and the negative effects of auto-reclosure failure has decreased on the system.

Additionally, beside the auto-reclosure methods, there are more system elements that need to be considered regarding their impacts on the reclosure application. As an example, in a line which needs reclosing supervision by sync. machine. For the system effect reduction, reclosing can be applied just to one of the line ends. There are other elements that may affect the reclosure are transformers, motors, generators, reactors, capacitors, multiple-terminal lines, etc. The auto-reclosing methods and the system element that may affect the reclosing of the breakers in a transmission line are discussed in the following in details.

### 2.6.3 Auto-reclosing methods

**High-speed auto-reclosing**

High-speed auto-reclosure scheme means to automatically close a circuit breaker with no predetermined delay more than what is adequate for deionization of the arc (see IEEE PSRC Report [2]). In order to have successful operations at auto-reclosing attempts for temporary faults, it is suggested to consider high-speed auto-reclosure schemes.

There are some benefits in application of high-speed reclosure including reduction in outage time, improvement in security and integrity of the system, higher probability of some recovery from multiple contingency outages and preserving machine stability.

When high-speed reclosure is considered, there are also some limitation considerations on system equipment, operating practices and configuration. Major limitations are as follows:

- Configuration of the system has to be able to hold the angle difference of two sides the opened breaker with a suitable variations.

- Voltages induced from circuits in parallel must not sustain the faults.

- For permanent faults, the system must be stable after a high-speed reclosing.

- High-speed protection must be considered to trip at all terminals of the line, simultaneously for all fault cases to provide enough time for deionization of the arc path.

- Evaluation of any harm to rotational power devices which are connected to the power system must be taken into account.

For a successful high-speed reclosing, the path of the arc must be sufficiently deionized so that the insulating properties can be re-established prior to re-energizing the transmission line.

There are some factors that are effective for a successful high-speed reclosing including:

- construction and design of the transmission line,
- time of the fault clearance,
- magnitude of the fault current,
- transmission line location compared to human-made or natural of any sources of danger,
- weather condition,
- lightning stroke various components,
- inductive and capacitive coupling with the circuits in parallel connection,
- instantaneous voltage value at the moment of the line re-energization,
- some other factors such as series capacitors, shunt reactors, tapped loads, etc.

### 2.6.4 Auto-reclosing settings

**Number of reclosing attempts**

The simplest auto-reclosure task in terms of number of attempts is single-shot reclosure, i.e., to reclose the breaker only once. Single-shot reclosure can be performed either delayed or high-speed.

The other option is to perform reclosing more than one time which is called multiple-shot reclosure. For performing multiple-shot reclosing, many factors such as the system stability considerations, possible system equipment failure due to fault currents, possible damages to the customer and other effects, etc., must be taken into account.

### Dead-time

There are some items to be considered for reclosure attempting when the relay has issued the trip signal. It is necessary to bring the faulted phase back to operation as fast as possible. However, if it is performed too early, considering a temporary fault case, there is a chance that the associated arc is not extinguished yet, and therefore the reclosure attempt will be unsuccessful as the arc will restrike.

During an arc restriking, the arc path, which is not deionized yet, will reconduct after an unsuccessful reclosure. The time interval which is needed for deionization is a function of the spacing of the conductors, the voltage level, the weather condition and the fault current magnitude [81]. A practical value for a minimum needed time-delay to avoid arc restriking can be obtained from (2.1) [5].

$$t = 10.5 + V_L/34.5 \tag{2.1}$$

in which $t$ is the time-delay, in power system cycles, and $V_L$ is the line rated voltage, in $kV$.

For some circuit breaker types, there is a need for adding a delay to either the auto-reclosure time or the breaker time to reach the deionization time of the arc. As an example, there are breakers available capable of reclosing in two to three cycles. For using these breakers, it is required to add a delay to prevent from reclosing while the arc is not extinguished yet.

The deionization time of the arc may increase even more in case single-phase tripping is employed and in circuit phases keep the arc on, or when a side parallel line supports the arc to be sustained.

### Auto-reclosure reset-time/lockout

After a successful auto-reclosure, the protective device must be reset and become ready for the next possible fault inception operation. This is done by a timer called reset timer. In case of a successful auto-reclosure, the reclosing protective device will go back to the rest condition after the reset time-delay. The reset time-delay selection depends on the fault nature and the expected fault clearance time. As an example, the chance of re-tripping and therefore, another reclosure will decrease if a longer reset time-delay is chosen. If the delay is shorter than the time needed for the arc extinction, then another tripping/recloser might happen which has its own effects on the system and the consumers. At the other hand, if the reset time is too long, some lockout operations might happen although excessive reclosing task will be avoided.

In case the auto-reclosing operation is unsuccessful, the protective device will move to the lockout condition in order to avoid the interruption device from automatic closing. Auto-reclosure is either locked out or terminated afterwards the predetermined attempts to the line re-energization are tried and completed, unsuccessfully. The lockout state can be beneficial to prevent too many wear on the relay from multiple operations caused by common line temporary faults, such as tree branches broken by wind, etc.

There are auto-reclosure systems which are capable of being programmed to prevent sequential auto-reclosure operations by providing a lockout situation in case the fault number reaches a predetermined value in a time window. For example, a 3-shot auto-reclosure method can be programmed to lockout in case 7 faulted cases occur in a 30-minute time window.

Another benefit of lockout is to prevent a relay from unwanted auto-reclosure while the closed condition is applied to the line, manually. This condition will be applied, automatically, if the breaker is manually closed, either remotely or locally, and the breaker will remain closed for a predetermined time period. Therefore, no fault will exist at the breaker closing time.

### 2.6.5 Auto-reclosing blocking

Auto-reclosure task is blocked typically in one of thee following conditions:

1) Operator tripping: Auto-reclosure will be blocked in case the breaker is opened either by remote control or manually, at the station . When this kind of opening happens to a breaker, the preference is to be under the control of operator for for closing.

2) Voltage supervisory monitoring of the line: Auto-reclosure could be blocked when there is voltage on the line. This kind of supervisory monitoring is considered usually when the line is connected to large generators, motors or other solid sources. Auto-reclosure will be blocked when these sources from downstream maintain the voltage on the line to avoid probable damages to the related rotary devices. The reason for the failure is establishment of an unwanted system operation condition or out-of-phase energization.

3) Fault in an underground cable, a transformer or a bus: This kind of fault is naturally permanent most of the times and a breaker's auto-reclosure can deepen the damage to that equipment. Therefore, auto-reclosing's both benefits and risks vs. blocking the auto-reclosure must be considered.

4) Unbalance of voltage: Auto-reclosing may be blocked when an unbalance is detected in the substation voltage. An open phase in the source-side may lead to such unbalances. Service restoration when the condition is not balanced can lead to customer equipment damage.

5) Circuit breaker failure protection: Circuit breaker failure protection basically trips all breakers which are directly connected to the bus or connected to the bus through the differential protection of the bus. Auto-reclosure of the breakers will be blocked till isolation of the failed breaker and restoration of the bus.

6) If closing of breaker fails: In case a breaker fails to close following an auto-reclosing attempt (auxiliary contact 52), closing take more time than expected, or detection of an open circuit (discontinuity), auto-reclosure attempts will be blocked to avoid further damages.

7) High-current faults: For blocking of auto-reclosure for close-in high-current faults, a high-set instantaneous element may be employed. This blocking type is usually applicable when the fault reaches the rating of damage of the generator transformer or other equipment. The fault type is probably permanent in the exit cables or equipment of the substation.

8) Cumulative operations lockout: This case is considered where the duty of fault approaches the preset rating of circuit breaker for auto-reclosure blocking after a predefined operation number till performing the necessary maintenance and inspections.

9) Receiving a transfer trip: Sometimes, a timer is initiated when a transfer trip signal is received. The reclosing sequence operation is avoided in case of the timer's time-out.

10) Backup tripping: A zone 3 distance zone (overreaching) employed for backup protection can be used for reclosure disabling as it shows a protection failure of another zone.

11) Under-voltage or under-frequency load shedding: Auto-reclosure is basically blocked for feeders tripped by load shedding.

### 2.6.6 Operation considerations

#### Lines with underground cables

For underground cables, faults are mostly of permanent nature and auto-reclosing must be applied according to the following guidelines. Lines that use underground cables partially and not for the whole length show special concerns for utilities to consider auto-reclosure.

If the line is made of cable, completely, auto-reclosing must be avoided. It is not needed to put the cable at risk of more damages and subject the power transformer of the substation, circuit breakers, buses and other parts of the power system to more potential damages and stresses. According to an IEEE Power System Relaying Committee Report, auto-reclosure application for underground cable lines is not recommended [2].

Based on the length and location of the cable portion compared to the total length of the line, utilities sometimes consider this feeder type as completely overhead and apply their own auto-reclosing practices. Some other utilities may consider a single-shot auto-reclosure to evaluate the line for a temporary fault or other possible conditions that might lead to misoperation of the relay. The other solution can be to use a sectionalizer for isolation of the cable part and a modified version of the auto-reclosure schemes, simultaneously. If the line is partially overhead and partially cable, auto-reclosing can be applied if absence of fault in the cable portion can be determined [2].

It must also be considered that which end of a combined line is to close-in as the first auto-reclosure attempt. Overvoltage studies based on a transient network analyzer might need to be performed to check for any possible problems may happen in case auto-reclosing is applied to the line. Such studies could be extremely essential in case a shunt reactor is connected to the line for controlling the effect of capacitances of the cable which increase the line voltage, called Ferranti effect [1, 2].

#### Auto-reclosing following bus faults

Auto-reclosure task following a fault on bus is sometimes applied to return the system to normal condition. The decision to use auto-reclosure task following a fault on a bus is made as a result of a trade-off between the reclosing consequences into a bus fault and the effect of an extended bus outage. As the buses of the power system usually end in couple of elements, both the bus fault and the outage of the bus might have considerable effects on the operability and the security of the system. The merits of auto-restoration of a bus after a temporary fault are usually evaluated versus the possible risks if the fault in fact is permanent. Some possible risks can be mentioned as probable damages to basic equipment, specially turbo-generators and transformers, and impacting the stability of the system.

For substations of type of open-air, in some cases, auto-reclosure on the breaker of a bus is done when protection device operates for the bus faults. Generally the auto-reclosure is delayed in time, e.g., for five seconds, and there is not supervision unless if buses could be connected to other sources. Such sources can be distributed on the transmission line or feed other transformers. An under-voltage relay might supervise the auto-reclosing in such conditions. Other conditions of the system may need for the auto-reclosing blocking, e.g., under-frequency, transformer differential, breaker failure, etc.

Similar to overhead distribution or transmission lines, a bus is subjected to faults external causes such as insulator flash-over, animals, lightning, etc, when employs open-air primarily as the insulation medium. An open strain bus or outdoor open rigid bus are examples of this bus type. If these fault types are cleared, immediately, a successful reclosure with no need for inspection would be probable. This probability may be affected by spacing of the conductors which itself depends on the voltage level of the bus. Temporary faults incepted due to presence of an animal are more likely to happen in distribution networks.

Open-air buses are not usually that exposed to public due to presence of substation barriers, fences, etc. However, this availability is lower for transmission lines. Therefore, application of reclosing in open-air buses could be considered as a greater threat for public that transmission line reclosure. Another danger of reclosing of open-air buses is for substation personnel during maintenance and other routine tasks. This second danger can be decreased by using the function of reclose cutoff which blocks the auto-reclosing during routine tasks, etc., in the substation. This generally will be similar to the live-line maintenance function which is usually considered for transmission and distribution circuits.

It is possible to protect a bus from external interference, physically, by an appropriate insulation method. Isolated phase bus, SF6 switchgear, metal-clad switchgear and insulated cable are examples of this kind of isolation. If a fault happens ion such buses, it will not be that likely to be cleared by itself and will not be beneficial to apply auto-reclosing to such kind of buses.

When auto-reclosure scheme is applied to a bus fault, it is possible to consider single-shot reclosure protective device for one of the breakers connected to the bus, to perform the breaker reclosing in case of dead-bus-live-live condition. In practice, it is common to choose a breaker for performing the testing task for the bus that will have the lowest effect on the system in case of permanent fault. Most of the times, it is the live circuit which has the lowest short-circuit capacity. But, the differential relay of the bus must be sensitive to the downgraded fault current level so that for permanent fault cases, tripping becomes possible. One solution for this is to decrease the pickup current threshold for a short time period during de-energization of the bus. Another solution can be considering an instantaneous over-current relay dedicated to reclosing. For the purpose of choosing a proper level of sensitivity for reclosing protection of the but, the effect of inrush currents provided by VTs and other bus equipment must be taken into account.

While reclosing the breakers connected to one bus, if the reclosing operation was successful for the first bus, auto-reclosing can be performed for the rest of the breakers of the bus considering the limitations and permissions issued for the live-bus condition.

#### Circuit breakers

A minimum amount of time between initiation of tripping and reclosing signals is needed for all interrupters and circuit breaker mechanisms. Such a gap in time is essential for the breaker insulator to stabilize the internal insulator, otherwise, the breaker will not be able to tolerate the rated electric field and will collapse in case the breaker reopens the circuit due to presence of fault. If this time delay is not included in the design of the breaker, it must be considered by the utilities and protection engineers. The minimum needed time is defined by the manufacturer of the circuit breaker.

The other factor to be considered regarding circuit breakers is the time needed for recharging the springs, compressed air and other mechanical components of the breaker for the next operation. The subsequent operation can not be performed, properly, if the recharging time is too short. In such conditions, an interlock scheme might be employed by the breaker so that adequate amount of energy is restored for the next operation.

Such features are mentioned in the associated standards for air and oil breakers' magnetic circuits in which the time gap between consequent faults is too short for strength recovery of the dielectrics. Such de-rating factors might not be needed for vacuum or SF6 puffer circuit breakers because for these technologies, the recovery time of the dielectric is shorter than open-interval time. But, if the duty cycle of the circuit breaker is different from the standard requirements, it is recommended to consult the manufacturer about the issue. For the case of oil circuit breakers, the capability for the circuit interruption is dependent on the fault current magnitude and the sequence of reclosing.

It is essential and required for circuit breakers to have a capability of interruption based on the standard duty cycle, Rated Standard Operation Duty. According to IEEE Std C37.04, the standard duty cycle is defined as two operations with a 15 s of interval between them or in other words, $CO + 15s + CO$, where $CO$ means close-open. If the time interval between operations is longer than 15 s or the setting of duty cycle characteristic of a circuit breaker is performed for more than two operations, the interrupting capability rating of the breaker will be modified. One or two of these characteristics can efficiently be incorporated by the auto-reclosing duty cycle to derate or reduce the interrupting rating. For allowing the recovery of the dielectric of the circuit breaker insulations, such derating is required.

#### Lines with automatic sectionalizing

For decreasing the amount of loads affected by short circuit fault, auto-sectionalization option might be used by radial lines which are connected at both ends to source buses, and distribution feeders. Also, for isolation of the faulted section of the line and therefore, the auto-reclosure permission for service restoration for the non-faulted sections of the line, automatic line sectionalizers or similar methods might be employed by radial distribution circuits.

Automatic sectionalizing might also be used in transmission lines with networked structure and tapped loads for improving the quality of the service to the loads. In this case, on each end of the line a potential device is required as an ideal practice to allow auto-reclosure voltage supervision. But, it is possible to coordinate the line-source breaker's auto-reclosing task with sectionalizing method to allow sectionalizing following the first shot and before the second shot of the auto-reclosing. It is better to perform the first shot of the auto-reclosing prior to sectionalizing. By this, it will be possible to restore all parts of the transmission line right without any delay. For this, the fault has to be temporary. In case of failure of the second shot, the line will be locked out as there would be an indicated fault between the sectionalizing spot and the source.

There is a similar reclosing considerations for networked or radial lines with loads under application of auto-transfer methods. Such methods are employed for transferring to reserve or second supply connected to another feeder or line. Timer of transferring will be initiated as a result of the primary supply loss. The transfer will be aborted and the transfer timer will stop and reset if the fault of the line is temporary and the primary supply is re-energized, successfully, before the time out of the transfer timer. Therefore, for coordination with the transfer time delay, the first reclosure attempt must be made with a short time delay. The second attempt should not be made till the auto-transfer method has time to perform and finish the transfer function in case the first reclosure attempt is not successful.

### Adaptive auto-reclosing

Nowadays, it is possible to implement many reclosure methods that can be adapted to different conditions including time of the day, heavy load or weather forecast. Such methods mostly depend on both the final consumer and the system. Following are some examples of installed and proposed adaptive reclosure methods:

1) A method disables or enables fuse saving by performing multiple-shot reclosure during weekends and evenings. The worst case scenario for an industrial customer is to experience any interruptions in the facility operation. Therefore, during operation hours it is not allowed to do fuse saving.

2) Operators are allowed by the method to disable or enable auto-reclosure depending on the weather conditions. There are some historical data provided by utilities showing that most of successful auto-reclosure operations have performed during thunderstorms.

3) Controlling the sequence of auto-reclosure on a line including downstream reclosers, using overcurrent element. In such method, an overcurrent relay contact is being closed when the current level reaches to a value associated with the downstream fault current. In case this contact is closed, it can be concluded that the downstream recloser has operated. This leads to the reclosing relay skip the initial reclosure attempt if ultimately the breaker is called on for the fault interruption.

4) Application of overcurrent element for detection of the load level to show if a consumer has started a large motor and it is desired that the recloser does not operate for such a condition.

5) Application of an impedance element or an overcurrent element of high-set for determination of any fault inception in the cable portion, between the transition to overhead and the breaker. For such a case, reclosure must be avoided.

6) Alarm of trip circuit monitor or breaker failure trip. In case a relay issues the tripping signal while the breaker does not open for during the time it should, for example 6-10 cycles, auto-reclosure is better to be blocked. It is also better to use an alarm for trip signal monitoring to block the reclosing operation in case the trip circuit continuity is detected by a logic circuit.

7) When a breaker fails to close. In case an auto-reclosing attempt is made but the breaker stays open during the pre-calculated closing time, more reclosing attempts must be blocked.

8) Postpone the auto-reclosure to the after the arc extinction. This needs the application of line-side voltage transformers [5].

9) For multi-phase faults, auto-reclosure methods must be blocked [5].

10) Perform reclosing operation immediately, if the trips are undesirable. Immediate reclosing initiation can be performed by a substation SCADA computer if the dat from fault shows there is a incorrect operation for relays.

11) If sync-check is employed for reclosing, change the sync-check angle. This angle can be set if there is a considerable disturbance in the system. But, there might be not enough speed ot capability of the algorithm to perform a fast angle calculation when there are rapid changes in the system conditions [5].

Having used smart breakers, it is feasible to set the number of permitted reclosing attempts or the reclosing time delay using the records of the operations of the breaker. As an example, in cases there are too many operations in a limited time interval, it might be better to increase the delay time length or to block the reclosing. But for faults with smaller currents might be performed with shorter delays. For faults with high resistances it is also better to block the reclosing. It is also possible for a computer to rotate the reclosure task for breaker-and-a-half and ring bus structures.

Using adaptive reclosing, it will be possible to set reclosure mode for different lines. Using WAN, wide area network, the dispatcher of the load can have communication with other substations and perform the online reclosure setting, i.e., using the current situation of the system.

### Time-delayed auto-reclosing

For the time-delayed reclosing scheme application some points should be considered as follows:

- Fault arc re-establishment probability reduction by increment in the predetermined time-delay.

- Time-delayed reclosure is useful provided that adequate protection system is not applicable for all of a transmission line terminals.

- The wanted re-establishment time of the system circuit, recognizing the number of terminals of the line, stability studies, requirements of the system, kinds of the loads and damping factors of the system.

Load-flow and stability studies must also be performed in case sync-check for unusually long fault-clearance time is needed. Sometimes, double-checking of the phase difference and being synchronous before application of the reclosure function is unnecessary due to the number of parallel paths with the faulted line.

Considering the time-delayed reclosure using the fastest reclosing schemes, usually only one of the line terminals is being reclosed each time for re-energizing the line. Also, relays for voltage monitoring are usually considered for determination of the system voltage presence on one of the breaker sides. Therefore, the user will be able to select the conditions of the system voltage in advance. Sometimes, users allow a delayed reclosing only when the phase difference between the contacts of the open breaker in a predefined range and stays synchronous with for a desired amount of time which is performed by sync-checks.

### Stability considerations

While considering high-speed reclosure schemes to increase the transient stability margin of the system, restore the important loads/customers, or restore some required interconnections in the system, it must be noted that there are both merits and risks together. For example, if the fault is permanent, there is absolutely no merit in performing the reclosing. For this purpose, it is recommended to perform stability analysis on the system.

### Switching surges

High-speed auto-reclosure schemes must not be employed if transient analysis studies on the voltage show that there is a chance of switching surge production with magnitudes reaching the design levels of the equipment.

### Time considerations

Generally speaking, regardless of series capacitor applications, the initial reclosing dead-time for the three-phase reclosure methods is between 0.5 to ten seconds for different systems and conditions. In power system transmission lines, the time delay for reclosing usually calculated by transmission line design engineers. For this purpose, stability analysis must be considered so that the possible oscillations of the system after disturbances be damped, properly. Also, transient stability considerations of the system must be covered by auto-reclosing function.

### Single-shot and multiple-shot auto-reclosing

Single-shot reclosure means either high-speed or time-delayed reclosing the breaker during a reclosing period, only for once. the other choice for reclosing, multiple-shot, is to reclose the circuit breaker during the considered duty cycle for more than one time.

A typical reclosure at a line terminal may include a high-speed reclosing which is not supervised by either sync-check or dead-line relaying, a time-delay reclosing which is supervised by dead line voltage protection. A successful reclosing would allow the other line terminals close by a time-delay, supervised by sync-check protection.

Generally speaking, modern high voltage and extra high voltage breakers are able to operate in any multiple-shot reclosure period, practically. Some special issues regarding the circuit breaker elements including opening or closing resistances, pressure of the available gas, air or fluid, or factor of derating based on the expected fault current and number of fault interruptions in a predefined time period in total can limit the effect on duty cycles or repetitive performances.

Before applying the multiple-shot reclosing, the user must make sure there would be no danger of system instability or other possible limitations in case the fault is permanent. As an example, multiple-shot reclosing is not practical when large motors or turbo-generators are danger of mechanical damage is probable. Also, it is more desirable to postpone the second reclosing shortly so that all transients of the previous reclosure are damped, properly.

Historically, single-shot reclosure of transmission lines has been in practice. But, later, multiple-shot reclosure also became desirable and practical. This is mostly due to the fact that most of the power system substations were not under supervisory control, traditionally. In such substations, it is not practical by the personnel to perform the second reclosure after one unsuccessful one. But, at substations where dispatching is performed by the personnel, an unsuccessful single-shot reclosing may lead to a later outage which is not necessary.

However, at those locations where an employee must be dispatched, a delayed outage may unnecessarily result if a single-shot reclosure is unsuccessful. About 25% and 10% of utilities have records of successful 2nd and 3rd reclosing functions, respectively. But at the same time, breaker constraints and reset time of the reclosing relays has to be taken into account not to have problems in the result of additional operations of the breakers in a predefined time duration. If there is no desire for single-shot reclosure schemes to be replace by multiple-shot methods, a considerable success may be achieved by single-shot reclosing schemes just by increasing the time-delay.

### Single-phase tripping and auto-reclosing

The difference between single-phase and three-phase reclosing is that in single-phase reclosing, tripping and reclosing is performed only to the faulted phase. In single-phase reclosing, electrical power can be transfered through the non-faulted phases while the faulted phase is open. This leads to decrement is rotor-angle drift rate between the synchronous machines and increases the stability margin of the system. The only major problem is affection of the ground protection of the system due to circulation of the ground currents.

During fault clearance in a single-phase reclosing, due to capacitive an also inductive coupling of the phases, there is an induced voltage in the de-energized line. The magnitude of this voltage depends on the mentioned capacitance values and therefore, on the transmission line's configuration and physical dimensions. This voltage may causes the arc to stay on for a longer time period while the faulted line is isolated. In this case, the arc is called the secondary arc.

The main purpose of considering the reclosing time-delay is to give enough time to the secondary arc to be extinguished and therefore, to avoid reclosing-onto-fault and arc restriking. The amount of this time-delay, called the dead-time, is chosen based on the system analysis. One of the differences between single-phase and three-phase reclosing schemes is the difference in the dead-time which is considerably shorter in three-phase reclosing.

In some cases of reclosing, the amount of the induced voltage on the secondary arc is really huge which can make the arc extinction time very long or even infinity. In such cases, one practical method for decrement of the arc extinction time is to compensate the line capacitances and therefore, to reduce the amount of the induced voltage. This is basically done using for-legged shunt reactor, i.e., a three-phase reactor with a neutral reactor. Another possible method is to close and reopen the grounding switches installed on the faulted phase in a fast manner.

In some special power system substation designing methodologies, single-phase tripping/reclosing and three-phase tripping/reclosing are considered independent and non-related. In such designs, it is the role of the protection system ro recognize the fault type, i.e., single-phase or multi-phase and also to introduce the faulted phase(s). In general, three-phase tripping (with no reclosing) are applicable when:

- There is a multi-phase fault,

- AG fault followed by an unsuccessful reclosure,

- Abnormal delay in performance of single-phase reclosure task while the fault is recognized as AG,

- More phases become involved in the fault while the main faulted phase is isolated.

### Blocking of auto-reclosing

There are different methods for blocking auto-reclosure schemes in transmission lines and depend mostly on the design criteria of the power system. As examples of conditions when reclosing should or must be blocked the following two items can be pointed:

- When there is a three-phase fault: Three-phase faults are not common on extra high voltage systems (345 kV and above). But when there is a three-phase faults, it is not expected to be temporary. Such faults are mostly caused by ground straps missed after the breaker maintenance or downed line structures. This means it is better to block a three-phase reclosure operation if there is a three-phase fault. As temporary three-phase faults are more likely for transmission lines of lower voltage levels, auto-reclosure task might be interesting if generation system stability are not affected, negatively.

- Out-of-step and power swing conditions: Auto-reclosing should be blocked when out-of-step or power swing condition is detected. This is because auto-reclosing can further stimulate an system which is already disturbed.

### Multiple-breaker line terminations

Regarding multi-terminal transmission lines, assuming that for all terminals, the stability of the system is not disturbed by reclosing on permanent fault and high-speed reclosing is considered for all terminals, It is possible to apply high-speed reclosing. Generally speaking, it is easier to apply high-speed reclosing to a two-terminal line than a multi-terminal one as at least a shorter dead-time will be required.

When applying reclosing to a multi-terminal line, the pilot relaying channel has to be considered. Also, relays must be set for each of the terminals to watch for all possible faults at that spot. This leads to more accurate performance as all terminals are being taken care all together. However, it could be more interesting to perform high-speed reclosing at one of the terminals and monitor other terminals for permanent fault detection.

Sometimes, it is practical to connect the line ends to more than one circuit breakers when dealing with extra high voltage systems. Breaker-and-a-half, double-breaker and ring-bus configurations are some examples for this purpose. For the fault clearance in such circuit arrangements, more than a breaker needs to be tripped.

However, applying the reclosure task to all breakers at the same time can lead to more fault duties. This means, the preference is to perform the line testing by applying reclosure to just one of the breakers and then move to the rest in case of success. This can be double-checked using sync-check and also by monitoring of the voltage. Sometime, the first reclosing is considered as high-speed.

### Sync-check

Sync-check or synchronism-check is employed for supervision of electrical connecting two parts of a system which are connected through ties in parallel with the path being closed [5]. Sync-check determines if the voltages of two side of the circuit breaker are closed enough, and the frequency difference (slip) and the phase angle difference between them is within a acceptable limit for a specific time interval. If the condition is not desirable, closing the circuit breaker might have a harmful effect on equipment such as circuit breakers and shafts of turbo-generators, and might also affect stability of the system as well. The setting of a sync-check relay is performed to prevent reclosure when reclosing under live-line/live-bus conditions will harmfully affect system operation and equipment.

Sync-check protection devices react to three main features related to the voltage phasors on either side of the open breaker including magnitude difference, and phase angle difference and slip. In some protection devices, specially microprocessor-based technologies, settings limitation can independently be applied to each of the characteristics. In other protection devices, specially old electromechanical designs, the characteristics are dependent so that separate limitations can not be applied. characteristics.

Studies show that the effect of the reclosure is lower than closure into a fault for the most of limits of sync-check angle employed by utilities and therefore, is not of concern. But, when taking into account the possible effects on turbo-generator systems, it is desired to assess the effect related to deliberate reclosure in a different manner than the effect of unavoidable faults. The critical trade-off is to balance the possible effect related to the reclosure under violated system conditions versus the possible effect on reliable operation of the system if reclosing is prevented by the sync-check setting.

In case the angle difference of two sides of the breaker is not in the sync-check angle limit, initially, it can be possible that the angle limit will be satisfied and met in a short time as a results of changes to the system structure, e.g., reclosure in other transmission lines after a considerable system disturbance or changes in generation dispatch. Logical circuit might disable the auto-reclosure task in case appropriate auto-reclosure conditions are not met during a predetermined time interval. The other possibility is that the logic might wait for acceptable conditions to be met, indefinitely. Both methods have benefits and drawbacks. Limiting the time interval in which a live-line/live-bus reclosing attempt is permitted will avoid having the reclosing attempt performs in future in a potentially undesirable and unpredictable way. But, this operation extends restoration of the system. The operation of indefinitely waiting will be beneficial for decrement of the restoration time after a major disturbance by permitting reclosure as soon as possible which is when the acceptable conditions exist. But, the unexpected breaker closing during system restoration may disturb the generation and load balance. This can lead to extend restoration time and subsequent outages. When this operation is employed, it has to be based on analysis of the potential conditions of the system for which auto-reclosing may happen for the purpose of managing the risk to system equipment and reliability. Regardless of which operation is employed, operators of the system are required to know how their system is designed and need to be trained adequately to act during a system-wide outage event in an appropriate manner.

### Leader-follower auto-reclosing of transmission lines

The leader-follower auto-reclosure method is common practice in auto-reclosing in transmission lines. Definition of the leader is the terminal of the line which performs auto-reclosing, first, and the follower is the terminal of the line which performs the reclosing, second. This is a different concept from the concept of lead-follow terminology employed for description of different breakers of a multi-breaker terminal.

In leader-follower scheme, the weaker source of the two ends of a transmission line is usually chosen as the leader end and is employed for testing of the line. This practice is employed to verify the fault clearance when imposing the minimum amount of disturbances to generation. But, it must be considered that the system testing from the weaker end might lead to a larger drop of voltage and also disturb critical loads. If auto-reclose attempt at the leader end is successful, auto-reclose attempt of the follower end which is supervised by sync-check and/or voltage functions, is then enabled and auto-reclosing is performed. This technique may be employed for restoration of either a tie line between two systems or a network line section.

A network line, i.e., a line at which the terminals are properly tied together by other parallel lines, might employ just the voltage presence for initiation of auto-reclosure task while there are adequate other network connections so that the difference of the voltage phase angles across the open breaker is small. A tie line, i.e., a line where there are no other parallel lines connecting the system tightly together, usually needs a sync-check relay to be applied so that the voltage phase-angle difference across the breaker lies in appropriate ranges.

Auto-reclosing tasks in EHV systems are basically the same regardless of application of series capacitors. But, overvoltage protection might be considered as well in case the voltage of the follower terminal is too high to allow a safe auto-reclosure operation. In such conditions, a transfer trip of the line's leader terminal will be activated by the overvoltage protection system.

# Chapter 3

# Modeling and Behavior Analysis During Single-phase Reclosing

In this Chapter, at first, modeling process of the studied power system is explained and then, behavior of the modeled system during single-phase reclosing is analyzed. In the following, a power system including a transmission line is modeled using PSCAD and the appropriate results are loaded to Matlab for more analysis. These results are used for performance evaluation of the proposed reclosing methods.

The main aim of the performed power system analysis in this Chapter is to propose methods to discriminate permanent and temporary faults based on the behavior of the faulted phase voltage after single-phase opening of the circuit breakers. For this purpose, at first, behavior of a simple three-phase transposed transmission line without shunt reactor is analyzed and then, the analysis is extended to more general cases. In this order, some simplifications have been made. As an example, resistances and inductances of equipment as well as source impedances of both ends are ignored as they are negligible compared to line coupling impedances among three phases [2].

## 3.1 Modeling of the Studied System

### 3.1.1 Power system modeling

In this study, PSCAD is employed for modeling a typical $500kV$ power system in which configuration of towers is set as horizontal. Single-line diagram of the network under study is shown in Figure 3.1. In this study, voltage sources are considered as 1.02 p.u. ($|V_s| = 510kV$) and $\angle V_s = 21$ Degrees for Side A and 1.0 p.u. ($|V_s| = 500kV$) and $\angle V_s = 0$ Degrees for Side B. Length of the line is also 320 km while source impedances are chosen as 0.175 p.u. and 0.12 p.u. for the right and left voltage sources, respectively.

For the purpose of modeling of the transmission line, the Frequency Dependent (Phase) model developed by Jose Marti is used [75]. In PSCAD two transmission line frequency dependent models are offered, namely the Frequency Dependent (Mode) model and the Frequency Dependent (Phase) model. It is recommended by PSCAD Users' Guide that for all new studies involving cables or transmission lines, the Frequency Dependent (Phase) model be employed. This model was specifically added to PSCAD to replace the Frequency Dependent (Mode) model. The Frequency Dependent (Phase) model can represent any type of transmission system including aerial/underground and symmetrical/asymmetrical, and is more stable and more accurate than Mode model [76].

The reason for choosing a $500kV$ transmission line for modeling and simulation is that it is the highest voltage level in Canada at which single-phase reclosing is applicable [66]-[70]. The parameters of the system are also chosen as typical values for such transmission lines. However, the developed methods in Chapters 4 and 5 are not dependent on system parameters, including voltage level, because of the normalization and filtering of the information considered in the structures of the methods. The performances of the developed methods are also verified using a real case study, a temporary fault case is a 765 kV transmission lne where the solidity of the methods is shown.

In order to perform a better behavior analysis, a power system with three different topologies of transmission lines, including ideally-transposed, untransposed and partially-transposed is used for simulation study and various permanent or transient faults inserted at proper locations. For the cases of ideally-transposed and untransposed lines, the line is divided into three parts as two 30% parts at the sides and one 40% part at the middle. Therefore, the fault occurrence at 0%, 30%, 70% and 100% distances from one side of the transmission line can be simulated.

For partially-transposed transmission line cases, the position of each conductor and/or line configuration is changed during the study. In other words, the line is divided into three parts with configurations of ’a-b-c’, ’c-a-b’, ’b-c-a’, which consist 50%, 30% and 20% of the line length, respectively. With this selection, the entire line is not transposed 100% and therefore, partially-transposed line is modeled. In the partially-transposed cases, the fault can occur at both end and middle of each line section. Therefore, fault occurrence at 0%, 25%, 50%, 65%, 80%, 90% and 100% of the line from Side A is considered for simulation. It should be noted that in the ’a-b-c’ horizontal configuration of towers, ’a’, ’b’ and ’c’ conductors are the left, the middle and the right conductors, respectively. Importance of the partially-transposed case is because in practice, it is not always possible to perform 100% transposition for transmission lines, mostly due to technical limitations.

For the purpose of performance evaluation of the proposed reclosing methods for shunt reactor compensated cases, a shunt reactor at each end with the three-phase reactive power of 158.7 $MVar$ are employed. Considering $X/R$ ratio of 50, each reactor has been modeled as $Z = (31.5 + j1575.3)\ \Omega$. Neutral reactor is also represented by series combination of a single-phase reactance and a resistance.

For the purpose of minimizing the secondary arc current, one common practice is to choose a proper value for the neutral reactance, called optimum neutral reactor. Using a method explained in references [2, 27, 28, 83, 84] for this purpose, the optimum neutral reactor value is

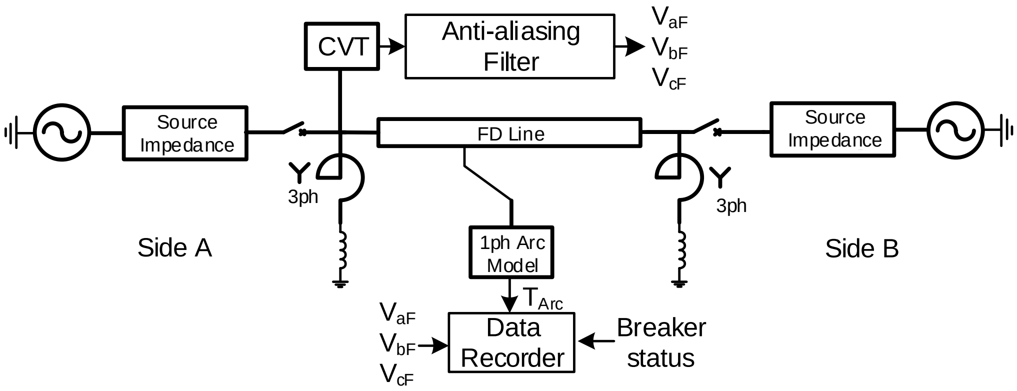

**Figure 3.1: Single-line diagram of the modeled power system.**

calculated as $X_n = 260\ \Omega$. Employing two similar shunt reactors at both line ends, a 520 Ω (= 2 × 260 Ω) reactor is used for their neutrals. In cases the optimum neutral reactor is not available, a larger/smaller reactor will be employed. In this study, neutral reactor impedances equal to $Z_n^{Large} = (14 + j700)\Omega$, $Z_n^{Optimum} = (10.2 + j510.8)\Omega$ and $Z_n^{Small} = (6 + j300)\Omega$ are used to cover possible larger, optimum and smaller reactances in practice, respectively. Similar to the shunt reactors, $X/R$ ratios of all neutral reactors are assumed as 50 as well.

Also, for the cases of permanent faults, typical fault resistance values of 1 Ω, 10 Ω and 100 Ω are selected for various faulted cases. For performance evaluation of the proposed method in presence of CVT transients, Lucas capacitive voltage transformer (CVT) model is used [85].

The modeled system in PSCAD with more details can be observed in Figures 3.2 and 3.3. As observed in Figure 3.2, the line is divided into three sections namely TLine1, TLine2 and TLine3 consisting 30%, 40% and 30% of the line, respectively. There are two four-legged shunt reactors connected to buses BusS and BusR for the purpose of shunt compensation. For uncompensated line cases, these shunt reactors must be ignored.

There is also a single-phase-to-ground fault applied to a bus employing a single-phase breaker, called BreakerF. Therefore, modeling of fault occurrence at 30% distance from Side A is shown in Figure 3.2. By applying similar faults at other buses of the system, it is possible to simulate fault occurrence at different locations of the transmission line. In the performed simulations, a constant value for the fault resistance, $R_F$, is used for the permanent fault cases. For the cases of temporary fault, the value of $R_F$, which now is a current-controlled resistor, is determined by the arc model to be explained in Subsection 3.1.2. At the moment of fault inception, the fault breaker closes and the arc resistor which has a very small value at that moment becomes energized which leads to a huge fault current. However, as the time passes, the arc resistance increases and therefore, the fault current decreases until becomes very small (less than 2 $A$ according to the standard [86]). At this moment, the arc is considered as extinguished.

The circuit breakers used at the left and right hand side of the circuit have the capability of both three-phase and single-phase operation. Therefore, it is possible to perform appropriate operations for permanent and temporary fault cases, including single-phase opening, single-phase reclosing and three-phase opening. The blocks shown in the top-left side of the Figure 3.2 are models of CT and CVT used for the measurement purposes. At the bottom of CT and CVT blocks, anti-aliasing filtering blocks are observed. The voltage and current data provided during simulations are recorded using Comtrade 91 coding system [87].

There is a similar scenario about the circuit shown in Figure 3.3 in which the partially-transposed transmission line is modeled. The only difference is combination of portions of the line which are 50%, 30% and 20%. Therefore, the fault occurrence at 0%, 25%, 50%, 65%, 80 %, 90% and 100% distance of the line from Side A can be considered.

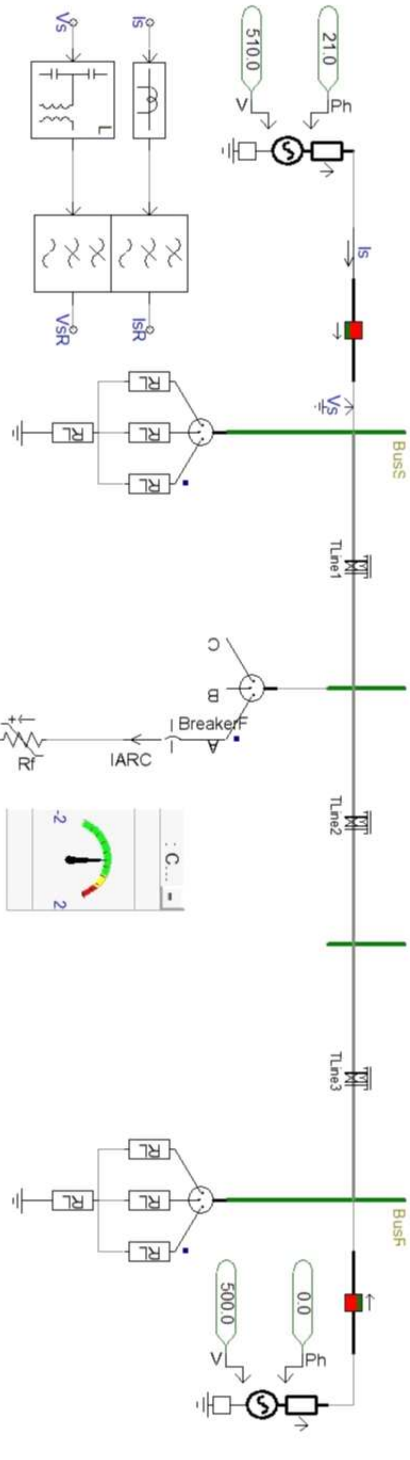

**Figure 3.2: Single-line diagram of a power system with ideally-transposed and untransposed transmission lines simulated in PSCAD.**

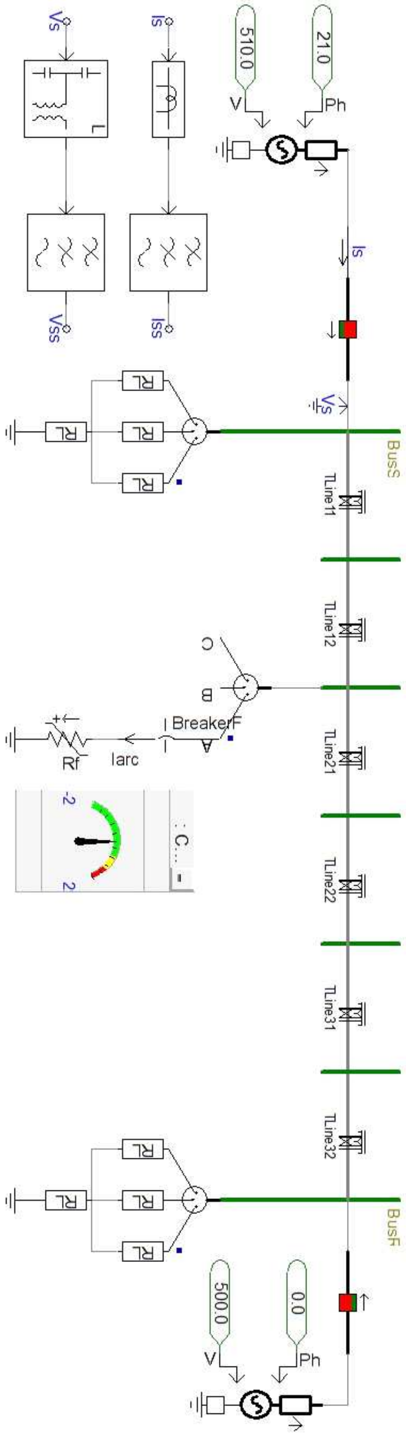

Figure 3.3: Single-line diagram of a power system with partially-transposed transmission line simulated in PSCAD.

### 3.1.2 Arc modeling

For the purpose of studying the reclosing in transmission lines, it is necessary to consider the arcing nature of the temporary faults. Based on their features, electrical arcs can be categorized into two groups, namely primary and secondary. A primary arc happens as the line insulator string flashes over which is caused by reasons such as lightning strike. However, a secondary arc, which is a more complicated phenomenon, appears following the primary arc while the faulted phase is isolated due to breaker opening. For more information about electric arcs in power systems see references [83]-[96].

There are few methods proposed for modeling of the secondary arc. In 1931, as the very first attempt, Warrington introduced his empirical formula for arc modeling [97]. For this purpose, he applied different voltage values across two electrodes with different distances and provided some test results. In his work, having assumed a resistive nature for electrical arc, he considered the relation between arc voltage and current as (3.1) where $U_a$ and $E_a$ are arc voltage and arc voltage gradient, respectively. $L$ is the length of the arc while $I$ is the arc current. Parameters $K$ and $n$ are defined using the test results. The assumption of resistive nature for arc was based on the fact that the arc voltages and the arc currents were in phase for each and every of the test results. In [98]-[108] Terzija modified Warrington's empirical formula considering some assumptions, e.g., Warrington's measurement devices were not accurate enough and the arc length changes during the arc life. Terzija enhances the formula by considering the effect of Gaussian noise.

$$U_a = E_a L = (K/I^n)L \tag{3.1}$$

The most accurate method for modeling secondary arc is proposed by Kizilcay. He presents a thermal model for secondary arc as (3.2) where $g_{arc}$ is the conductance of the arc, $\tau$ is the arc time constant, $G$ is the stationary arc conductance, $i_{arc}$ is the arc current, $u0$ is the characteristic voltage of the arc, $r$ is the characteristic resistance of the arc per arc length, $l_{arc}$ is the instantaneous length of arc and $t$ is the time variable [89]-[92].

$$\begin{gathered} dg_{arc}/dt = 1/\tau \times (G - g_{arc}) \\ G = \frac{|i_{arc}|}{(u_0 + r|i_{arc}|)|l_{arc}|} \end{gathered} \tag{3.2}$$

Parameters $u_0$ and $r$ can be obtained based on measurements. For primary arcs, $\tau$ and $l_{arc}$ are constant and equal to their initial values $\tau_0$ and $l_0$, respectively, while they change by time for secondary arcs. The time constant of the secondary arc is proportional to the arc length, inversely, as defined in (3.3).

$$\tau = \tau_0 \times (l_{arc}/l_0)^{\alpha} \tag{3.3}$$

In (3.3), $\tau_0$ and $l_0$ are the initial time constant and length of the arc while $\alpha$ is a coefficient in the range of 0.1 to 0.6. The length of the primary arc, which is the length of the flash-over, is assumed to be 10% longer than the length of the line insulators string [92]. The length of the secondary arc varies by time and is different for different wind speeds. For relatively slow winds (slower than 1 m/s), the change of arc length is as (3.4) where $l_s(tr)$ is the time-dependent length of the secondary arc with initial value of $l0$ and $t_r$ is the time duration starting from the secondary arc initiation [86].

$$\begin{gathered} l_s(t_r)/l_0 = 1,\ t_r < 0.1 \\ l_s(t_r)/l_0 = 10t_r,\ t_r > 0.1 \end{gathered} \tag{3.4}$$

**Table 3.1: Modeled Arc Parametrs.**

| Arc number | $\tau_0$ (ms) | $l_0$ (m) | $u_0$ (v/cm) |
|---|---|---|---|
| 1 | 0.714 | 3.5 | 12 |
| 2 | 0.555 | 3.15 | 8 |
| 3 | 0.833 | 3.5 | 11 |

In this study, secondary arc is modeled in PSCAD based on the model developed by Kizilcay using equations (3.2)-(3.4) [89]. For this purpose, the arc resistor shown as a block in Figure 3.1 is considered as a current-controlled resistor. This means the value of the arc resistor at each moment is considered to be in a non-linear relation with the arc current at that moment. In should be noted that this relation is neither a function nor one-to-one as the history of the arc and the initial conditions have the major roles in the arc behavior. In the performed research study, three different sets of arc parameters available in Table 3.1 are employed for providing needed arc characteristics using [96]. In Table 3.1, $l_0$ and $\tau_0$ are the arc's initial length and time constant, while $u_0$ is the characteristic voltage of the arc.

The detailed model of the arc used for simulation in PSCAD is shown in Figure 3.4. For a better understanding of the arc model, it is easier to move in reverse direction, i.e., to start from the output $R_F$ and reach the input $i_{arc}$. In Figure 3.4, variable $g_{arc}$, the instantaneous value of the arc conductivity is obtained by going back one step from output $R_F$ simply after a reversing operation. Going one more step back leads to a variable equal to $\tau_0 \times dg_{arc}/dt$ to be named $VRBL$. This is because the passed element of the circuit is an integrator with coefficient value of $1/\tau_0$. Using (3.2), $VRBL$ equals to $(G - g_{arc}) \times (\tau_0/\tau)$ and this can be confirmed in Figure 3.4 as $VRBL$ is the result of division of two variables $NUM$ and $DNUM$. However, $NUM$ itself equals to $POS$ minus $NEG$ which are equal to $|i_{arc}|/[(u_0 + r|i_{arc}|)|l_{arc}|]$ and $g_{arc}$, respectively, using Figure 3.4. This means the value of $NUM$ exactly equals $G - g_{arc}$ according to (3.2). At the other hand, $DNUM$ equals to $[(l_{arc}/l_0])^{\alpha}$ which is exactly $\tau/\tau_0$ using (3.3). Therefore, the term $VRBL = (G - g_{arc}) \times (\tau_0/\tau)$ is verified as $VRBL = NUM/DNUM$.

### 3.1.3 Protective relay modeling

A fourth order low-pass butter-worth anti-aliasing filter with cut off frequency of 1536 Hz is used for filtering the outputs of the three-phase CVT models. The sampling rate for recording the PSCAD results is also 20 kHz. The recorded data is imported to Matlab and decimated to the sampling rate of 3840 Hz. Three phase voltages are passed through a CVT transient filter proposed in [116] to obtain smoother waveforms for the phase voltages.

For the purpose of phasor estimation of the waveforms, including voltage and current waveforms, Cosine algorithm is used [130]. It must be noted that in theory, digital Fourier transform filter, DFT, is the main filter to be used for phasor estimation. But, the output of this filter is a combination of two different filters, called Sine and Cosine filters. However, it can be shown that for systems with slow changes such as electric power system, the output of the Sine filter can be approximated by the output of the Cosine filter delayed by one quarter of a power system cycle length. Therefore, it is a common practice in power system measurement and relaying to use Cosine filter, instead of DFT. Protection pass of the system is also considered as 1/16 of a cycle. Therefore, the protection algorithm is performed every 4 samples as each power system cycle consists of 64 samples of data.

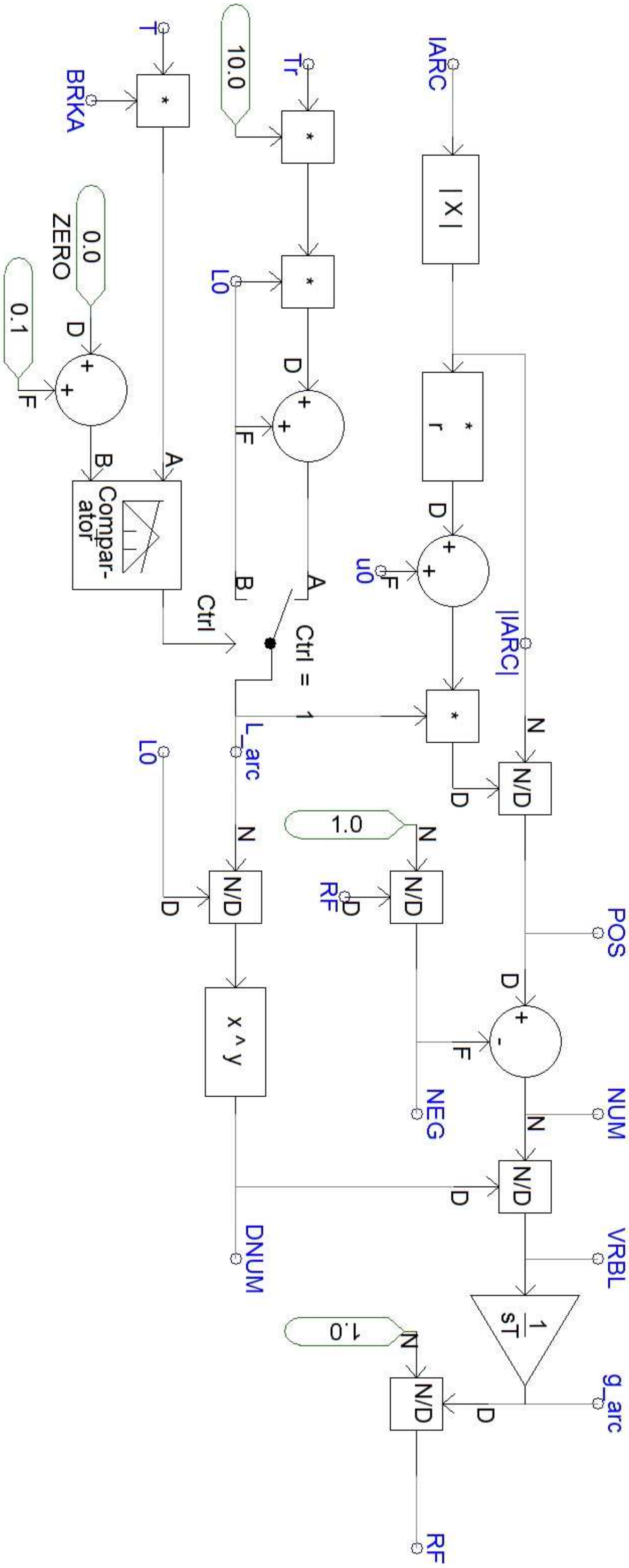

Figure 3.4: Details of the arc model simulated in PSCAD.

## 3.2 Behavior Analysis of the System During Single-Phase Reclosing

### 3.2.1 Transposed line

#### Absence of shunt reactor

After single-phase opening of the circuit breaker in a transmission line, the secondary arc current is fed due to capacitive and inductive coupling with other phases. Figure 3.5 (a) shows the capacitive coupling circuit for a transposed line without shunt reactor. The simplified version of the circuit is also shown in Figure 3.5 (b). In this figure, $E_x$ ($x$ is $h$, $k$ or $s$) is the average of phase x voltages at both line ends (sending and receiving ends). It should be noted that this simplification approach is common in secondary arc analysis as presented in [21] and is only employed to derive the proposed adaptive reclosing methods while accurate simulations are performed to verify the performances of the proposed techniques.

The inductive component of induced voltage to the faulted phase depends on load currents in healthy phases as well as mutual inductive couplings between healthy and faulted phases [22]. The inductive component could be modeled as an impedance in series with the equivalent voltage source, i.e., $E_s$, shown in Figure 3.5 (b). But, it is negligible and consistent considering the fact that the healthy line load currents do not change considerably after line isolation. Therefore, the inductive component is ignored in all the analyses in this Section.

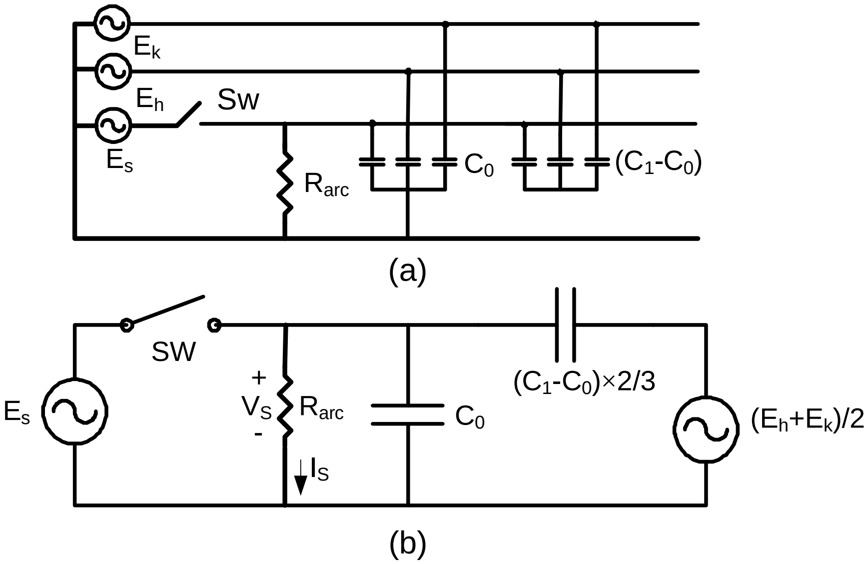

**Figure 3.5: (a) Equivalent circuit of a transposed line without shunt reactor in case of single-phase reclosing of phase *s*, (b) rearranged circuit.**

As per equivalent circuit shown in Figure 3.5, immediately after isolation of the faulted phase, the phase voltage $V_s$ can be estimated as (3.5).

$$V_s = \frac{R_{arc}||(\frac{1}{j\omega C_0})}{R_{arc}||(\frac{1}{j\omega C_0}) + \frac{1}{j\omega\frac{2}{3}(C_1-C_0)}}\left(\frac{E_h + E_k}{2}\right) \tag{3.5}$$

where $V_s$ is the faulted phase voltage measured by the line protection relays; $R_{arc}$ is the arc resistance; $C_0$ is zero sequence capacitance of transmission line; $C_1$ is positive sequence capacitance of transmission line; $E_h$ is the source voltage of the healthy phase (average of both ends); $E_k$ is the source voltage of the healthy phase (average of both ends); $\omega$ is the angular velocity; $j$ is the complex operand and || stands for the impedance parallel operand.

Immediately after operation of the circuit breakers of both line ends, the arc resistance is still small as compared to the line shunt capacitive impedance. Therefore, (3.5) can be approximated to (3.6). According to (3.6), in case of low resistive faults, the magnitude of $V_s$ is very small and the angle of $V_s$ leads $(E_h + E_k)$ by 90 degrees. This condition remains if there is a permanent fault. However, for the case of a temporary fault, $R_{arc}$ would increase, ideally to infinity as the arc extinguishes. In this case, (3.5) could be approximated as (3.7). For a typical transmission line, $C_1$ is about 1.5 times of $C_0$ [83]. As a result, $|Vs|$ would be about 12.5% of $(E_h + E_k)$ if arc is extinguished. In this case, $V_s$ would be in phase with $(E_h + E_k)$ if arc resistance increases, considerably.

$$V_s = j\omega\tfrac{2}{3}R_{arc}(C_1 - C_0)\left(\tfrac{E_h+E_k}{2}\right) \tag{3.6}$$
$$\text{if } R_{arc} << \tfrac{1}{j\omega C_0} \text{ and } R_{arc} << \tfrac{1}{j\omega\frac{2}{3}(C_1-C_0)}$$

$$V_s = \tfrac{2(C_1-C_0)}{2C_1+C_0}\left(\tfrac{E_h+E_k}{2}\right) \text{ if } R_{arc} >> \tfrac{1}{j\omega C_0} \tag{3.7}$$

To perform a better comparison, it is proper to define $V_{sn}$, i.e., normalized $V_s$, as per (3.8). Magnitude and angle of $V_{sn}$ versus $R_{arc}$ are shown in Figure 3.6 for the case of transmission line without shunt reactor . As depicted, in case of a permanent fault where $R_{arc}$ remains small even after circuit beaker interruption, $|V_{sn}|$ will be close to zero while $\angle V_{sn}$ is almost 90°. In case of a temporary fault where $R_{arc}$ reaches a large value, $|Vs|$ could reach a value about 12.5% depending on line positive and zero sequence capacitances. For such large values of arc resistor, $\angle V_{sn}$ drops to zero. This can be confirmed using (3.7). In addition, for temporary faults, as shown in Figure 3.6, both magnitude and angle of $V_{sn}$ change rapidly almost in a linear manner versus arc resistance if $R_{arc}$ is below a certain value (knee point in 3.6), e.g., about 900Ω in this case. For arc resistance values above this number, both magnitude and angle of $V_{sn}$ change considerably slowly until they settle down.

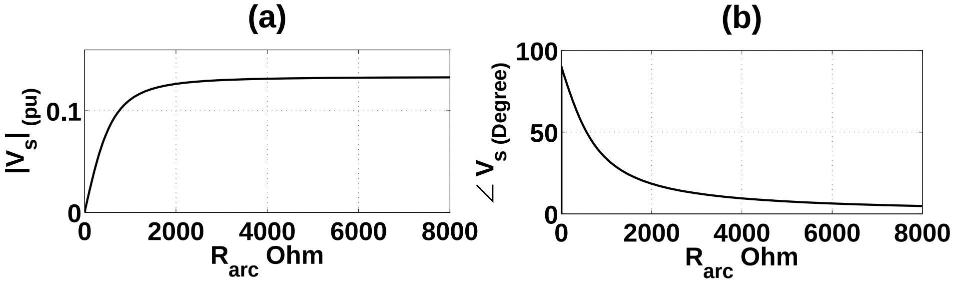

**Figure 3.6: Normalized (a) magnitude and (b) phase angle of the faulted phase voltage.**

$$V_{sn} = V_s/(E_h + E_k) \tag{3.8}$$

Regarding the above phasor analysis, it must be considered that this analysis is been used only for obtaining the ideas and explanation of the developed concepts. In Chapters 4 and 5, the methods are developed and evaluated not using phasor analysis, but transient simulation results. However, there are two points regarding the validity of the phasor analysis for idea development that must be indicated. The first point is that in the analysis of this Section, only two states of the system are known for us, which are pre-fault and post-fault-clearance system states. For obtaining the exact process in which the power system moves from pre-fault state to post-fault-clearance state, a transient analysis must be performed. But, the results obtained from the phasor analysis can be used as initial and final conditions. Also, considering the fact that the main interest of the performed research study is power system protection, only the fundamental frequency components of the voltage/current variables are of interest. Therefore, results obtained from the phasor-analysis are valid for single-phase reclosing applications.

### Presence of shunt reactor

In case of ideally-transposed transmission lines where shunt reactors are required, use of four-legged shunt reactors is a common practice in industry to limit the secondary arc current for faster and more successful single-phase reclosing scheme [20, 21]. The value of neutral reactor can be selected as recommended in [2, 27, 28, 83, 84]. Equivalent circuit of a transposed transmission line with four-legged shunt reactor is shown in Figure 3.7. As shown in Figure 3.7 (b), there is an inductive branch appeared in parallel with the capacitive branch. These two inductive and capacitive branches would cancel out each other if the neutral reactor is selected in such a way that parallel branches resonate. However, as the compensation is not 100% in practice due to possible errors in line parameter estimation and other limitations discussed in [62], eventually the equivalent circuit of the parallel branches would be either a large inductor or a small capacitor. Therefore, share of the arc resistance from the feeding voltage, i.e., $(E_h + E_k)$, is even less than the case without shunt reactor, thus, the arc would be extinguished faster.

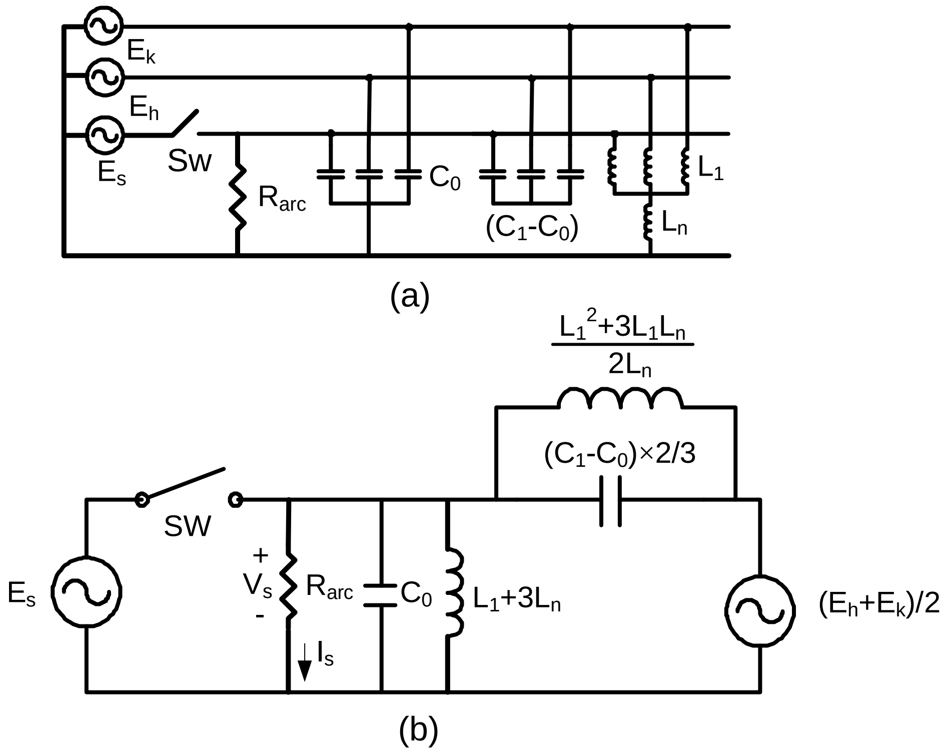

**Figure 3.7: (a) Equivalent circuit of a transposed transmission line with four-legged shunt reactor, (b) simplified circuit.**

In this case, the measured voltage by the line protection relays can be estimated as (3.9). Similar to the approach adopted earlier, immediately after operation of the circuit breakers of both line ends when arc resistance is small, (3.9) can be estimated by (3.10). According to (3.10), there is a linear relation between $|Vs|$ and $R_{arc}$ in case of small arc resistances. Also, the faulted phase voltage would either lead or lag the equivalent voltage source, $(E_h + E_k)$ by 90° depending on capacitive or inductive nature of $X$ where $X$ is the equivalent reactance of the parallel branch. This would stay the case for permanent faults as fault resistance remains small. However, for temporary faults, the arc resistance would increase to a considerably large value. So, (3.9) could be estimated by (3.11) for such cases. Using (3.11), $|Vs|$ still is a factor of $(E_h + E_k)$ although the factor is most probably smaller than the one in transposed lines without shunt reactor. This is the case since $X$ is typically a large value especially for cases at which the neutral reactor is chosen properly. $\angle V_s$ also depends on capacitive or inductive nature of nominator and denominator of (3.11). However, as both the nominator and the denominator are imaginary reactances, (3.11) would have either a positive or a negative real value. Therefore, $V_s$ would be either in phase or out of phase with $(E_h + E_k)$.

$$V_s = \frac{R_{arc}||(\frac{1}{j\omega C_0})||(j\omega(L_1 + 3L_n))}{R_{arc}||(\frac{1}{j\omega C_0})||(j\omega(L_1 + 3L_n) + jX}(\frac{E_h + E_k}{2}) \tag{3.9}$$

It should be noted that the case of transmission line compensated by shunt reactors with grounded neutrals is excluded in this research project. This is due to long arc extinction time for this case. Therefore, single-phase reclosing is not recommended and is not practical in such conditions [2].

$$V_s = \frac{R_{arc}}{jX}\left(\frac{E_h+E_k}{2}\right) \tag{3.10}$$

If $R_{arc} << \frac{1}{j\omega C_0}$ and $R_{arc} << j\omega(L_1 + 3L_n)$

$$V_s = \frac{(\frac{1}{j\omega C_0})||(j\omega(L_1+3L_n))}{jX}\left(\frac{E_h+E_k}{2}\right) \tag{3.11}$$

If $R_{arc} >> \frac{1}{j\omega C_0}$ , $R_{arc} >> j\omega(L_1 + 3L_n)$

and $\frac{1}{j\omega C_0}||j\omega(L_1 + 3L_n) << jX$

## 3.2.2 Untransposed line

### Absence of shunt reactor

The equivalent circuit of an untransposed transmission line without shunt reactor is shown in Figure 3.8-(a). Simplified version of this circuit is also shown in Figure 3.8-(b). Based on the circuit shown in Figure 3.8-(b), faulted phase voltage would be obtained as (3.12).

$$V_s = \frac{R_{arc}||(\frac{1}{j\omega C_sn})}{R_{arc}||(\frac{1}{j\omega C_{sn}}) + \frac{1}{j\omega(C_{sh}+C_{sk})}}\left(\frac{C_{sh}E_h + C_{sk}E_k}{C_{sh} + C_{sk}}\right) \tag{3.12}$$

Comparing (3.5) and (3.12), $Vs$ in both cases depends on $R_{arc}$ in similar ways and using (7), it could be shown that voltage profiles similar to Figure 3.6-(a) would be obtained. The only difference is that there would be a phase shift because of non-transposition. In other words, $E_h$ and $E_k$ would have different participations to the equivalent voltage source for faults on the side wire as $C_{sh}$ and $C_{sk}$ have different values.

### Presence of shunt reactor

Equivalent circuits of the untransposed line and the simplified version of it in presence of four-legged shunt reactor are shown in Figure 3.9. Using Figure 3.9-(c), the faulted phase voltage would be as (3.13).

$$V_s = \frac{R_{arc}||(\frac{1}{j\omega C_s n})||(j\omega(L_1 + 3L_n)}{R_{arc}||(\frac{1}{j\omega C_{sn}})||(j\omega(L_1 + 3L_n)) + X_{eq}} E_{eq} \tag{3.13}$$

where $X_{eq}$ and $E_q$ are Thevenin equivalent reactance and source of the grayed circuit, respectively.

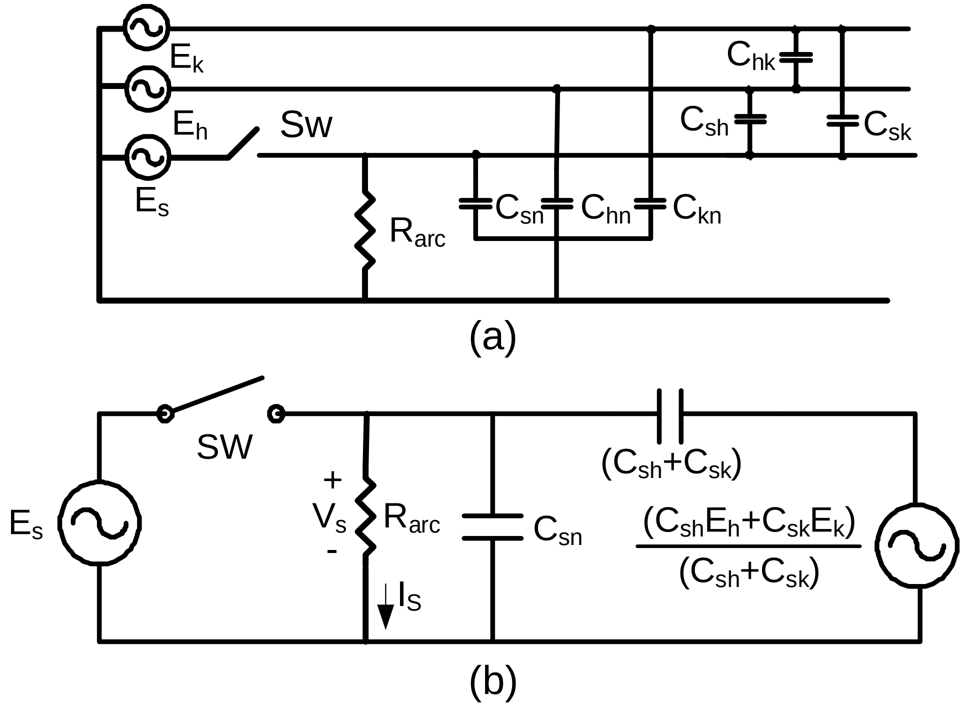

**Figure 3.8: (a) Equivalent circuit of an untransposed transmission line without shunt reactor, (b) simplified circuit.**

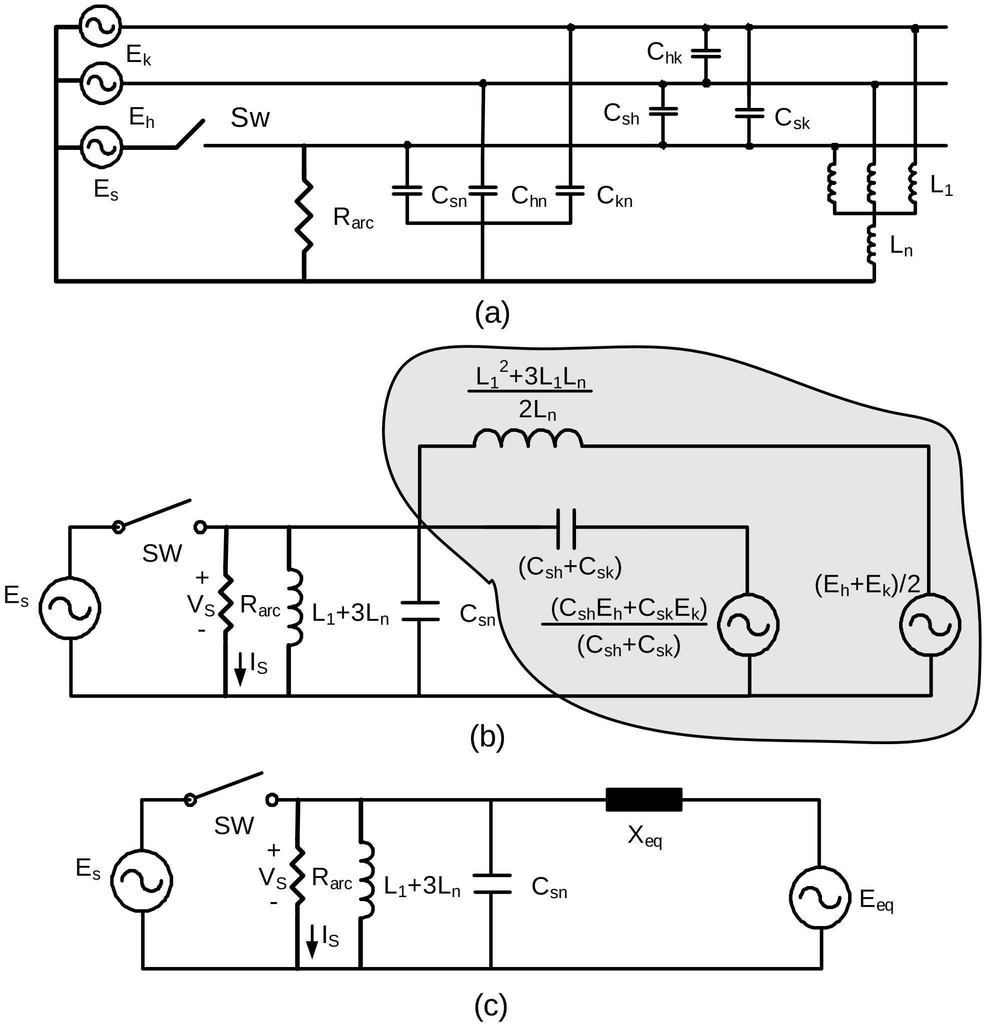

**Figure 3.9: (a) Equivalent circuit of an untransposed transmission line with four-legged shunt reactor, (b) rearranged circuit, (c) simplified circuit.**

Comparing (3.12) and (3.13) shows a great similarity in dependence of the faulted phase voltage on the arc resistance. In other words, amplitude of the voltage increases in a similar manner in both cases while arc resistance is increasing. Therefore, a similar voltage pattern, close to Figure 3.6, is expected for this case as well. Again, similar to Subsection 3.2.1 for the untransposed line without shunt reactors, there would be a different phase difference between the voltages which is due to un-transposition.

## 3.3 Summary

In this Section, at first modeling process of the studied system, including the power system, electric arc and the protection relay was explained. Then, it was shown that the general behavior of the faulted phase voltage is somehow the same for all configurations of power systems. In other words, when single-phase fault happens, voltage of the faulted point drops to rather small values. This could remain the case if the fault is permanent. However, in case of temporary faults, arc resistance starts increasing after the single-phase isolation of the line. This would lead to increment of the faulted phase voltage to a considerable percentage of the rated voltage once the arc is extinguished. This pattern of the faulted phase voltage magnitude and angle behavior is the base for developing the proposed methods in this research study.

# Chapter 4

# Fault Type Recognition and Arc Extinction Detection

In this Chapter, the voltage magnitude and phase angle patterns of the faulted phase voltage after the line single-phase isolation are analyzed to perform adaptive single-phase reclosing. For this purpose, two reclosing methods are proposed. In the first proposed adaptive single-phase reclosing method to be called the angle-based method, the phase angle of the faulted phase voltage is used for both fault type identification, i.e., permanent or temporary, and for arc extinction detection in case the fault type is identified as temporary. In the second proposed reclosing method to be called the phasor-based method, the first derivation of the faulted phase voltage magnitude is used for the fault type recognition while the combination of first derivation of angle and magnitude of the faulted phase voltage is used to quickly detect the arc extinction for the temporary fault cases. Both proposed method are effective for shunt compensated and uncompensated lines and for ideally-transposed, untransposed and partially-transposed transmission lines.

## 4.1 Fundamentals of the Reclosing Methods

In this Section, several simulated case studies are employed to verify the expected behavior of the faulted phase voltage after the line single-phase isolation, derived in the Chapter 3. For this purpose, permanent and temporary faults have been simulated and related waveforms are presented. Voltage and current waveforms of the electric arcs/faults for six different temporary fault cases are shown in Figures 4.1 to 4.6. For the all simulations, the single-phase-to-ground fault inception time is 0.2s. The line single-phase isolation times are also 0.27s and 0.28s for Sides A and B, respectively. Therefore, the faulted phase is completely isolated after t=0.28s.

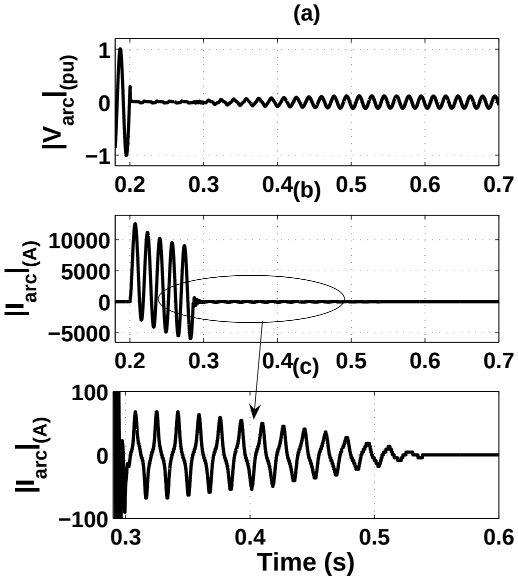

**Figure 4.1: Electric arc voltage and current for the case of a temporary fault in an ideally-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

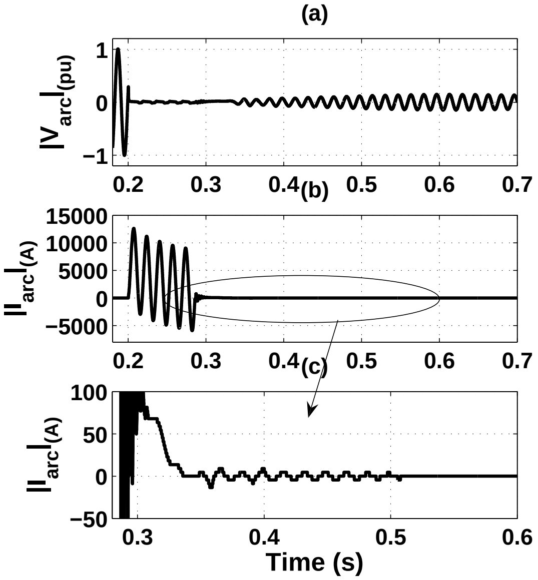

**Figure 4.2: Electric arc voltage and current for the case of a temporary fault in an ideally-transposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

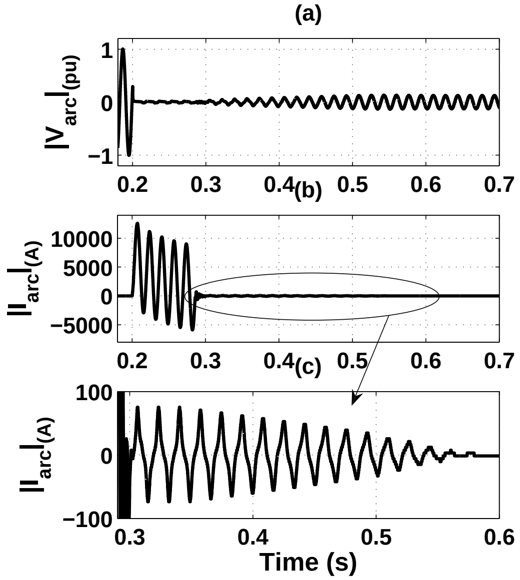

**Figure 4.3: Electric arc voltage and current for the case of a temporary fault in an un-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

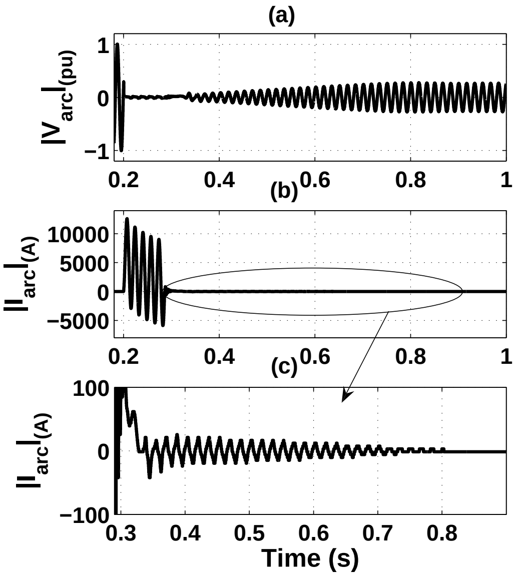

**Figure 4.4: Electric arc voltage and current for the case of a temporary fault in an untransposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

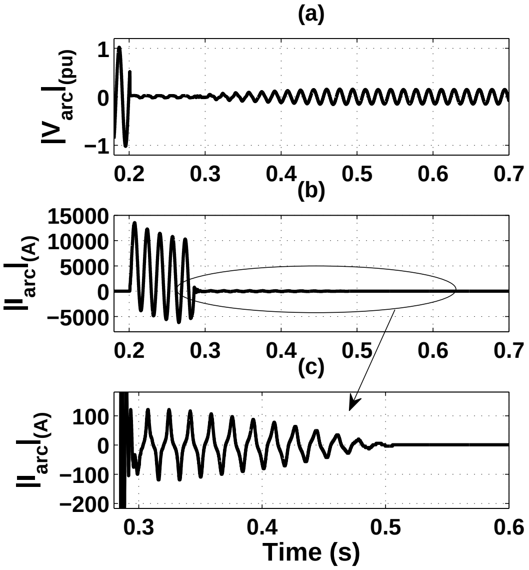

**Figure 4.5: Electric arc voltage and current for the case of a temporary fault in a partially-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

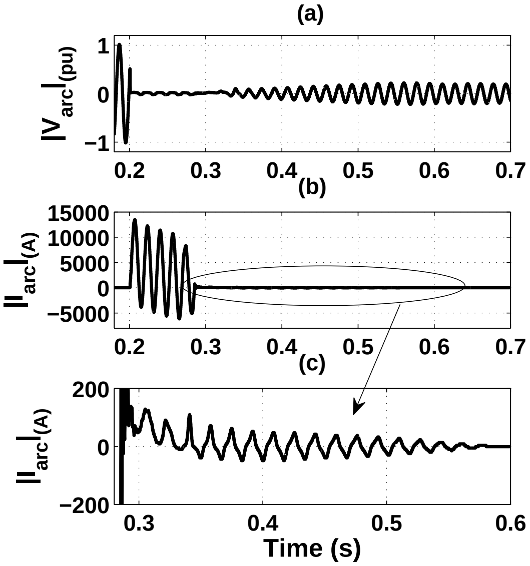

**Figure 4.6: Electric arc voltage and current for the case of a temporary fault in a partially-transposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

### 4.1.1 Angle-based analysis

The faulted voltage phase angle, $\delta$, the phase difference between the faulted phase voltage and summation of the voltages of the non-faulted phases, as defined in (4.1), plays a major role in the angle-based reclosing method. In (4.1), $V_h = V_b$, $V_k = V_c$ and $V_s = V_a$ in case of AG fault. The negative signs in (4.1) are used to assign the pre-fault value of zero for $\delta$ and therefore, to avoid $\delta$ values jumping from $-180\circ$ to $180\circ$ as much as possible. As the phase angle measured by Cosine algorithm is rotatory, a reference is needed in order to utilize the phase angle for the proposed application. Considering the fact that the single-phase-to-ground fault is the only interest of this research study, summation of voltage phasors of the non-faulted phases has been chosen as a reference according to (4.1). This assumption also secures the proposed algorithm against power system dynamics after line single-phase isolation since any system oscillation appears almost equally in all three phase. Selection of this reference eliminates the effect of angle variations due to system dynamics while it maintains the effect of arc extinction.

$$\delta = \angle[-V_s/(V_h + V_k)] \tag{4.1}$$

Variable $\delta_{mean}$, the mean value of the phase angle $\delta$ over the last power system cycle at each time spot is the main variable employed in the angle-based method proposed in this research. By averaging, the phase angle waveform becomes as smooth as possible which makes the decision makings more reliable and more accurate.

### Ideally-transposed line

Simulation results of two permanent fault cases in an ideally-transposed line are shown in Figures 4.7 and 4.8. In both simulated cases, the fault resistance is equal to 1 Ω and the fault occurs at 30% distance of the sending side, i.e., Side A. For the case shown in Figure 4.7, the line is not compensated while shunt compensation is used for the case of Figure 4.8.

As observed, in the both cases $\delta_{mean}$ is around zero prior to the breakers' single-phase opening at $t = 0.27\,\mathrm{s}$. This means the faulted phase and summation of the two non-faulted phase voltages (with negative sign) are still in phase. But after single-phase isolation of the faulted line, $\delta_{mean}$ increases and after some transients finally settles down at a value around 90° to be called the-first-lock-angle, slightly after the single-phase isolation of the line. This matches with what predicted in Section 3.2.

In Figures 4.9 and 4.10 two temporary fault simulated cases in an ideally-transposed line without and with shunt compensation are shown, respectively. In both cases, the temporary fault happens at 30% distance from the sending side. As observed, in both cases the variable $\delta_{mean}$ is zero before the fault inception and slightly after the line isolation jumps to the-first-lock-angle which is around 90°. This is similar to the previously explained permanent fault cases of Figures 4.7 and 4.8. Variable $\delta_{mean}$ stays around the-first-lock-angle for a short period of time which is because the arc resistor has a very small value right after the single-phase isolation of the line. However, as the arc extinguishes and the arc resistor increases to very large values, $\delta_{mean}$ increases to another value around 180° to be called the-second-lock-angle. This means $\delta_{mean}$ turns almost out-of-phase respect to the equivalent voltage source of the faulted phase after the arc extinction. In other word, an arcing/temporary fault is initially very similar to a permanent fault when the arc resistor has a small value. However, as the arc resistance increases, the difference between two fault types become more clear. This was also predicted precisely in Section 3.2. The difference between the compensated and the non-compensated cases is that there are some oscillations after the arc extinction at around $t = 0.65\,\mathrm{s}$ for the compensated case. These oscillations which happen between the shunt reactors and the line capacitors do not exist for the un-compensated cases.

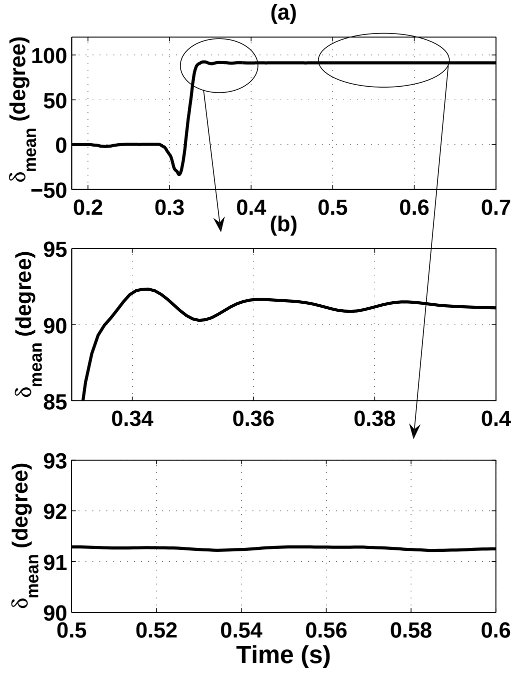

**Figure 4.7: (a) $\delta_{mean}$ for the case of a permanent fault in an ideally-transposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

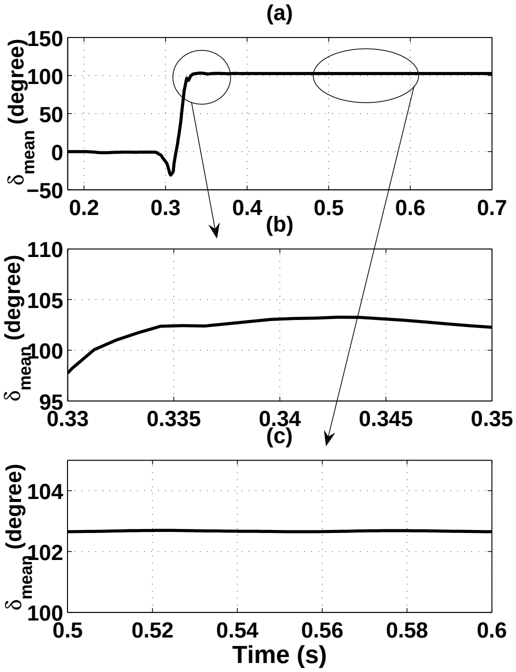

**Figure 4.8: (a) $\delta_{mean}$ for the case of a permanent fault in an ideally-transposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

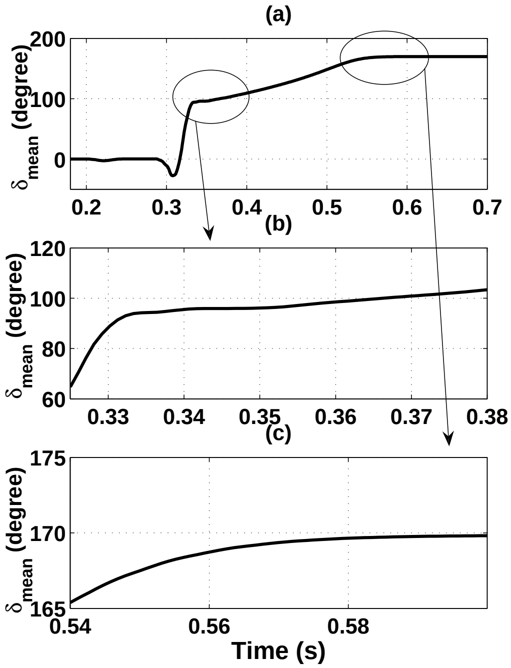

**Figure 4.9: (a) $\delta_{mean}$ for the case of a temporary fault in an ideally-transposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

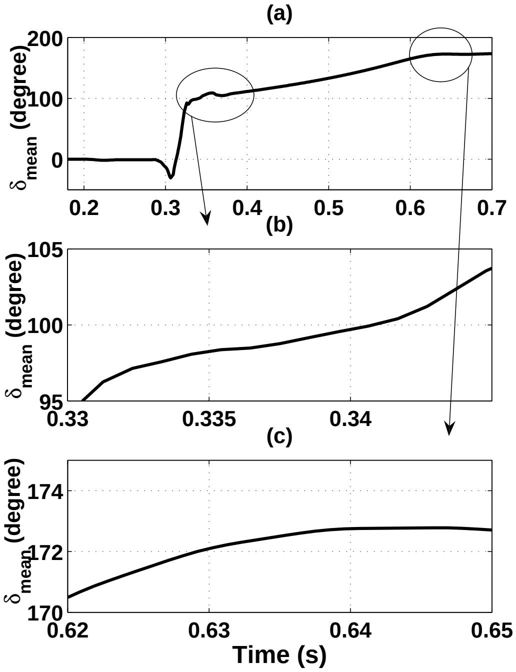

**Figure 4.10: (a) $\delta_{mean}$ for the case of a temporary fault in an ideally-transposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

Comparing the simulation results, it is confirmed that the main difference between the permanent and temporary fault cases is in the final value of $\delta_{mean}$ variable after the arc extinction. In fact, as predicted in Section 3.2, for both permanent and temporary fault cases, $\delta_{mean}$ variable has values around $90^\circ$ right after the line isolation. But, as the arc becomes extinguished for temporary fault cases, $\delta_{mean}$ increases toward a number around $180^\circ$ and settles down/resonates around it while stays around $90^\circ$ for the cases of permanent faults. This means, shortly after the line isolation, $\delta_{mean}$ moves ideally 90 more degrees for temporary fault cases.

### Untransposed line

$\delta_{mean}$ waveforms for two permanent fault cases in an untransposed line are shown in Figures 4.11 and 4.12. In both simulated cases, the fault resistance is equal to 1 $\Omega$ and happens at 30% distance of the sending side, i.e., Side A. For the case shown in Figure 4.11 the line is not compensated while shunt compensation is used for the case of Figure 4.11. As observed, in both cases $\delta_{mean}$ is around zero prior to the breaker opening at t = 0.27s. Similar to ideally-transposed line cases, this means the faulted phase and summation of the two non-faulted phase voltages (with negative sign) are still in phase. But after the single-phase isolation of the line, $\delta_{mean}$ increases and after some transients, finally settles down around the-first-lock-angle equal to 75° which is different from the-first-lock-angle associated with the ideally-transposed line cases. This difference in the phase angle value after the single-phase isolation of the line is because of the difference in phase angle of the equivalent voltage source behind the arc, which itself is due to the asymmetry in the values of the coupling capacitors in untransposed lines.

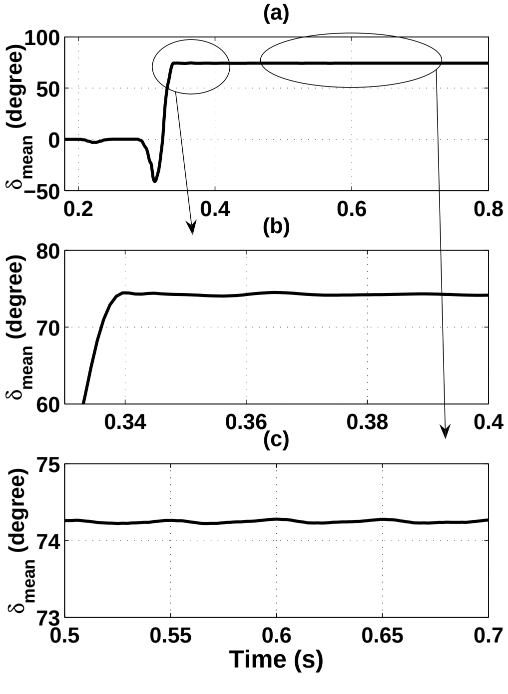

**Figure 4.11: (a) $\delta_{mean}$ for the case of a permanent fault in an untransposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

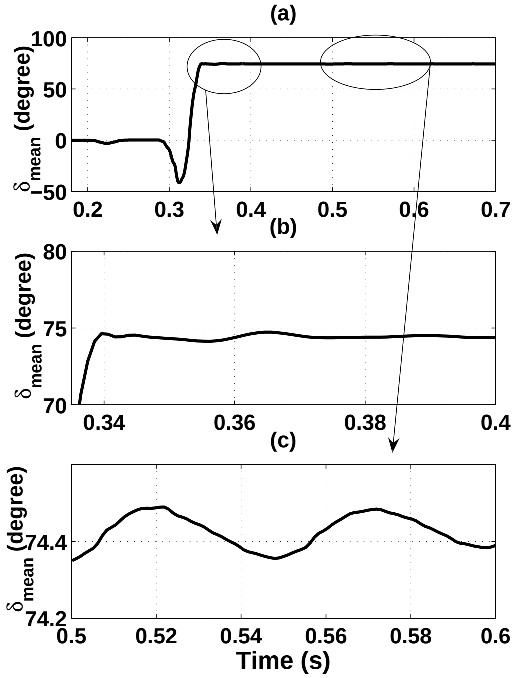

**Figure 4.12: (a) $\delta_{mean}$ for the case of a permanent fault in an untransposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

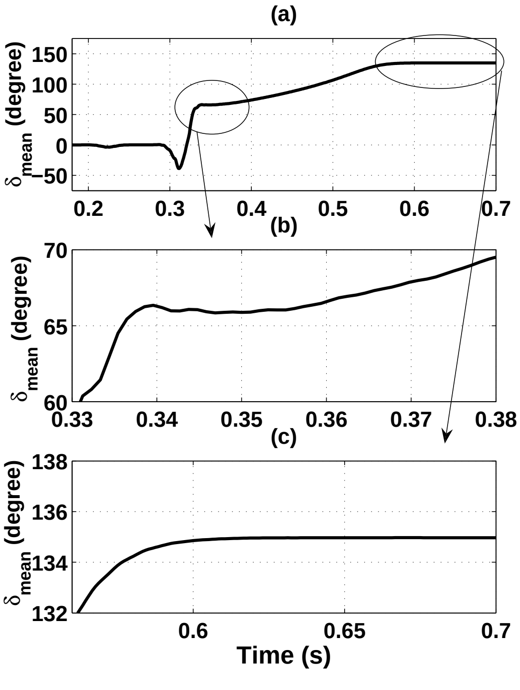

**Figure 4.13: (a) $\delta_{mean}$ for the case of a temporary fault in an untransposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

Similar to what discussed for the ideally-transposed cases, in untransposed line cases also, the phase angle has similar behaviors right after the line isolation for permanent and temporary faults. In fact, in untransposed lines, variable $\delta_{mean}$ is around 90° right after the line isolation. But this variable starts increasing slightly after the line isolation as the arc is becoming extinguished. This can be seen in Figures 4.13 and 4.14 in which variable $\delta_{mean}$ is shown for temporary fault cases in absence and presence of shunt reactor, respectively. As seen in both figures, the $\delta_{mean}$ value is zero before the line isolation, then jumps to the-first-lock-angle slightly after the isolation and then, slowly moves toward the-second-lock-angle as the arc is extinguishing. For uncompensated line cases, $\delta_{mean}$ settles down at the-second-lock-angle value after the arc extinction while it resonates around it if the line is compensated.

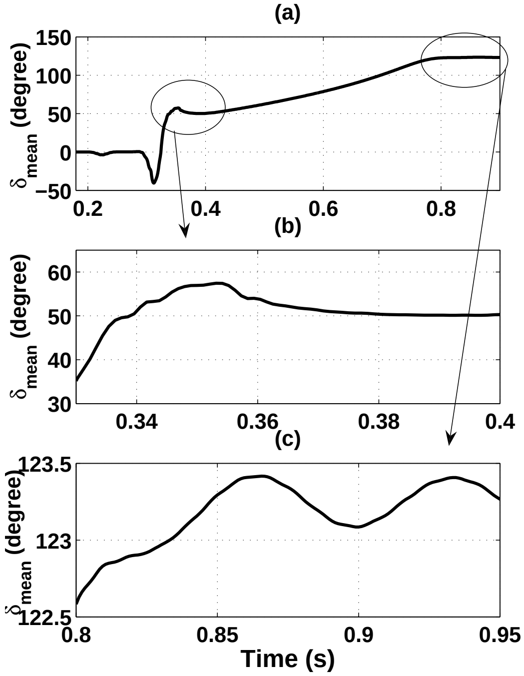

**Figure 4.14: (a) $\delta_{mean}$ for the case of a temporary fault in an untransposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

### Partially-transposed line

General behavior of $\delta_{mean}$ in partially-transposed lines is similar to ideally-transposed and untransposed line cases. In other words, this variable jumps from zero to the-first-lock-angle slightly after the line isolation for the both fault types, stays there for permanent faults while moves about 90 more degrees toward the-second-lock-angle for temporary fault cases. It is almost predictable as partially-transposed line is the midway of ideally-transposed and untransposed lines. $\delta_{mean}$ waveforms for permanent and temporary fault cases in absence and presence of shunt reactor are shown in Figures 4.15 to 4.18.

Considering the shown cases, for all three transmission line structures including ideally-transposed, untransposed and partially-transposed, and for both line compensation conditions including shunt compensated and uncompensated, they have a general pattern in common that helps for the fault discrimination, i.e., discrimination between permanent and temporary fault cases. In the all simulated cases, the phase angle $\delta_{mean}$ jumps from zero to the-first-lock-angle, some values around 90°, shortly after the line isolation. This variable stays there for permanent fault cases while it moves about 90 more degrees and reaches the-second-lock-angle for the cases of temporary faults. This feature is used for fault type identification in the proposed angle-based method.

If temporary fault is detected, the next step is to detect the arc extinction time as reclosing on fault is so harmful for the power system stability and system equipment. In fact, the feature of arc extinction detection is considered as very basic feature for an adaptive reclosing method. For this purpose, behavior of the variable $\delta_{mean}$ must be monitored. In fact, as discussed earlier in this Section, $\delta_{mean}$ either settles down at the-second-lock-angle, some values around 180°, for un-compensated line case or resonates around it for the cases of compensated lines. Therefore, the arc extinction signal will be activated when the settling down/oscillation is detected.

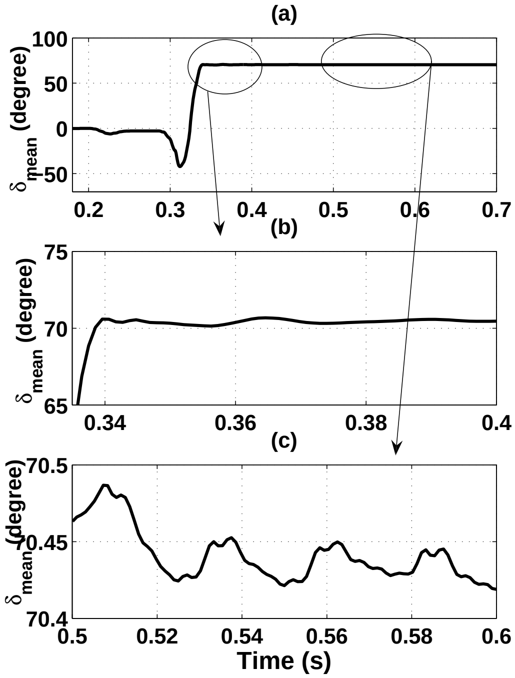

**Figure 4.15: (a) $\delta_{mean}$ for the case of a permanent fault in a partially-transposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

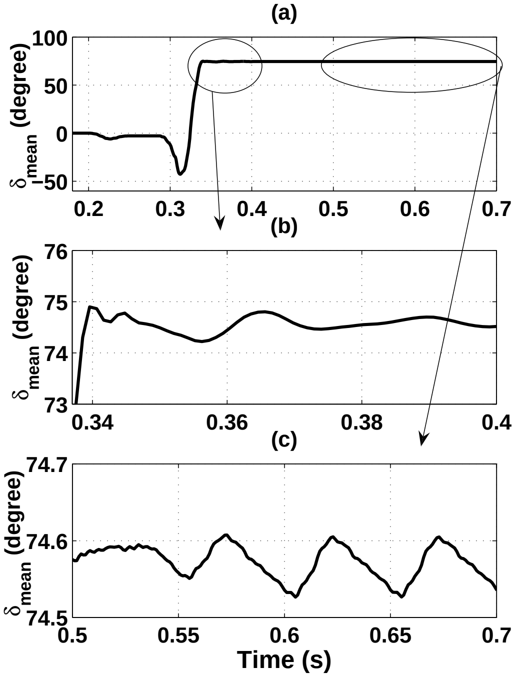

**Figure 4.16: (a) $\delta_{mean}$ for the case of a permanent fault in a partially-transposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

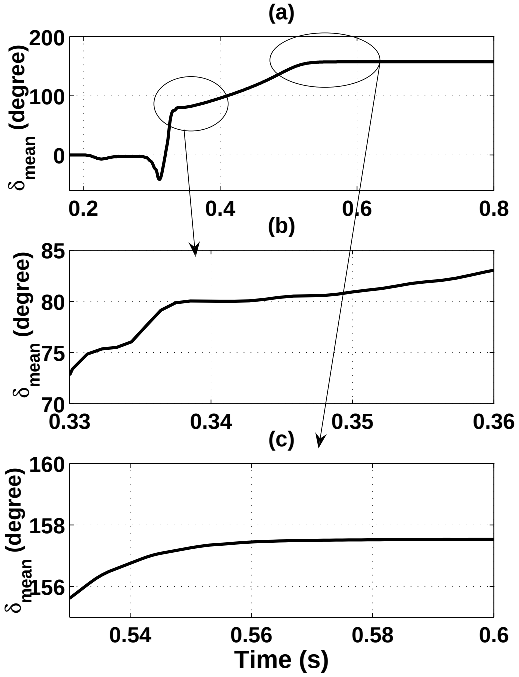

**Figure 4.17: (a) $\delta_{mean}$ for the case of a temporary fault in a partially-transposed transmission line, in absence of shunt reactor; (a) is zoomed in (b) and (c).**

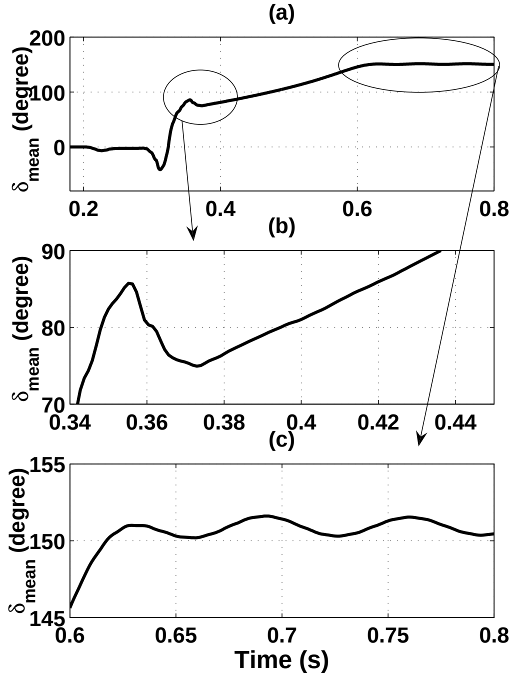

**Figure 4.18: (a) $\delta_{mean}$ for the case of a temporary fault in a partially-transposed transmission line, in presence of shunt reactor; (a) is zoomed in (b) and (c).**

### 4.1.2 Phasor-based analysis

In the phasor-based proposed single-phase reclosing method, similar to Chapter 3, normalized version of $V_s$, i.e., $V_{sn}$ as defined in (3.8) is considered to make easier comparisons. In this method, the major roles are being played by $V_{snD}$, the first derivative of $|V_{sn}|$ as define in (4.2), and by $\delta_D$, the first derivative of $\delta$. The derivation process for both variables are performed using Least Error Square (LES) method. For this purpose, a window of data (here $|V_{sn}|$ or $\delta$) of length of a half a power system cycle is approximated by a straight line while the window is moving toward positive numbers' side in time axis. The amount of the derivative ($V_{snD}$ or $\delta_D$) at each step is the slope of the straight line at that step. This process is done to guarantee smooth waveforms for $V_{snD}$ and $\delta_D$ as any rapid change may lead to maloperation of the relay.

$$V_{snD} = d(|V_{sn}|)/dt \tag{4.2}$$

**Permanent fault**

$|V_{sn}|$ and $V_{snD}$ for three different permanent fault cases are shown in Figures 4.19 to 4.21. Waveforms shown in Figure 4.19 stand for a permanent fault case with a fault resistance of 1 Ω at 30% of the line from Side A in an ideally-transposed transmission line with no shunt compensation. Figure 4.20 also represents the results for a permanent fault case while the line is shunt-compensated untransposed and the fault resistance is 10 Ω. Figure 4.21 also shows a permanent fault with 1 Ω resistance at 25% distance on an uncompensated line which is partially-transposed. As shown for all three cases, $|V_{sn}|$ drops during fault, i.e., the time interval between 0.2 s and 0.28 s. The amount of voltage drop depends on the fault location, fault characteristics and system strength.

Once the line is single-phase isolated at 0.28 s, $|V_{sn}|$ further drops to a considerably small value and remains constant after transients due to system configuration change, filtering and phasor estimation. This behavior of $|V_{sn}|$ exactly matches with the expected one derived by the theoretical analysis presented in Section 3.2. After the line single-phase isolation, $V_{snD}$ also drops smoothly from zero to its negative peak and then recovers again to zero as $|V_{sn}|$ has already become steady. This negative peak of $V_{snD}$, which will be used in the following sections, is registered as $V_{snD^N}$. After line single-phase isolation, ideally $V_{snD}$ has no positive peak as the faulted phase voltage is not recovered for permanent faults, while there can be a small positive peak as observed in Figures 4.19-(c), 4.20-(c) and 4.21-(c), named $V_{snD^P}$, which is because of system transients and filtering errors and $V_{snD}$ drops to zero after one power system cycle in the worst case. It should be noted that presence of shunt reactor has no effect on the waveforms in case of permanent faults because of the fact that shunt reactor draws negligible current from the faulted phase due to the presence of small amount of faulted phase voltage in both cases.

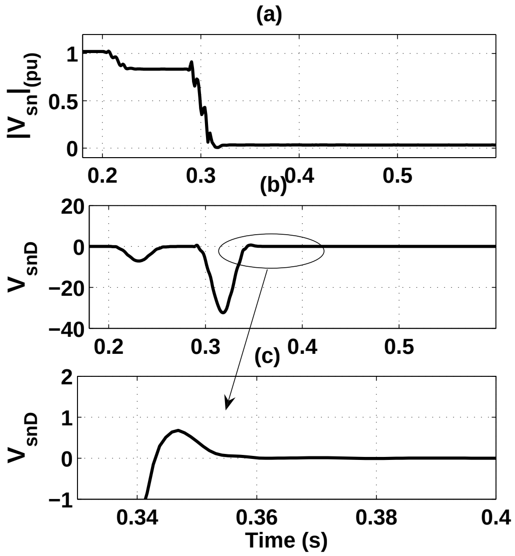

**Figure 4.19: Normalized faulted phase voltage magnitude and its first derivative for a permanent fault case in an ideally-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

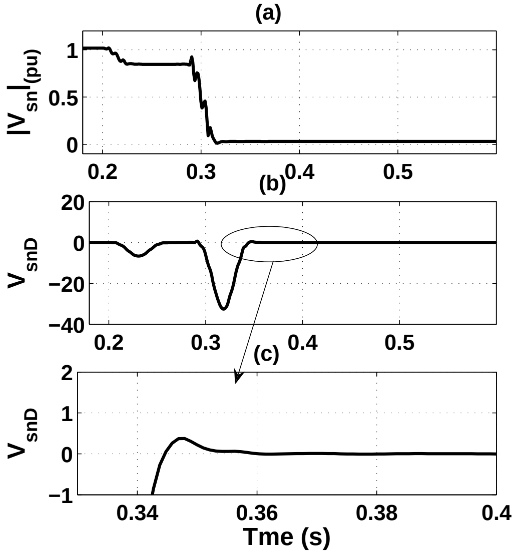

**Figure 4.20: Normalized faulted phase voltage magnitude and its first derivative for a permanent fault case in an untransposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

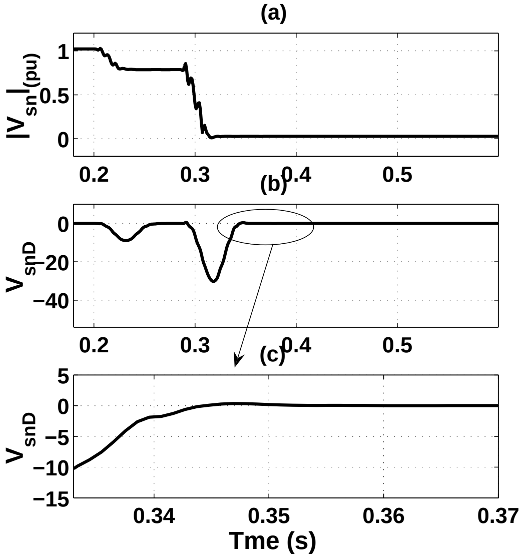

**Figure 4.21: Normalized faulted phase voltage magnitude and its first derivative for a permanent fault case in a partially-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

When the faulted phase voltage drops to zero due to the line single-phase isolation at $t$ = 0.28s, $V_{snD}$ must ideally reach a considerable negative value and then recover to zero in a very short time interval, as the voltage drops almost instantaneously. However, as observed in Figure 4.19, there is a time delay which is because of filtering, phasor estimation, and LES-based derivation calculation delays each equal to 1.5, 1.25 and 0.5 cycles, respectively. Therefore, it takes about 3.25 power system cycles for $V_{snD}$ to drop to $V_{snD^P}$ and then recover to zero after the line single-phase isolation.

### Temporary fault

To validate the expected voltage behavior of the faulted phase derived in Section 3.2 for temporary faults, several faults are simulated in ideally-transposed, untransposed and partially-transposed lines, in absence and presence of shunt reactor, and at different fault locations. Also for the purpose of arc modeling, Arc1 characteristics of Table 3.1 is used.

$|V_{sn}|$ and $V_{snD}$ for the six temporary fault cases are shown in Figures 4.22 to 4.27. As observed, once the line is single-phase isolated at 0.28s, $|V_{sn}|$ reaches a considerably small value, similar to the earlier permanent fault cases, and $V_{snD_N}$ can be obtained similar to permanent faults cases. However, voltage magnitude increases later as arc resistance increases. Comparing Figures 4.22 to 4.27 with Figures 4.19 to 4.21, $|V_{sn}|$ of temporary fault cases recovers to a higher value as compared to the permanent faults, after line single-phase isolation ($t$ = 0.28 s). This pattern exactly matches with the expected behavior derived by the analytical analysis presented in Section 3.2. $V_{snD}$ also makes a larger positive peak, to be called $V_{snD^P}$, after voltage recovery compared to the permanent fault cases. In addition, $V_{snD}$ keeps holding large positive values for a considerable time interval while the voltage is being recovered. This can be observed by comparing Figures 4.22-(c), 4.23-(c), 4.24-(c), 4.25-(c), 4.26-(c) and 4.27-(c) with Figures 4.19-(c), 4.20-(c) and 4.21-(c).

Regardless of the fault type, smaller $|V_{snD^N}|$ and $V_{snD^P}$ are obtained for the case of stronger systems as the system resists against the faulted phase voltage change. This is also true for the case of larger fault resistances as the fault is not that strong to change the system voltage. However, the key point is that for the equal values of $|V_{snD^N}|$, larger $V_{snD^P}$ values will be obtained for temporary faults compared to permanent fault cases and in fact, there is a considerable gap between $V_{snD^P}$ values. This is actually true not only for $V_{snD^P}$, but also for all $V_{snD}$ values after the second voltage recovery. This gap is even larger for $V_{snD}$ values after the positive peak as $V_{snD}$ drops to zero considerably faster for permanent faults compared to temporary fault cases. This is valid for all possible cases including ideally-transposed, untransposed and partially-transposed transmission lines and even presence or absence of shunt and/or neutral reactors has no effect on this fact. This feature is the main measure to discriminate temporary and permanent faults in this research study.

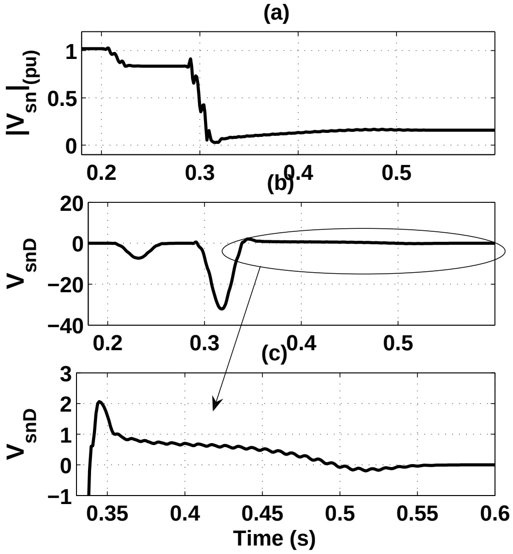

**Figure 4.22: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in an ideally-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

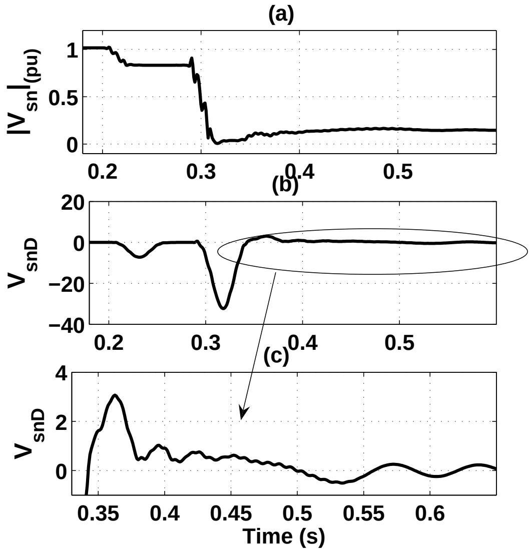

**Figure 4.23: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in an ideally-transposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

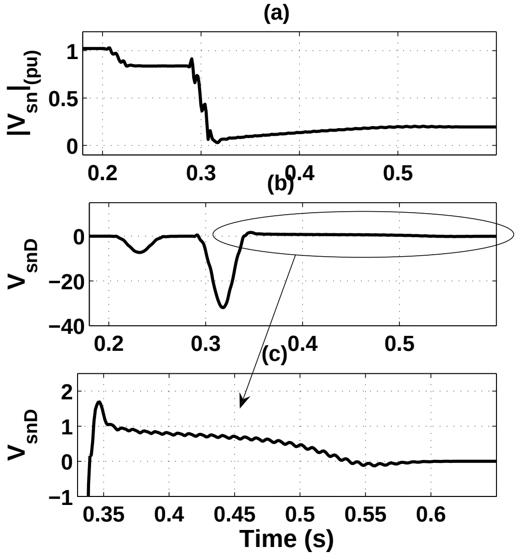

**Figure 4.24: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in an untransposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).**

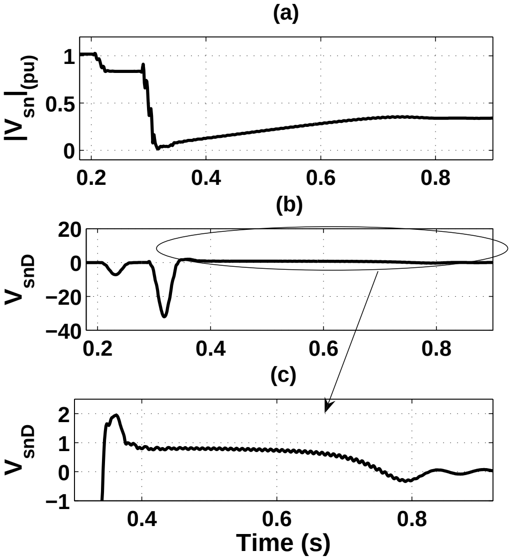

Figure 4.25: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in an untransposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).

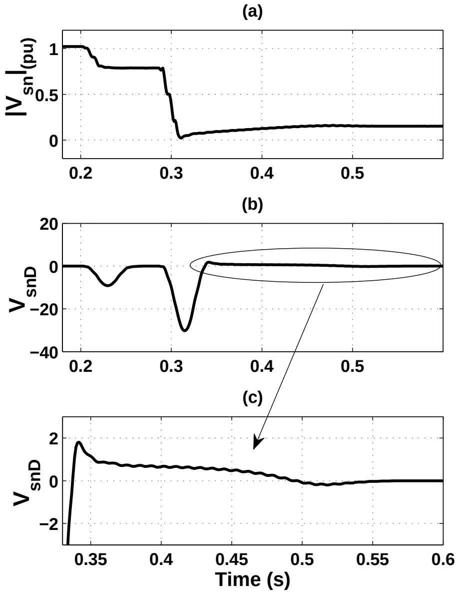

Figure 4.26: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in a partially-transposed transmission line, in absence of shunt reactor; (b) is zoomed in (c).

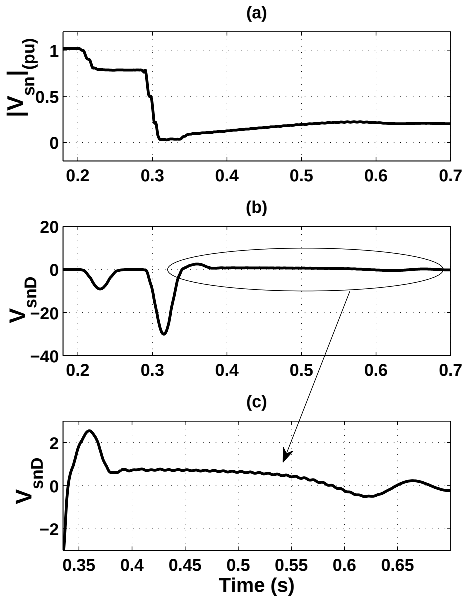

**Figure 4.27: Normalized faulted phase voltage magnitude and its first derivative for a temporary fault case in a partially-transposed transmission line, in presence of shunt reactor; (b) is zoomed in (c).**

### Arc extinction

The other vital point about temporary fault cases to consider is how to recognize arc extinction as the breaker is not supposed to reclose before real arc extinction. This is done in the phasor-based method based on the fact that after the arc extinction, some kind of stability appears in the system. Therefore, both $V_{snD}$ and $\delta_D$ variables, i.e., the first derivations of $|V_{sn}|$ and $\delta$, either settle down at or resonate around their final values which is zero for both variables.

In the PSCAD simulations, the arc current is monitored to determine the actual arc extinction time. The time instance when the current is above 2A for the last time is recorded as the actual arc extinction time [84]. Having done this for 275 temporary fault cases, it is observed that the arc extinction time estimated using the above-mentioned features is very close to the actual arc extinction time.

For the purpose of arc extinction detection, both variables of $V_{snD}$ and $\delta_D$ are employed. $\delta_D$ for two temporary fault cases in an untransposed line is shown in Figures 4.28 and 4.29. In these figures, $\delta_D$ settles down (Figure 4.28-(b)) or resonates (Figure 4.29-(b)) at $t = 0.6$s and $t = 0.82$s, respectively, while the arc extinction times using $V_{snD}$ are $t = 0.55$s and $t = 0.75$s. Comparing the obtained arc extinction times with PSCAD results of $t = 0.57$s and $t = 0.78$s, it has been observed that $\delta_D$ settles down or resonates slightly later than reality while $V_{snD}$ reacts faster than the actual arc. This was the case for almost all of the temporary fault simulated cases. In the phasor-based reclosing method, both $V_{snD}$ and $\delta_D$ are used for the arc extinction detection purpose.

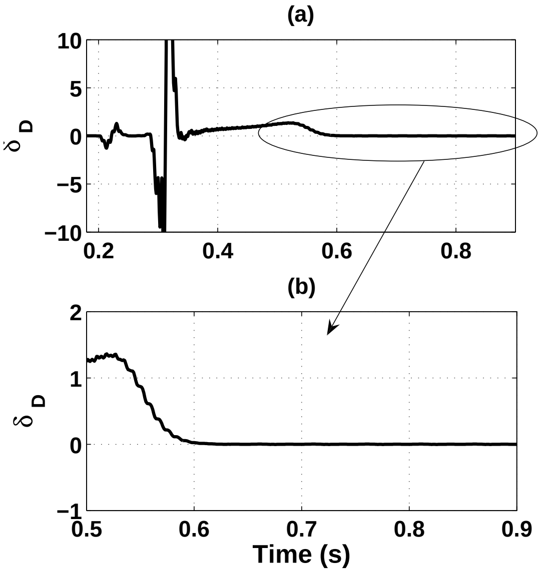

**Figure 4.28: First angle derivative for the case of a temporary fault case in an untransposed transmission line, in absence of shunt reactor; (a) is zoomed in (b).**

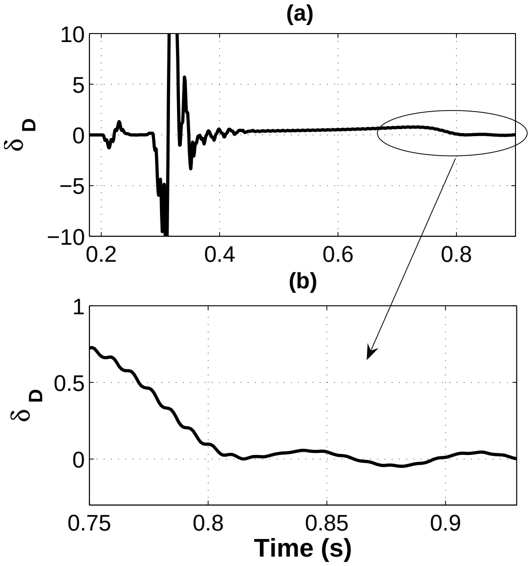

**Figure 4.29: First angle derivative for the case of a temporary fault case in an untransposed transmission line, in presence of shunt reactor; (a) is zoomed in (b).**

## 4.2 Proposed Adaptive Reclosing Algorithms

### 4.2.1 Angle-based algorithm

Block diagram of the proposed angle-based adaptive single-phase reclosing algorithm is shown in Figure 4.30. The angle-based algorithm can be initiated either by auxiliary contacts of the line circuit breakers or through analyzing CT secondary current as proposed in [19]. The faulted phase is determined and the process starts if single-phase-to-ground fault inception is confirmed. Present-day line protection relays are equipped with phase selector function which reliably determines the faulted phases.

According to the shown diagram in Figure 4.30, voltage values of all three phases and the breaker interruption information are used for calculation of the $\delta$ parameter after anti-aliasing and CVT temporary filtering and phasor estimation [116]. Having $\delta$ in hand, $\delta_{mean}$ is obtained using an averaging unit. This averaging unit is simply a combination of an accumulator and a divider, together a digital filter.

The obtained $\delta_{mean}$ variable is used for fault type identification. In case the detected fault type is permanent, three-phase trip signal will be issued. But in case temporary fault is identified, single-phase reclosing signal will be issued after arc extinction detection. Arc extinction process itself is performed using $\delta_{mean}$ variable too.

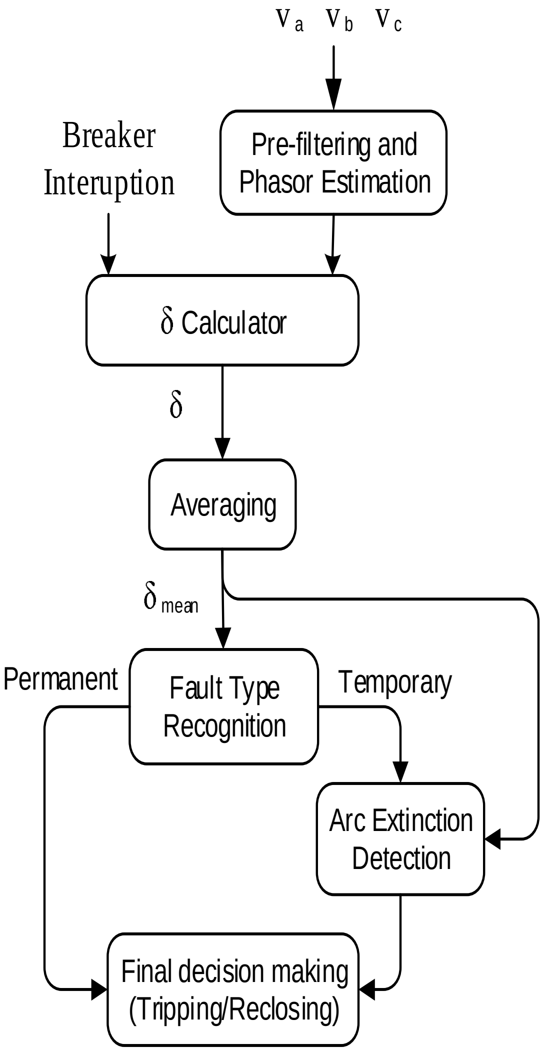

**Figure 4.30: Block diagram of the proposed angle-based adaptive single-phase reclosing algorithm.**

### Fault type recognition

As mentioned in Subsection 4.1.1, similarity between permanent and temporary faults is that for both cases, $\delta_{mean}$ moves from zero to an angle around 90°, called the-first-lock-angle. The-first-lock-angle is dependent on the line structure and the faulted phase, but in an ideally-transposed line, it is 90°, ideally. The difference between the two fault types projected to $\delta_{mean}$ is that for permanent faults, $\delta_{mean}$ stays at the-first-lock-angle while it moves about more 90 degrees for temporary fault cases, either in positive or negative direction, and settles down/resonates around another phase angle value called the second-lock-angle. Therefore, it is possible to recognize the fault type in two simple steps as:

1) To find the-first-lock-angle,

2) To realize if $\delta_{mean}$ stays around the-first-lock-angle or moves toward another value, i.e., the second-locked-angle.

In the proposed algorithm, $\delta_{mean}$ is monitored after the line isolation to see if it stays around any value with variation as small as 5° for one full length of the power system cycle. This angle value is detected as the-first-lock-angle. In the next step, $\delta_{mean}$ is monitored for 5 more power system cycles. The fault type will be detected permanent if $\delta_{mean}$ stays in the range, i.e., at the-first-lock-angle ±2.5°, for at least five power system cycles. Otherwise, it is a temporary fault.

### Arc extinction detection

For temporary fault cases, the next step after the fault type identification is arc extinction detection so that reclosing onto fault is prevented. The detected time for the arc extinction must be slightly after the real arc extinction, as too long arc extinction detected time means the system will have to work in unbalanced condition, unnecessarily. For this purpose, two different cases are possible, shunt compensated and uncompensated lines. For the both cases, the variable $\delta_{mean}$ increases toward the-second-lock-angle. It will stay there in case the line in not compensated while it will resonate around the-second-lock-angle for shunt compensated lines.

In the proposed arc extinction detection algorithm, technically, there are two blocks that can detect the arc extinction, settling-down detection and resonance detection. The initial duty of the settling-down detector is to detect the second-locked-angle. This happens when $\delta_{mean}$ increases to a value and stays around ±2.5° for at least 3 full cycles. This can be done by simply monitoring the $\delta_{mean}$ variable. The other possible case is when $\delta_{mean}$ resonates around the second-locked-angle. In such a case, at first the peak and the next dip right afterward around the second-locked-angle are detected. Then, the very first time at which $\delta_{mean}$ reaches the average value of the peak and the dip is recognized as the arc extinction time.

### 4.2.2 Phasor-based algorithm

Block diagram of the proposed phasor-based reclosing algorithm is shown in Figure 4.31. Similar to the angle-based reclosing method, the phasor-based algorithm can also be initiated either by auxiliary contacts of the line circuit breakers or through analyzing CT secondary current as proposed in [19]. The faulted phase is determined and the process starts if single-phase-to-ground fault inception is confirmed. Present day line protection relays are equipped with phase selector function which reliably determines the faulted phases. In the proposed algorithm, assuming that the faulted phase is known, $V_{snD}$ and $\delta_D$ are obtained by derivating $|V_{sn}|$ and $\delta$ by means of half-cycle LES algorithm, after anti-aliasing and CVT temporary filtering and phasor estimation [116]. Using these variables, first, the fault type is identified. For the permanent fault cases, three-phase tripping will be initiated immediately, while single-phase reclosing will be commanded once arc extinction is detected, for temporary faults.

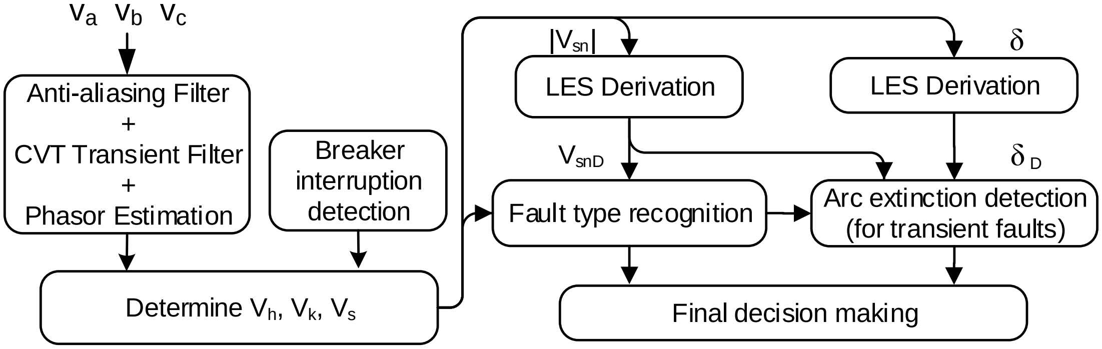

**Figure 4.31: Block diagram of the proposed adaptive single-phase reclosing algorithm.**

**Fault type recognition**

As mentioned in Subsection 4.1.2, after the line single-phase isolation, the ratio of $V_{snD}$ to $|V_{snD^N}|$ is larger for temporary faults than permanent fault cases and the difference becomes even larger after the positive peak, $V_{snD^P}$. Hence, the voltage derivative ratio, *VDR*, as given in (4.3) is defined for fault identification.

$$VDR = |\frac{V_{snD}}{V_{snD^N}}| \ (\%) \tag{4.3}$$

To calculate *VDR*, $V_{snD}$ must be monitored after the line single-phase isolation to obtain $V_{snD^N}$. Considering the fact that it takes around 3.25 cycles for $V_{snD}$ to make a negative peak and then recover to zero after the line single-phase isolation, as mentioned in Subsection 4.1.2, $V_{snD^N}$ must be obtained within this time interval. For permanent fault cases, $V_{snD^P}$ appears slightly after 3.25 cycles and then $V_{snD}$ drops to zero shortly, while it will remain positive as the arc is being extinguished in cases of temporary fault. Therefore, by monitoring $V_{snD}$ for a sufficient time interval after the line single-phase isolation, the fault type can be identified.

In this research study, considering various delays such as local circuit breaker opening detection, delay between circuit breaker operation at both line ends, CVT temporary and relay filtering and estimations, it is proposed to monitor $V_{snD}$ for 6 cycles or 100 ms after the line single-phase isolation. Then, $VDR$ is calculated at each protection pass for the $6^{th}$ cycle, i.e. the time interval within 83ms to 100ms. In this case, 16 values for $VDR$ will be obtained for the $6^{th}$ cycle. The fault type will be recognized using $VDR^t$, the summation of the 16 obtained $VDR$ values. In cases of permanent fault, $VDR^t$ is ideally zero although in practice it can have a very small value due to various sources of error. In cases of temporary fault, $VDR^t$ is considerably larger than the one obtained for permanent faults. In this research study, $VDR^t = 5\%$ has been chosen as a threshold for discrimination. For temporary fault detection, $VDR$ must be larger than 5%, while, $VDR < 5\%$ leads to permanent fault detection.

In the case of a close-in fault with very small resistance, voltage drops to zero immediately after the fault inception. Therefore, line single-phase isolation does not lead to further voltage drop. This means $V_{snD^N}$ will be detected as zero and this will be the case for all 16 values of $V_{snD}$ of the $6^{th}$ monitored cycle. To cover this condition, permanent fault is detected in case the faulted phase voltage magnitude stays less than 0.5% of the rated voltage for the entire 100ms monitoring time interval.

### Arc extinction detection

In case of temporary faults, the main sign of arc extinction is some kind of settlement in system variables. In this case, both $V_{snD}$ and $\delta_D$ settle down at/resonate around their final values as the arc extinguishes and they are chosen for arc extinction detection purpose as discussed in Subsection 4.1.2.

Based on the comprehensive simulation study performed, it was observed that in most of the cases, the signs of the arc extinction appear in $V_{snD}$ about or before the real arc extinction, whereas, these signs show up in $\delta_D$ always after the real arc extinction. Further, in case of fast arc extinction, it is hard to find a proper reference time to start monitoring $\delta_D$ for arc extinction detection as there are large transients on $\delta_D$ after the line single-phase isolation as shown in Figures 4.28 and 4.29. In addition, the arc extinction algorithm requires to analyze $V_{snD}$ or $\delta_D$

for several samples after real arc extinction to reliably detect the arc extinction. In this research study, it is proposed to use both quantities to increase the reliability and speed of detection.

In the proposed method, having recognized the temporary fault, initial arc extinction is detected if $V_{snD}$ becomes less that 10% of $V_{snD^P}$ for three consecutive protection passes. Then, this initial arc extinction is confirmed by observing $\delta_D$ smaller than a very small value; $0.1°/s$ is considered in this research study. This strategy increases the security of the reclosing algorithm and also the reclosing speed by eliminating the waiting time for arc extinction detection. The merit of involving $V_{snD^P}$ in the arc extinction detection algorithm is to provide an adaptive threshold for $V_{snD}$ settlement detection as faster extinguishing arcs result in larger $V_{snD^P}$. Therefore, it is not needed to wait for $V_{snD}$ settlement detection for too long in such cases, while for slower arcs, the algorithm will wait longer to ensure reliable detection as $V_{snD^P}$ is smaller.

## 4.3 Simulation Results

In this research, 550 simulated cases have been used for performance evaluation of the proposed method. The simulated cases can be categorized into three groups based on the transposition method considered for the transmission line including ideally-transposed (100 cases), untransposed (210 cases) and partially-transposed (240 cases). Various cases are different in terms of fault location, arc type (Arcs 1 to 3 for temporary fault cases as per Table 3.1), arc resistance (for permanent fault cases) and presence/absence of shunt/neutral reactor.

### 4.3.1 Angle-based method

According to the algorithm of the angle-based reclosing method, variable $\delta_{mean}$ is used for fault type recognition. In this order, if this variable stays at the-first-lock-angle ±2.5° for 5 power system cycles, then the fault is considered as permanent, otherwise it is a temporary fault and therefore, the next step would be to find the arc extinction time to activate the reclosing signal.

Average fault type detection time, i.e., temporary or permanent, for transmission lines with ideally-transposed, untransposed and partially-transposed structures are available in Tables 4.1 to 4.3. In these tables, fault location is the distance of the fault inception point from the sending end, in percent of the line length. Using these tables, the average time for ideally-transposed and untransposed lines is from 9ms to 233ms, and from 7ms to 221ms, respectively. This is 7 ms to 194ms for fault type detection in the partially-transposed line.

Average needed time for detection of a temporary fault in ideally-transposed, untransposed and partially-transposed lines are 69ms, 88ms and 81ms, respectively. The same values with the same order for permanent fault detection are 155 ms, 122 ms and 150 ms. Average time needed for detection of a temporary fault including all temporary fault cases is 91ms while it is 139ms for all permanent fault cases. As observed, there is considerably longer time needed for permanent fault type detection than for temporary. The reason is that the algorithm has to wait for 5 power system cycles to make sure if it is a permanent fault, while it can detect a temporary fault any time after the-first-lock-angle as soon as the sign of the temporary fault appears, i.e., increment of the variable $\delta_{mean}$ more than 2.5°.

Considering the compensation condition of the lines, regardless of the fault type, the average needed time for the fault detection is 106ms and 115ms for the ideally-transposed line in absence and presence of shunt reactor, respectively. For the untransposed line, it is 95ms and 108ms and for the partially-transposed line, it is 83ms and 92ms, respectively. This means, the proposed algorithm has a better performance for uncompensated lines.

**Table 4.1: Average temporary fault detection time for an ideally-transposed and an untransposed line using the angle-based method (ms).**

| Fault location | | | 0% | 30% | 70% | 100% |
|---|---|---|---|---|---|---|
| Ideally Transposed | No shunt reactor | | 9 | 76 | 76 | 72 |
| | With shunt reactor | | 43 | 101 | 77 | 69 |
| Untrans-posed | Side conductor | No shunt reactor | 73 | 89 | 86 | 79 |
| | | With shunt reactor | 68 | 78 | 48 | 66 |
| | Middle conductor | No shunt reactor | 7 | 75 | 74 | 74 |
| | | With shunt reactor | 68 | 78 | 48 | 66 |

**Table 4.2: Average permanent fault detection time for an ideally-transposed and an untransposed lines using the angle-based method (ms).**

| Fault location | | | 0% | 30% | 70% | 100% |
|---|---|---|---|---|---|---|
| Ideally Transposed | No shunt reactor | | 226 | 131 | 131 | 128 |
| | With shunt reactor | | 233 | 131 | 131 | 128 |
| Untrans-posed | Side conductor | No shunt reactor | 160 | 146 | 143 | 141 |
| | | With shunt reactor | 153 | 146 | 144 | 142 |
| | Middle conductor | No shunt reactor | 112 | 145 | 139 | 141 |
| | | With shunt reactor | 221 | 146 | 139 | 141 |

**Table 4.3: Average fault type recognition time for a partially transposed transmission line using the angle-based method (ms).**

| Fault location | | 0% | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|
| Temporary | No shunt reactor | 7 | 73 | 71 | 70 | 71 | 68 | 70 |
| | With shunt reactor | 102 | 83 | 79 | 79 | 85 | 82 | 84 |
| Permanent | No shunt reactor | 194 | 146 | 144 | 142 | 140 | 140 | 143 |
| | Wth shunt reactor | 193 | 147 | 145 | 144 | 143 | 141 | 142 |

The average fault detection time including all the simulated cases for ideally-transposed, untransposed and partially-transposed lines is 224 ms, 105 ms and 92 ms, respectively. This means the algorithm has the fastest operation for the partially-transposed line while it is the slowest for the ideally-transposed line. This can be a good sign as partially-transposition is the most practical structure of the lines while there is no ideally-transposed line in practice. And finally, the average fault detection time including all the simulated cases is 140ms.

Average fault type recognition times, including both temporary and permanent, for ideally-transposed, untransposed and partially-transposed lines in absence and presence of shunt reactor are shown in Figures 4.32 to 4.35. As observed, for faults not so close to the relay location, the temporary fault recognition speed is considerably close for ideally-transposed and untransposed line cases. This is also true for permanent fault type cases. However, for partially-transposed line, the fault recognition speed is considerably faster, for both temporary and permanent fault cases. Also, in general, the performance of the method is faster for uncompensated lines than for compensated lines considering all three line configurations.

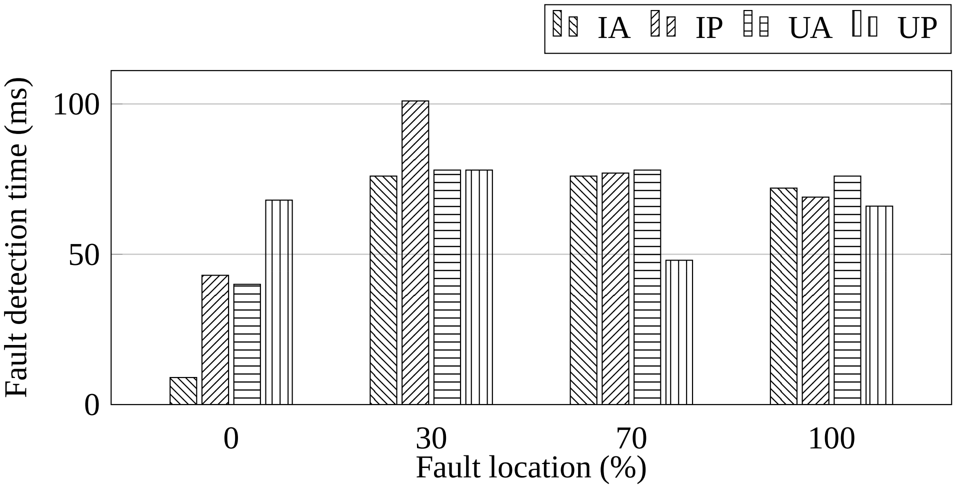

**Figure 4.32: Average temporary fault detection time for an ideally-transposed and an untransposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

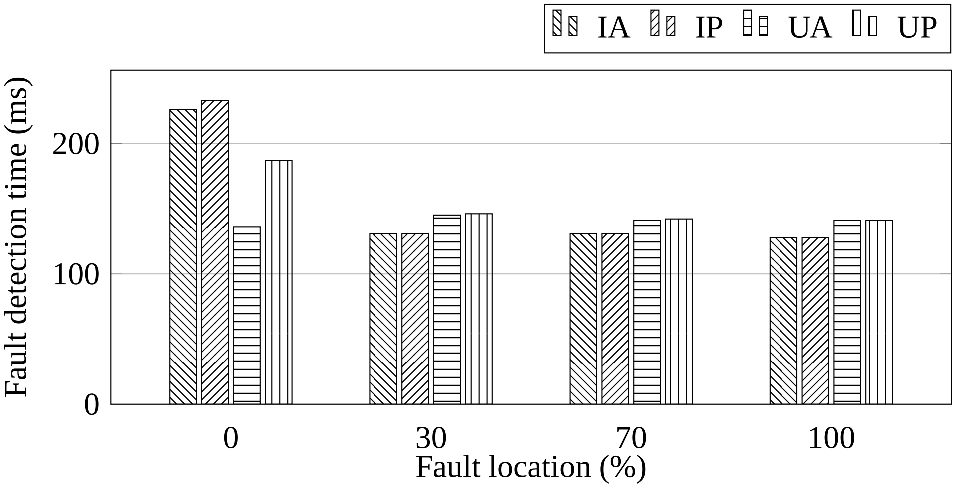

**Figure 4.33: Average permanent fault detection time for an ideally-transposed and an untransposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

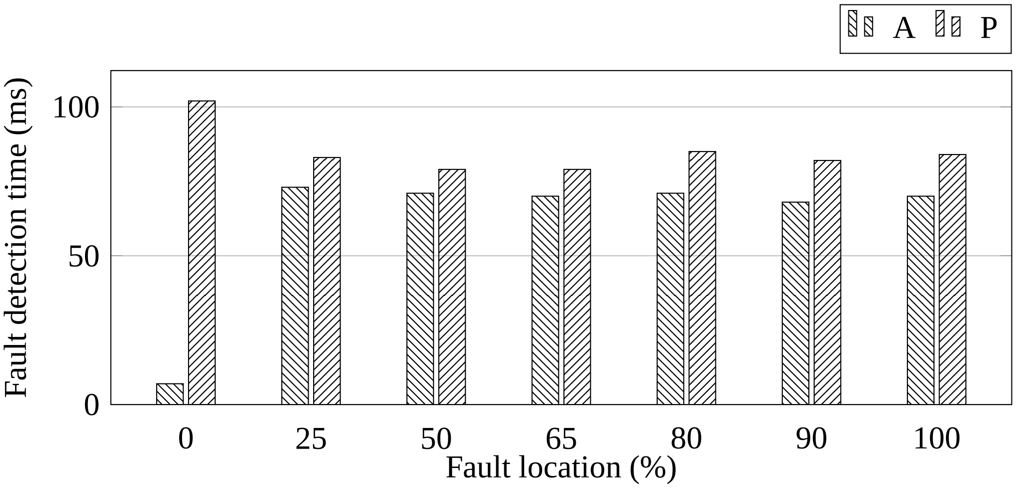

**Figure 4.34: Average temporary fault detection time for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

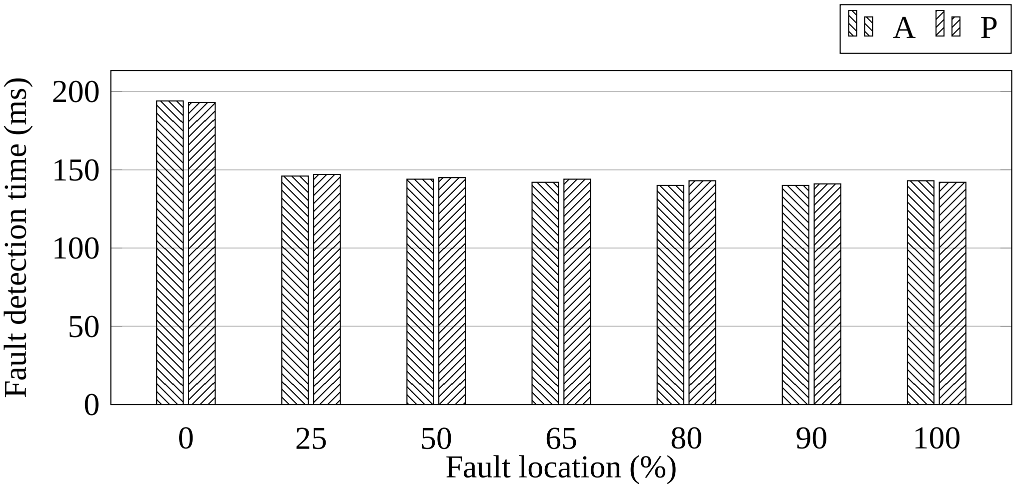

**Figure 4.35: Average permanent fault detection time for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

After the fault type recognition, a proper decision must be made by the relay. For permanent fault cases, the proper decision is always to issue the three-phase trip signal as there is no hope for the fault to be cleared by itself. However, there is a chance for fault clearance if the fault is temporary. For such cases, the next step is to issue the single-phase reclosing signal. But, reclosing has to happen in a reasonable amount of time after the arc extinction. If reclosing happens too late, the system has worked in an unbalanced condition for some amounts of time, unnecessarily, and if it happens before the arc extinction, it is harmful for the system equipment and the system stability. For this purpose, an adaptive method must be able to detect the exact arc extinction time.

Average and maximum reclosing time delay, the time distance between the arc extinction detection moment proposed by the adaptive angle-based algorithm and the real arc extinction time obtained based on PSCAD simulations, for ideally-transposed, untransposed and partially-transposed line simulated cases are presented in tables 4.4 to 4.6. For each fault location and/or transmission line configuration, the averaging is applied to three time delay values obtained for three sets of arc parameters, including faster/medium/slower arcs.

In table 4.4, the average reclosing time delay for the ideally-transposed case is between 48 and 59ms. The same values for untransposed and partially-transposed cases are 45 to 114ms and 18 to 74ms, respectively. Therefore, the overall performance of the method is between 18 and 114ms including all temporary fault cases. However, reclosing delay is between 70 and 160ms for the method proposed in [62]. Method of [56] also provides the average processing times between 29 and 67ms for temporary faults. Therefore, the method of this research study has been faster than the method of [62] but slower in total than the method proposed in [56]. It might be considered that the proposed method in [56] is only applicable for ideally-transposed lines. In addition, it employs data of both sides of the transmission line and requires communication facilities too, while the proposed technique in this research study is based on local data application. The proposed technique is also effective for any kind of system transposition configuration and absence/presence of shunt reactor has no effect on the technique's performance.

The average arc extinction detection delay of the proposed phase angle-based algorithm for the ideally-transposed line is 49 ms and 57 ms in absence and presence of shunt reactor, respectively. For the untransposed line, these values are 60ms and 74ms. Also, they are 46ms and 50ms for the cases of the partially-transposed line. This shows that the proposed algorithm can detect the arc extinction faster when the line is not compensated.

Regardless of the shunt compensation condition of the line, the arc extinction detection delay of the algorithm is 55 ms, 70 ms and 49 ms respectively for the ideally-transposed, untransposed and partially-transposed lines. This means the proposed algorithm shows the highest performance for the partially-transposed line while the slowest performance belongs to the untransposed line. Finally, the overall delay of the algorithm in detection of the arc extinction is 58ms.

**Table 4.4: Average reclosing time delay for an ideally-transposed and an untransposed lines using the angle-based method (ms).**

| Fault location | | | 0% | 30% | 70% | 100% |
|---|---|---|---|---|---|---|
| Ideally Transposed | No shunt reactor | | 50 | 49 | 48 | 48 |
| | With shunt reactor | | 57 | 59 | 59 | 52 |
| Untrans-posed | Side conductor | No shunt reactor | 60 | 56 | 63 | 65 |
| | | With shunt reactor | 45 | 102 | 114 | 105 |
| | Middle conductor | No shunt reactor | 60 | 59 | 57 | 61 |
| | | With shunt reactor | 55 | 54 | 51 | 61 |

**Table 4.5: Maximum reclosing time delay for an ideally-transposed and an untransposed lines using the angle-based method (ms).**

| Fault location | | | 0% | 30% | 70% | 100% |
|---|---|---|---|---|---|---|
| Ideally Transposed | No shunt reactor | | 56 | 57 | 57 | 57 |
| | With shunt reactor | | 64 | 62 | 62 | 55 |
| Untrans-posed | Side conductor | No shunt reactor | 62 | 67 | 65 | 65 |
| | | With shunt reactor | 63 | 149 | 148 | 145 |
| | Middle conductor | No shunt reactor | 62 | 65 | 63 | 65 |
| | | With shunt reactor | 70 | 71 | 69 | 65 |

**Table 4.6: Average and maximum reclosing time delay for a partially transposed transmission line using the angle-based method (ms).**

| Fault location | | 0% | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|
| Ave-rage | No shunt reactor | 54 | 62 | 60 | 48 | 35 | 21 | 41 |
| | With shunt reactor | 74 | 89 | 71 | 53 | 36 | 18 | 18 |
| Max-imum | No shunt reactor | 61 | 70 | 67 | 58 | 47 | 36 | 52 |
| | Wth shunt reactor | 89 | 104 | 78 | 61 | 63 | 32 | 45 |

Average and maximum reclosing time delay for ideally-transposed, untransposed and partially-transposed lines are shown in Figures 4.36 to 4.39. First of all, it is observed that average and maximum reclosing time delay values are considerably close to each other for each fault location/line configuration. This means, for each fault location/line configuration, the proposed method is able to detect the arc extinction after almost the same time delay regardless of the arc extinction speed/arc parameters. Hence, it can be concluded that the proposed method is not considerably sensitive to the arc parameters.

It is also observed that, beside the close-in fault cases, the fault location does not have specific effect on the average and maximum reclosing time delays for ideally-transposed and untransposed lines. Also, the method has had a better performance for ideally-transposed line. However, for partially-transposed line cases, average performance of the method increases by increment of the fault distance from the relay location. This means, for the faults at further locations, the method has better performances. However, the maximum reclosing delay is smaller for faults at the middle of the line.

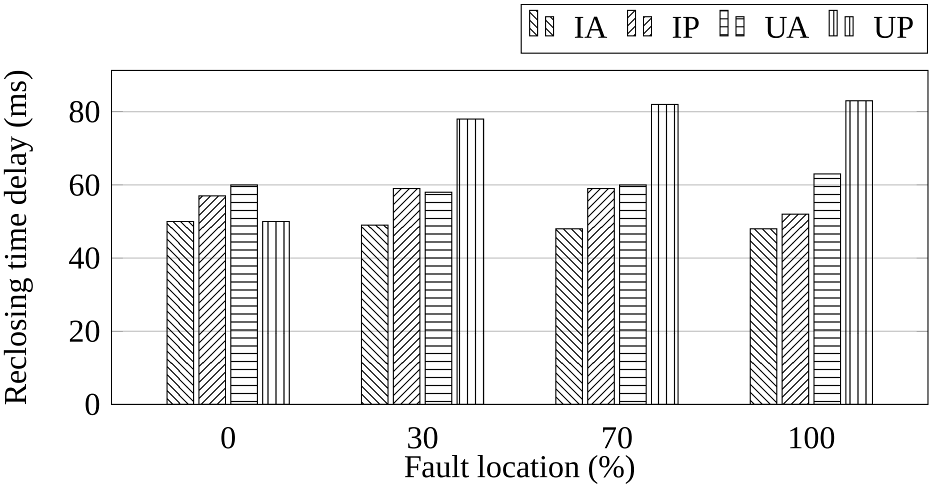

**Figure 4.36: Average reclosing time delay for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

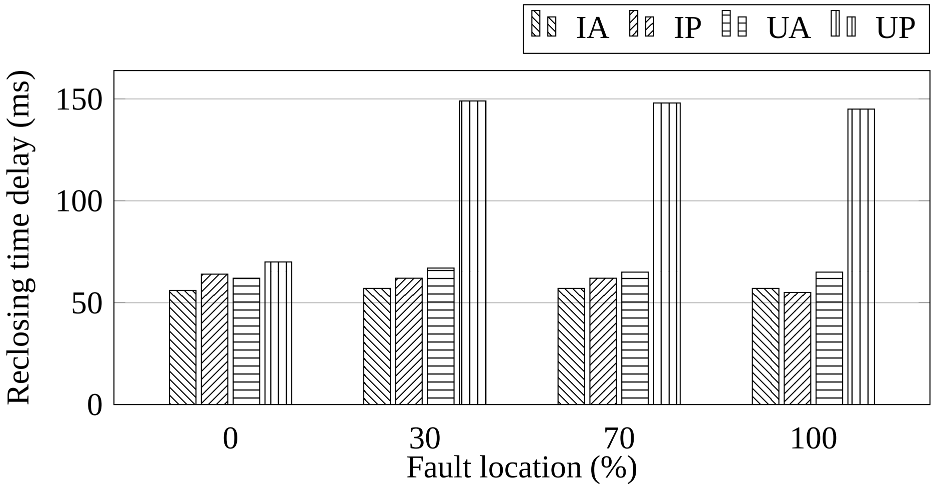

Figure 4.37: Maximum reclosing time delay for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).

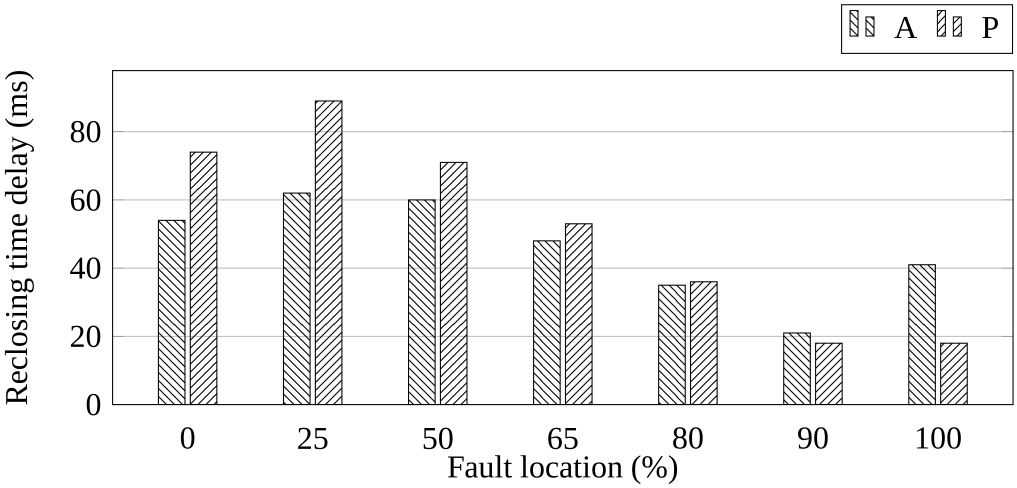

Figure 4.38: Average reclosing time delay for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).

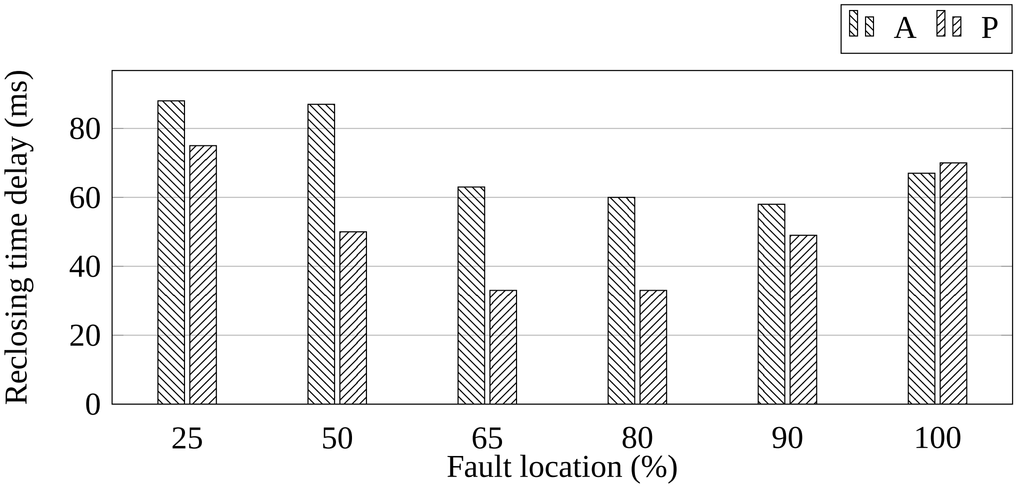

**Figure 4.39: Maximum reclosing time delay for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the angle-based method (ms).**

The proposed algorithm has also been applied to a field recorded data, a temporary AG fault in 765 kV Rockport substation in American Electric Power grid [62]. The faulted line is untransposed compensated by shunt reactor with switching technology only at one end [21, 22].

Time domain waveforms of the normalized faulted phase voltage magnitude, $|V_{sn}|$, and the mean value of its phase angle, $\delta_{mean}$ are shown in Figure 4.40. The fault inception time and the line single-phase isolation time are 100ms and 177ms, respectively. Using the event recorder time reference, reclosing occurs at 630 ms. As per the depicted waveforms, the fault is a temporary fault which becomes clear at about 300ms.

The proposed algorithm recognizes the-first-lock-angle as 99.3° at $t = 219$ms. Then, the temporary fault is detected at $t = 249$ ms where $\delta_{mean}$ does not stay around the-first-lock-angle and moves toward negative values. Finally, the resonance of $\delta_{mean}$ around $-50$ Degrees is detected at $t = 326$ms which means the arc is extinguished. The developed arc extinction technique is 304ms faster than the actual reclosing and 84ms faster than the technique proposed in [62]. Therefore, the proposed algorthm has a successful performance for the considered field recorded temporary fault case.

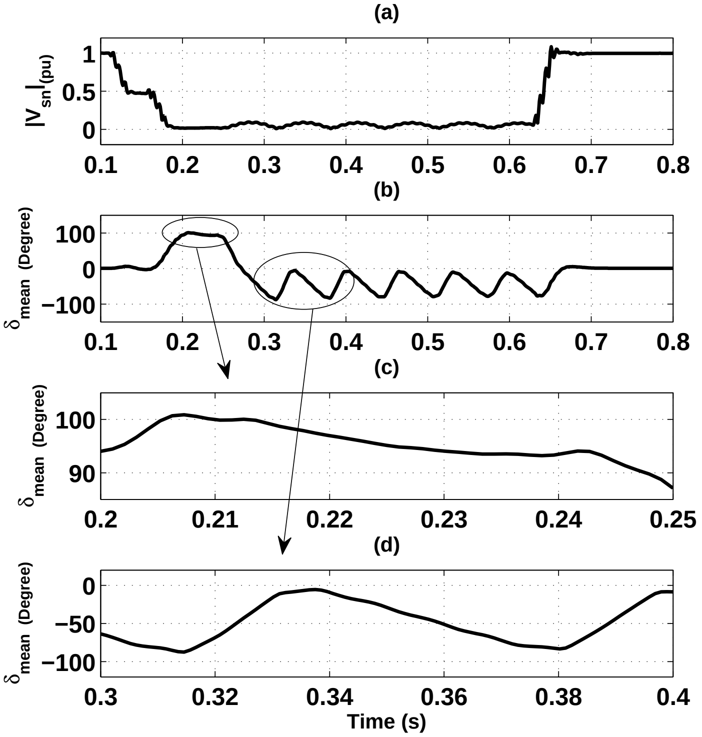

**Figure 4.40: Waveforms of a temporary fault case in Rockport 765 kV station in American Electric Power grid, (a) normalized voltage magnitude of the faulted phase and (b) average value of the faulted phase voltage angle; (b) is zoomed in (c) and (d).**

### 4.3.2 Phasor-based method

According to Subsection 4.2.2, the fault type is recognized by means of $VDR^t$ values. For all simulated cases, the gap between $VDR^t$ values for temporary and permanent faults is large enough. In fact, the minimum $VDR^t$ value for temporary faults is 20%, while it is never larger than 0.5% for any permanent fault case. The average $VDR^t$ values for temporary and permanent fault cases are also 180% and 0.15%, respectively. The proposed algorithm has had successful performance for all simulated cases. The fault type for all cases is recognized 100ms after the line single-phase isolation. This is considerably faster than the method introduced in [62] with permanent fault detection times within 220ms to 280ms and almost equal to the communication aided technique proposed in [56] with detection times within 99ms to 108ms.

The average and maximum reclosing time delay, the time distance between the proposed algorithm arc extinction detection moment and the real arc extinction time obtained based on PSCAD simulations, for ideally-transposed, untransposed and partially-transposed line simulated cases are presented in tables 4.7 and 4.8. For each fault location and/or transmission line configuration, the averaging is applied to three time delay values obtained for three sets of arc parameters, including faster/medium/slower arcs. It is observed that the average and maximum time delays and/or individual time delays related to the each arc parameter set are pretty close for each fault location/line configuration. This means, for each fault location/line configuration, the proposed method is able to detect the arc extinction after almost the same time delay regardless of the arc extinction speed. Hence, it can be concluded that the proposed method is not considerably sensitive to the arc parameters.

**Table 4.7: Average/maximum reclosing time delay for an ideally-transposed and an untransposed lines using the phasor-based method (ms); Sh.R.: Shunt Reactor; S.C./M.C.: Fault on Side/Middle Conductor.**

| | Fault location | | 0% | 30% | 70% | 100% |
|---|---|---|---|---|---|---|
| Ideally Transposed | No Sh.R. | | 89 / 93 | 91 / 103 | 91 / 103 | 81 / 85 |
| | With Sh.R. | | 39 / 44 | 40 / 43 | 40 / 43 | 32 / 39 |
| Untrans-posed | S.C. | No Sh.R. | 90 / 94 | 83 / 97 | 100 / 111 | 97 / 105 |
| | | With Sh.R. | 86 / 91 | 76 / 86 | 62 / 92 | 65 / 86 |
| | M.C. | No Sh.R. | 92 / 97 | 91 / 99 | 75 / 90 | 83 / 100 |
| | | With Sh.R. | 72 / 91 | 70 / 86 | 68 / 92 | 59 / 86 |

**Table 4.8: Average and maximum reclosing time delay for a partially transposed transmission line using the phasor-based method (ms); Sh.R.: Shunt Reactor.**

| Fault location | | 0% | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|
| Average | No Sh.R. | 76 | 85 | 77 | 61 | 51 | 45 | 56 |
| | With Sh.R. | 49 | 60 | 42 | 32 | 31 | 42 | 60 |
| Maximum | No Sh.R. | 78 | 88 | 87 | 63 | 60 | 58 | 67 |
| | Wth Sh.R. | 60 | 75 | 50 | 33 | 33 | 49 | 70 |

In tables 4.7 and 4.8, the average reclosing time delay for temporary fault cases is 32 to 91 ms while this between 70 and 160ms for the method proposed in [62]. Method of [56] also provides the average processing times between 29 and 67ms for temporary faults. Therefore, the method of this research study has been faster than the method of [62] but slightly slower in total than the method proposed in [56]. It might be considered that the proposed method in [56] is only applicable for ideally-transposed lines. In addition, it employs data of both sides of the transmission line and requires communication facilities too, while the proposed technique in this research study is based on local data application. The proposed technique is also effective for any kind of system transposition configuration and absence/presence of shunt reactor has no effect on the technique's performance.

Average and maximum reclosing time delay for ideally-transposed, untransposed and partially-transposed lines are shown in Figures 4.41 to 4.44. Similar to the angle-based method, for the phasor-based method is also observed that average and maximum reclosing time delay values are considerably close to each other for each fault location/line configuration. This means, for each fault location/line configuration, the proposed method is able to detect the arc extinction after almost the same time delay regardless of the arc extinction speed. Therefore, the conclusion is that the proposed method is considerably insensitive to the arc parameters.

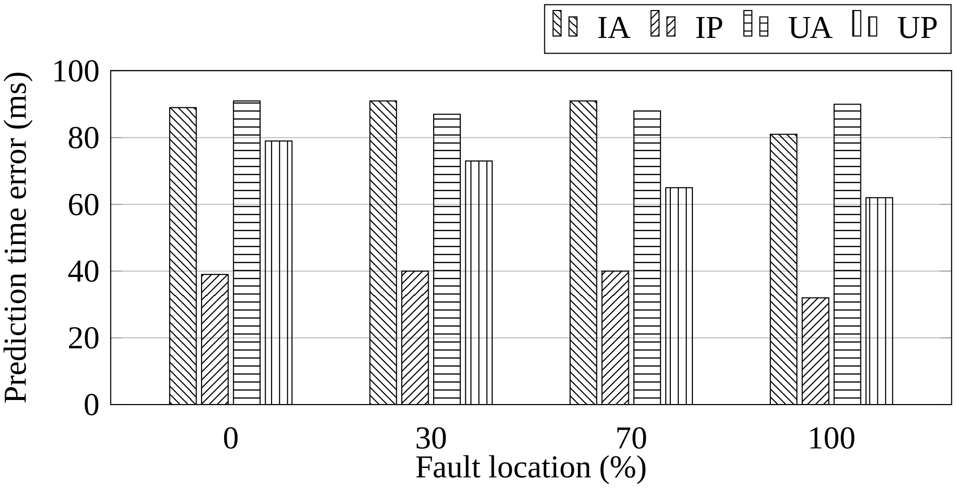

**Figure 4.41: Average reclosing time delay for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Presence (P) of shunt reactor using the phasor-based method (ms).**

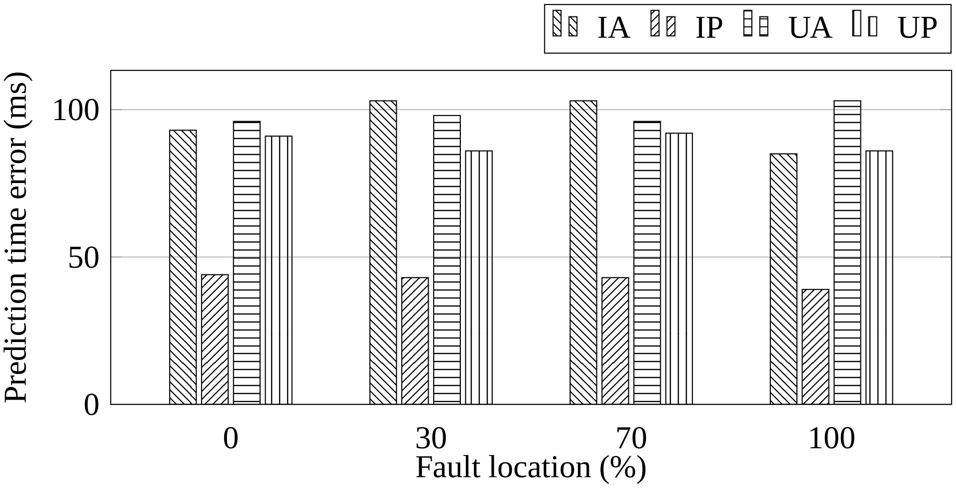

**Figure 4.42: Maximum reclosing time delay for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Presence (P) of shunt reactor using the phasor-based method (ms).**

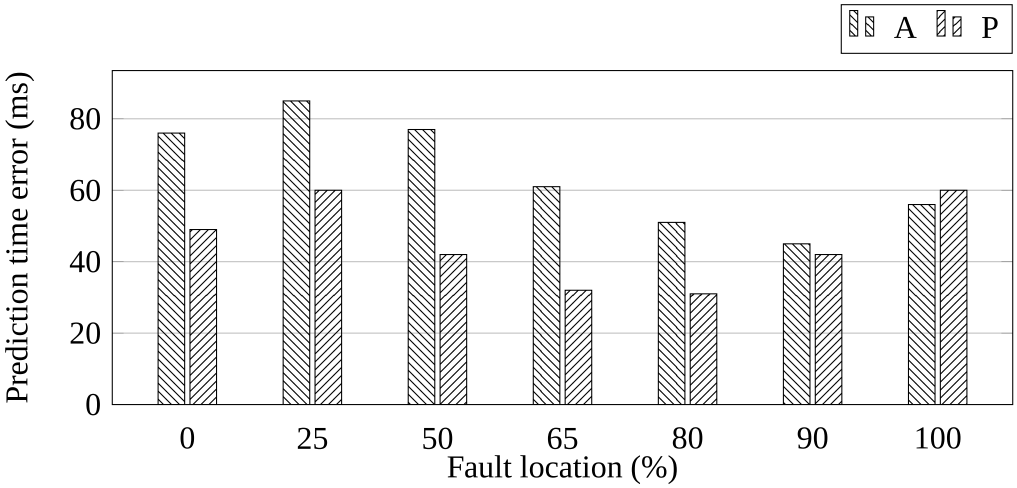

**Figure 4.43: Average reclosing time delay for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the phasor-based method (ms).**

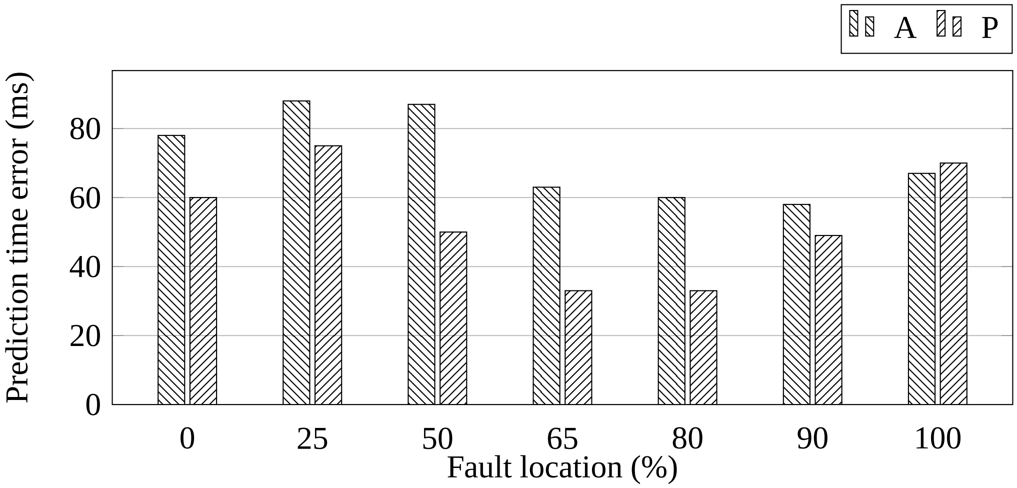

**Figure 4.44: Maximum reclosing time delay for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor using the phasor-based method (ms).**

It is also observed that for the ideally-transposed and untransposed line cases, the fault location has no considerable effect on the reclosing delay while for the partially-transposed cases the method has a better performance when the fault happens at the middle of the line.

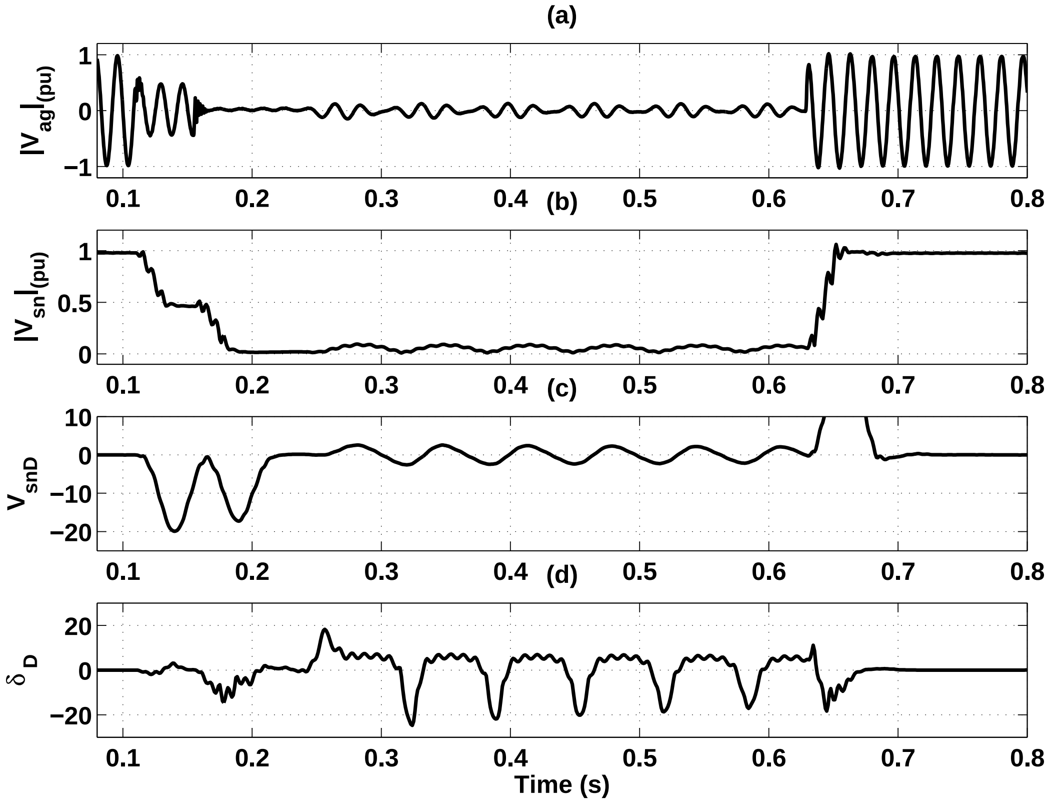

**Figure 4.45: Waveforms of a temporary fault case in Rockport 765 kV station in American Electric Power grid, (a) normalized instantaneous voltage waveform of the faulted phase, (b) normalized voltage magnitude of the faulted phase and (b) its first derivative, (c) first angle derivative.**

Similar to the angle-based method, performance of the phasor-based algorithm is also evaluated using a field recorded data, a temporary AG fault in American Electric Power grid [62]. The fault happened in Rockport substation on a 765 kV untransposed line which employs shunt reactor with switching technology only at one end [21, 22]. Instantaneous waveform, magnitude and the first derivation of the faulted phase voltage as well as the first derivation of its phase angle are shown in Figure 4.45(a) to 4.45(d). The fault inception time and the line single-phase isolation time are 100ms and 177ms, respectively. Using the event recorder time reference, reclosing also occurs at 630 ms. As per the depicted waveforms, the fault is a temporary fault which becomes clear at about 300ms.

The proposed algorithm correctly recognizes the fault type based on the calculated $VDR^t = 150\%$ at $t = 280\,\text{ms}$ or $100\,\text{ms}$ after the line single-phase isolation. Then, according to the algorithm of the phasor-based method, the arc extinction process has two steps. At first, there is an initial arc extinction detection based on $V_{snD}$ and then, this has to be confirmed by $\delta_D$. Using the proposed method, the initial arc extinction has been detected at 300ms. This is the time at which $V_{snD}$ becomes less than 10% of $V_{snD}$'s positive peak for the first time after line single-phase isolation and stays there for three samples as shown in Figure 4.45 (c). Then, this is confirmed at 320ms at which $\delta_D$ becomes negative as shown in Figure 4.45 (d). So, the final arc extinction time obtained using the algorithm is 320ms. This is 310ms faster than the actual reclosing and 90ms faster than the technique proposed in [62].

### 4.3.3 Comparison of the reclosing methods

Two proposed adaptive single-phase reclosing methods, i.e., the angle-based and the phasor-based methods, have different structures, algorithms and logics and therefore, they will have different performance in different situation. However, using all simulated cases, both methods have had a successful operation and the difference is only in operation speed.

In term of structure of the methods, the angle-based method has a simpler structure as uses only the phase angle of the faulted phase while the phasor-based method uses the faulted phase voltage magnitude and derivatives of both magnitude and phase angle of the voltage.

In therms of fault type recognition, the logic of the angle-based method is based on immediate/late detection of temporary/permanent faults. In fact, the default fault type is permanent in this method and this is double checked throughout a predetermined time period of length of five power system cycles or 83ms after the first-angle-locked detection, while temporary faults can be detected anytime in that period of time. In fact, the average time needed for detection of a temporary/permanent fault including all simulated cases is 91/139ms for the angle-based method. Therefore, the angle-based method has a faster fault type detection performance for temporary faults than permanent faults.

However, the phasor-based method has no default fault type and has has to wait until the end of its 100ms time period for the fault type recognition. But, the time period is shorter than the period used for the angle-based method. Therefore, for temporary faults, the angle-based method has had a faster performance while phasor-based method acts faster for permanent fault cases. But, the fault type recognition speed is more important for permanent fault cases than for temporary faults. The reason is that after the permanent fault detection, the next step is three-phase tripping while the recloser is to wait for the arc extinction for temporary faults. Therefore, the phasor-based method has a better performance in fault type recognition.

In terms of reclosing time delay, the angle-based method is able to detect the arc extinction 18 to 114 ms after the arc extinction while it is 32 to 91 ms for the phasor-based method. Therefore, the time delay values are more diverse for the angle-based method than the phasor-based. Considering all temporary fault simulated cases, the angle-based method has a reclosing time delay not longer than 59ms while the phasor-based method can do the same job not later than 80ms after the real arc extinction, in average. Therefore, when the fault is temporary, the phase-angel-based method acts faster at both fault detection and arc extinction detection.

As a comparison of the performances of the methods with the existing adaptive reclosing methods, two of the best existing methods were chosen, including one local and one communication-based method, using [62] and [56]. The local method was able to detect the arc extinction 70 to 160ms after the line isolation while the communication-based method was faster and could do the same job in 29 to 67ms. Therefore, the proposed methods, which are local, were faster than the local method, while they were slightly slower the communication-based method, in average. Therefore, the improvement is observed in their performances compared to the existing reclosing methods.

## 4.4 Summary

In this Chapter, two methods for adaptive single-phase reclosing in transmission lines were proposed. The first method, called the angle-based method, uses phase angle of the faulted phase, both to recognize the fault type, i.e., permanent or temporary, and to detect the arc extinction in case the fault is temporary. The second method, the phasor-based method, uses the first derivative of the faulted phase voltage magnitude for fault type recognition, and the first derivatives of both magnitude and angle of the faulted phase voltage, for arc extinction detection.

Both methods had successful performances for transmission lines with various transposition configurations, including ideally-transposed, untransposed and partially-transposed. Compensation condition was not also an important factor to affect the performance of the methods.

Both methods were evaluated using 550 different simulated cases as well as a real case study, and the results confirmed the capabilities of the methods. Both methods had a successful performances for all of the simulated cases. The angle-based method had a better performance for temporary fault cases while the phasor-based method acted better when the fault type was permanent. In terms of the structures of the methods, the angle-based method has a simpler structure and also, can be considered as the more reliable method as used the data itself and not the derivative of the data. Performances of the proposed methods was also compared with two of the best existing adaptive reclosing methods, one local and one communication-based. Methods had better performances than the local method while they were slightly slower than the existing communication-based method.

# Chapter 5

# Arc Extinction Time Prediction

When single-phase reclosing function is considered, what normally happens for a temporary fault case is to open the faulted phase and reclose the circuit breaker after a delay. The traditional single-phase reclosing uses a predetermined time delay to avoid arc restriking. This time delay must be chosen properly as reclosing the breaker when temporary fault has not been cleared yet can further damage the equipment and put the system stability at risk.

Adaptive single-phase reclosing methods have been proposed in the literature to identify the fault type including temporary and permanent, and then, to recognize if the arc is extinguished [55]. However, all the proposed adaptive single-phase reclosing methods have to wait for the arc to be extinguished if the fault is temporary. The problem is that, in some cases, the arc extinction speed is too low and it is harmful for the system to serve with one phase open for a long time which leads to issues such as injection of negative sequence component to the system. Therefore, it would be beneficial to predict the arc extinction time for temporary faults well in advance to initiate three-phase tripping signal in case of a slow extinguishing arc. However, prediction of the arc extinction time after breaker interruption has not been investigated in the literature.

In this Chapter, voltage magnitude of the faulted phase after single-phase isolation of the line is used to predict the arc extinction time for temporary faults. For this purpose, there are two methods proposed and the results are compared. The proposed methods are effective for both uncompensated and compensated transmission lines with shunt reactor and are considerably insensitive to transposition condition of the line.

## 5.1 Fundamentals of The Proposed Prediction Methods

To verify the special behaviors of the faulted phase voltage during arc extinction, six simulated temporary fault case studies are used in this Section. In all six simulated cases, a temporary single-phase-to-ground fault incepts at $t$ = 0.2s. At $t$ = 0.27s and $t$ = 0.28s, breakers of Sides A and B isolate the faulted line by performing single-phase opening. Therefore, after $t$ = 0.28s the faulted phase is fully isolated. For performing an easier and more clear comparison, similar to Chapter 4, $V_{sn}$ and $V_{snD}$ variables are employed in this Chapter as well, as defined in (3.8).

### 5.1.1 Analysis of the faulted phase voltage waveforms

Waveforms of arc voltage and current for six different temporary fault cases on an ideally-transposed, an untransposed and a partially-transposed line in absence and presence of shunt reactor are shown in Figures 5.1 to 5.3. As observed in all three figures, the arc voltage is very small immediately after fault inception, i.e., $t$ = 0.2s, while the arc current is very large. However, the arc voltage increases and the arc current drops to small values as the arc extinguishes gradually, after single-phase opening of the breakers at $t$ = 0.28s.

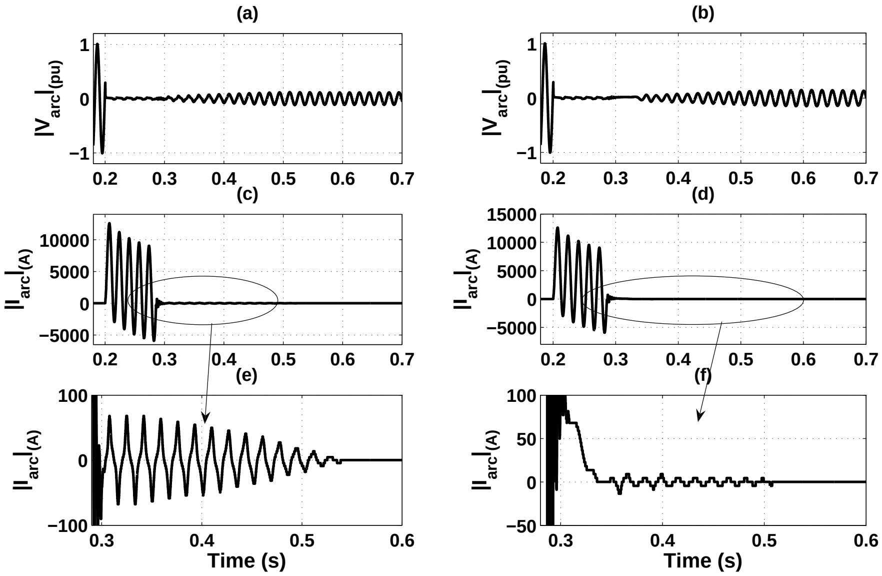

**Figure 5.1: Electric arc voltage and current for the case of two temporary faults in an ideally-transposed transmission line in {(a) and (c)} absence and {(b) and (d)} presence of shunt reactor; (c) and (d) are zoomed in (e) and (f), respectively.**

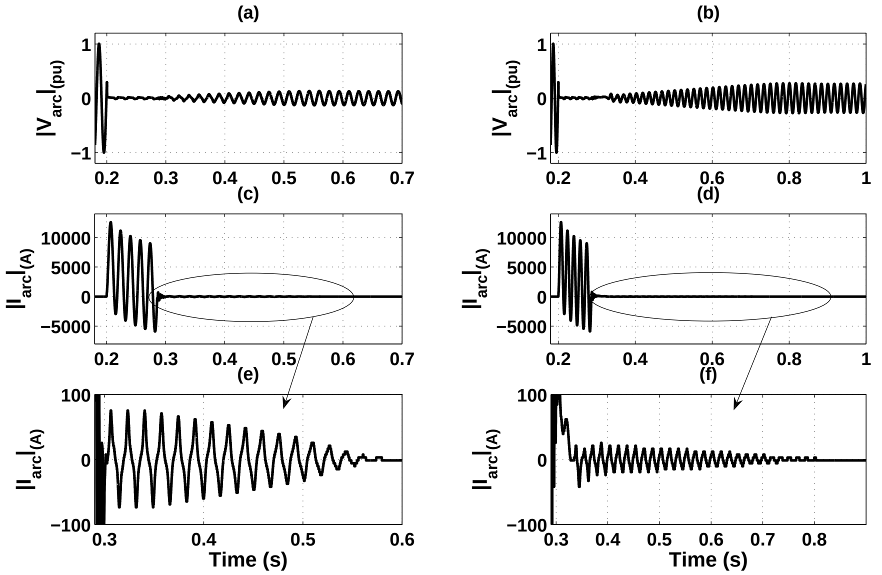

**Figure 5.2: Electric arc voltage and current for the case of two temporary faults in an untransposed transmission line in {(a) and (c)} absence and {(b) and (d)} presence of shunt reactor; (c) and (d) are zoomed in (e) and (f), respectively.**

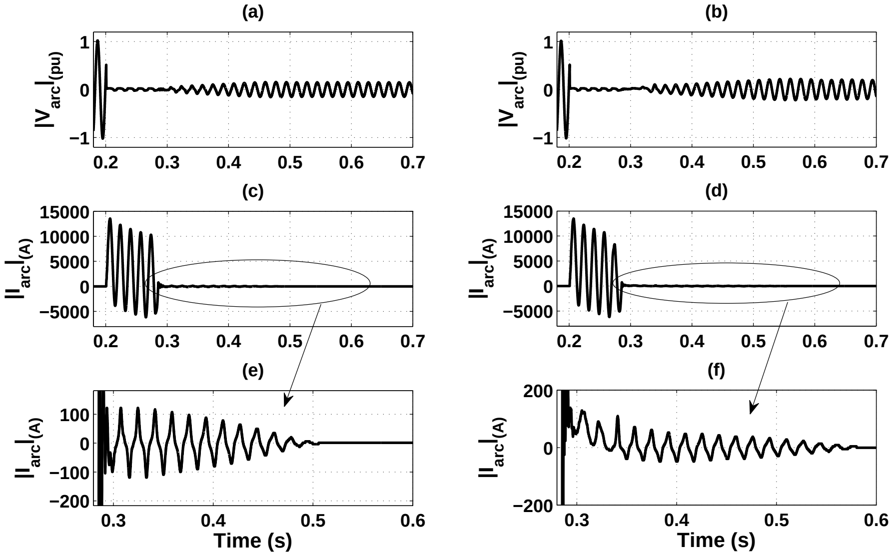

**Figure 5.3: Electric arc voltage and current for the case of two temporary faults in a partially-transposed transmission line in {(a) and (c)} absence and {(b) and (d)} presence of shunt reactor; (c) and (d) are zoomed in (e) and (f), respectively.**

Waveforms of $|V_{sn}|$, magnitude of $V_{sn}$, and $V_{snD}$, associated with the six simulated temporary fault cases are shown in Figures 5.4 to 5.6. As seen in Figures 5.4 to 5.6, (a) and (b), during the time interval between the fault occurrence moment and single-phase opening of the beakers, i.e., $t = 0.2$s to $t = 0.28$s, $|V_{sn}|$ decreases to some extent depending on system strength and also characteristics and location of the fault. Following isolation of the faulted line at $t = 0.28$s, $|V_{sn}|$ drops considerably and then, is recovered slowly by increment of the arc resistance. At the same time, as observed in Figures 5.4 to 5.6, (c) and (d), $V_{snD}$ drops to a negative number after single-phase line isolation, recovers to zero and registers a positive peak to be called $V_{snD^{Peak}}$ as shown in Figures 5.4 to 5.6, (e) and (f). $V_{snD}$ stays above the horizontal axis for a considerable time interval during the voltage recovery and eventually resonates/settles down around zero in presence/absence of shunt reactor after the arc extinction.

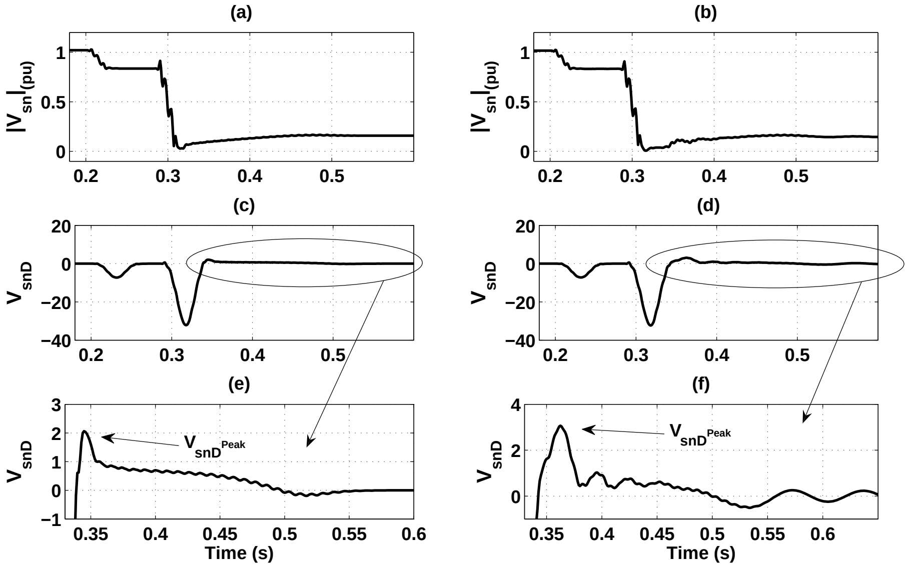

**Figure 5.4: Normalized faulted phase voltage magnitude and its first derivative for the temporary fault cases in an ideally-transposed transmission line shown in Figure 5.1; (c) and (d) are zoomed in (e) and (f), respectively.**

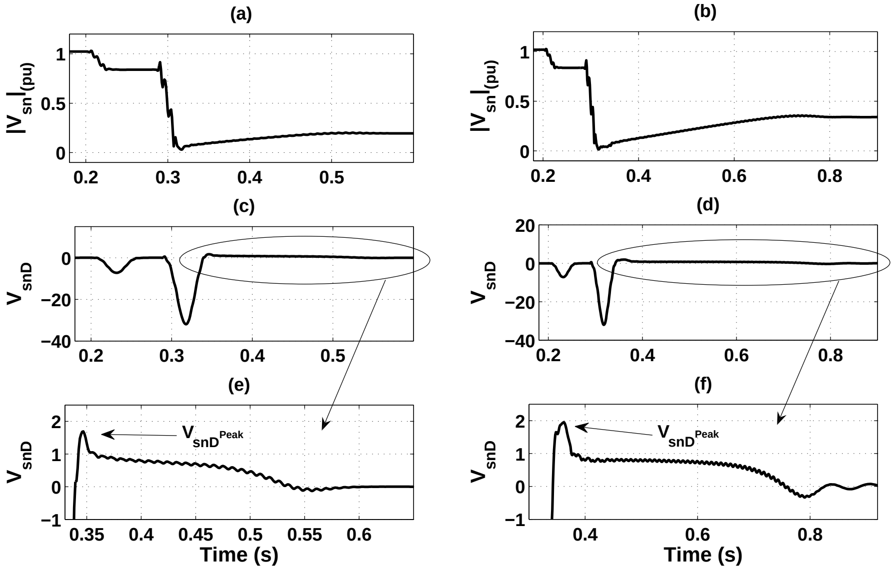

**Figure 5.5: Normalized faulted phase voltage magnitude and its first derivative for the temporary fault cases in an untransposed transmission line shown in Figure 5.2; (c) and (d) are zoomed in (e) and (f), respectively.**

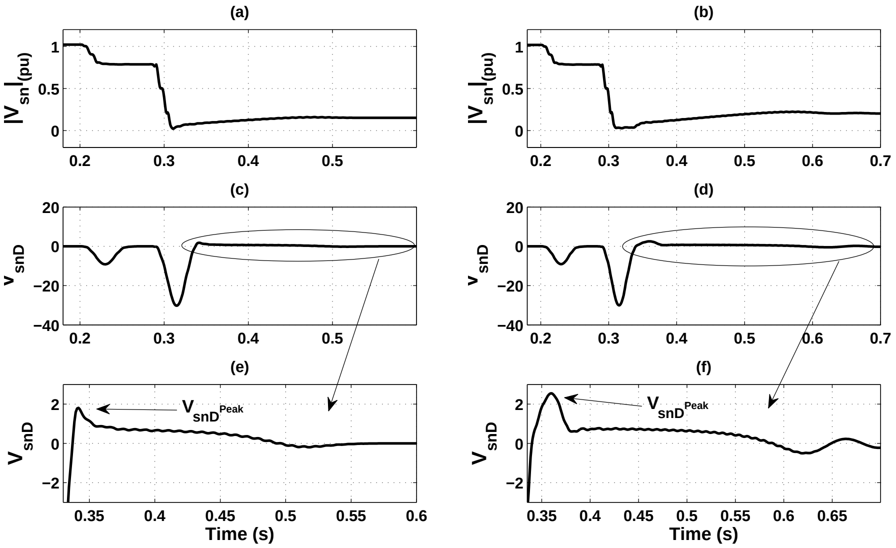

**Figure 5.6: Normalized faulted phase voltage magnitude and its first derivative for the temporary fault cases in a partially-transposed transmission line shown in Figure 5.3; (c) and (d) are zoomed in (e) and (f), respectively.**

For a temporary fault case in which single-phase reclosing of the line is considered, $V_{snD}$ waveform can be approximated by a decaying exponential curve for the arc extinction time interval, i.e., from the moment at which $V_{snD} = V_{snD^{Peak}}$ to the arc extinction moment. By this choice, it is possible to predict the arc extinction time by finding the zero-crossing point of the approximating exponential curve.

## 5.2 Proposed Prediction Methods

In this Section, two different methods are proposed for the purpose of prediction of the arc extinction time during single-phase reclosing, namely, the point-based and the window-based methods. In the following, the proposed methods are explained, the prediction results are compared, and merits and drawbacks of the methods are expressed.

### 5.2.1 Point-based method

#### Exponential curve approximation for the point-based method

A decaying exponential function is defined as $x = ke^{-t/T}$ where $k$ and $T$ are magnitude and decaying time constant, respectively, where $T$ determines the decaying speed. Both $k$ and $T$ can be obtained having the data of only two points of the curve, e.g. $(t_1, x_1)$ and $(t_2, x_2)$ using (5.1) where $x_1 = ke^{-t_1/T}$ and $x_2 = ke^{-t_2/T}$. Having $k$ and $T$, $t_o$, the time spot associated with any desired $x_o$ value can be calculated as (5.2).

$$x_1/x_2 = e^{(t_2-t_1)/T} \;=> \tag{5.1}$$

$$T = \frac{t_2-t_1}{Ln(x_1/x_2)} \text{ and } k = x_1/e^{(-t_1/T)}$$

$$t_o = Ln(k/x_o)T \tag{5.2}$$

#### Proposed algorithm for the point-based method

According to Figures 5.5, (e) and (f), $V_{snD}$ increases from negative to positive values as the arc is being extinguished after the line isolation. Then, it makes a positive peak and decreases toward zero. After the arc extinction, $V_{snD}$ either settles down at zero for the uncompensated line cases, or resonates for the lines with shunt/neutral reactor. It is desired that the point-based method be able to make decision within 100 ms after the single-phase line isolation. In this order, if the after-peak part of the $V_{snD}$ curve is approximated by a decaying exponential curve, it will be possible to predict the arc extinction time. Having the predicted arc extinction time, one of the possible choices, reclosing or three-phase tripping will be selected.

For obtaining the approximating exponential curve, all needed is the information of two points of the curve as discussed in the first paragraph of this Subsection. The first chosen point is the point of the $V_{snD}$ peak, called $V_{snD^{Peak}}$. The second chosen point is the point of the minimum value for $V_{snD}$ after the peak point and before the decision making time, called $V_{snD^{Min}}$. It was mentioned in the previous paragraph that the decision is made within 100 ms after the single-phase line isolation of the faulted phase. Applying the information of these two points to (5.1), parameters $k$ and $T$ of the approximating exponential curve and therefore, the constants of the approximating exponential equation are available.

$V_{snD}$ curves drawn in Figure 5.5 associated with two temporary fault cases of Figure 5.2, as well as the related approximating curves using the point-based prediction method, are shown in Figure 5.7.

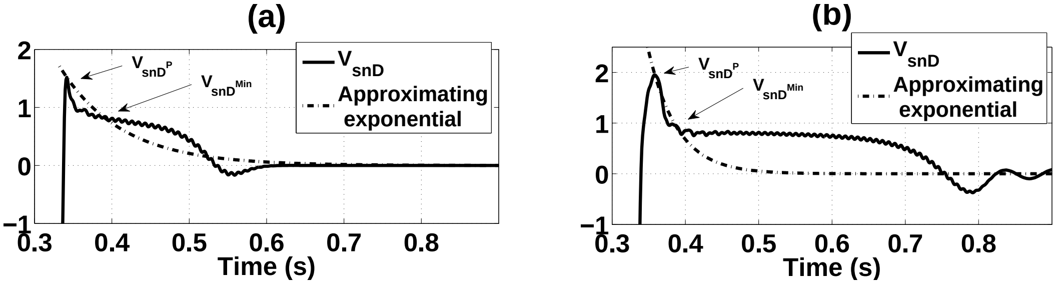

**Figure 5.7: $V_{snD}$ and the approximating exponentials associated with the temporary fault cases shown in Figure 5.5.**

The last step is to obtain the estimated arc extinction time, the time at which the approximated $V_{snD}$ becomes zero. But, an exponential curve becomes zero at $t = \infty$, theoretically. Therefore, a threshold must be set for $V_{snD}$, i.e. $V_{snD^{Th}}$, and the predicted arc extinction time will be the time at which the approximated $V_{snD}$ becomes smaller than the threshold $V_{snD^{Th}}$. In this research, two values for the threshold have been chosen, $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$. At the end, the chosen parameter must be applied to (5.2), i.e. $x_o = V_{snD^{Th}}$, to obtain the predicted arc extinction time.

### 5.2.2 Window-based method

#### Exponential curve approximation for the window-based method

An exponential curve is defined as (5.3) where $k$ is the magnitude, $T$ is the decaying time constant and $c$ is the DC offset [131]. For negative values of $T$, the exponential curve eventually approaches the dc offset $c$. Equation (5.3) can be simplified and rearranged to the form of a linear equation, i.e., y=at+b, according to (5.4) where $y = Ln(x - c)$, $a = -1/T$ and $b = Ln(k)$.

$$x = ke^{-t/T} + c \tag{5.3}$$

$$x - c = ke^{-t/T} => Ln(x - c) = -t/T + Ln(k) \tag{5.4}$$

The problem is to find an appropriate set of $k$, $T$ and $c$ parameters through curve fitting using some samples of (t,x) data sets. However, it can be shown that the curve fitting process leads to a nonlinear set of equations due to appearance of $x$ and $c$ together in variable $y$ [131]. Solving such a nonlinear equation needs a high processing power and is hard to implement in practical protective relays. The other problem is that, the curve fitting process has to result in a negative values for $c$. Otherwise, the approximating exponential equation of (5.3) will have a positive DC offset. This means the approximating curve will never cross the horizontal axis, the equation $ke^{-t/T} + c = 0$ will have no real root and no real arc extinction time prediction can be performed using this method.

In the performed research work, equation (5.4) is solved by assuming a negative value for parameter $c$ instead of obtaining it through solving the equations. By this assumption, the nonlinear equation becomes a linear one as $c$ is a constant and not a variable anymore. Therefore, the arc extinction time prediction method can be appropriately implemented in a practical relay and also, a real output for the arc extinction time prediction method is guaranteed.

**Proposed algorithm for the window-based method**

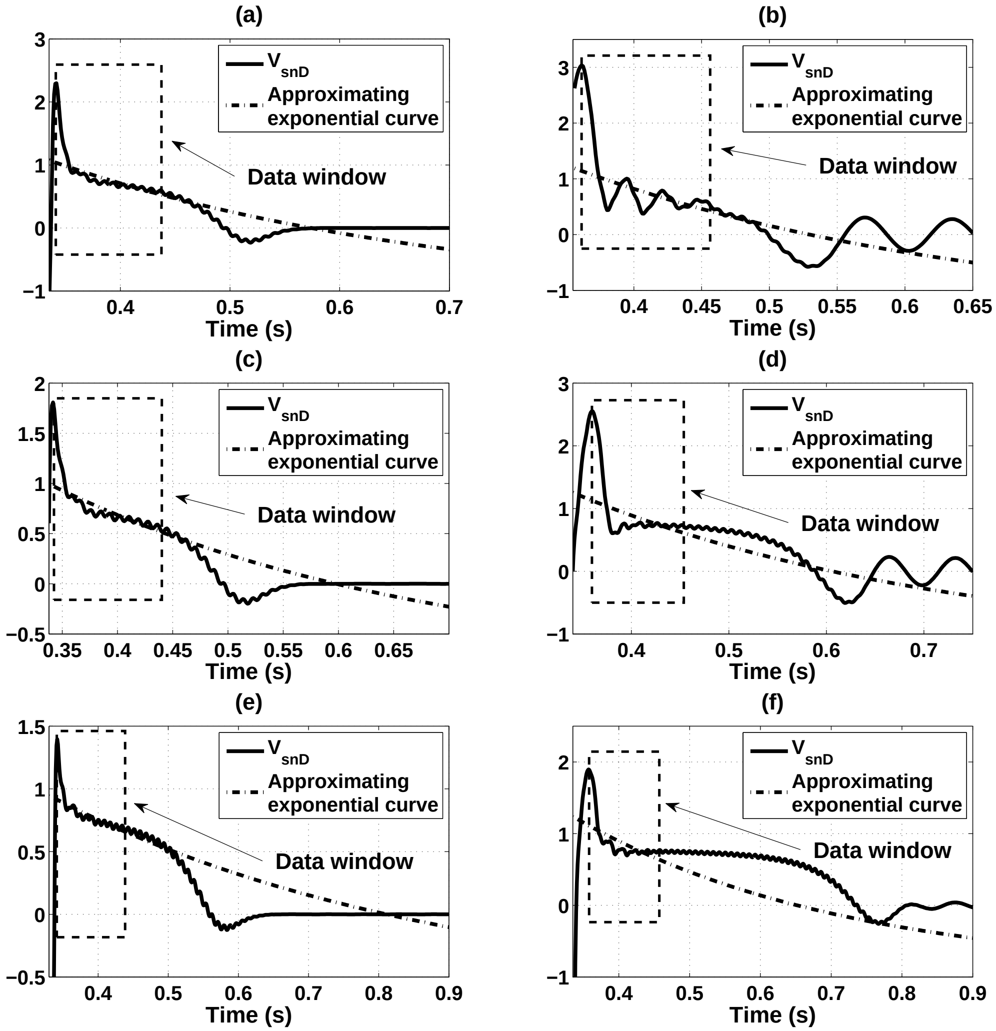

**Figure 5.8:** $V_{snD}$ **curves shown in (a) Figure 5.4-(e), (b) Figure 5.4-(f), (c) Figure 5.5-(e), (d) Figure 5.5-(f), (e) Figure 5.6-(e) and (f) Figure 5.6-(f), and the associated approximating exponentials.**

$V_{snD}$ curves shown in Figures 5.4 to 5.6, and the associated approximating exponentials using the window-based method are shown in Figure 5.8. As mentioned in Subsection 5.1.1, for the time spots after the peak $V_{snD^{Peak}}$, $V_{snD}$ curve can be approximated by a decaying exponential curve. So, in this research, a window of $V_{snD}$ data of length of six power system cycles, equal to 100ms, starting from the moment of the peak is used for the exponential curve approximation as shown in Figure 5.8.

For the purpose of approximation, parameter $c$ is assumed equal to $-50\%$ of $V_{snD^{Peak}}$. This way, the term $Ln(x-c)$ in (5.4) becomes only a function of $x$ as $c$ becomes just a constant. Therefore, parameters $k$ and $T$ can easily be obtained by a simple linear curve fitting according to (5.4) and (5.5). Having the parameter set of $k$, $T$ and $c$, the root of the exponential approximating curve in (5.3) is obtained according to (5.6). This root is the zero-crossing point of the curve which in fact, is the predicted arc extinction time. If the arc extinction prediction time is recognized as “too long”, immediate three-phase trip instead of single-phase reclosing will be performed despite the temporary fault type recognition.

$$k = e^{b} \text{ and } T = -1/a \tag{5.5}$$

$$ke^{-t/T} + c = 0 \Rightarrow t = T.Ln(k/|c|) \tag{5.6}$$

## 5.3 Simulation Results

In this research, 225 simulated temporary fault cases have been used for performance evaluation of the proposed method. The simulated cases can be categorized into three groups based on the transposition condition of the transmission line including ideally-transposed (45 cases), untransposed (90 cases) and partially-transposed (90 cases). Various cases are different in terms of fault location, arc type (Arcs 1 to 3 for temporary fault cases as per Table 3.1), and presence/absence of shunt/neutral reactor. As mentioned in the opening part of this Chapter, the proper decision for the case of close-in fault is immediate three-phase trip signal activation as the faulted phase voltage drops almost to zero at the relay location. So, temporary fault inception cases at 0% distance from Side A is not considered in the studies of this Chapter.

### 5.3.1 Point-based method

Average arc extinction prediction time error, the difference between the arc extinction prediction time by the proposed method and the real arc extinction time obtained from PSCAD simulations, for ideally-transposed, untransposed and partially-transposed line simulated cases are presented in Tables 5.1-5.3. The prediction time errors are available in both milliseconds and percentage of the real arc extinction duration, the time difference between the single-phase line isolation and the real arc extinction moments. There are two sets of data presented for $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$ to have access to a wider range of results. In averaging of the results, absolute values of the time differences are used to consider both early and late predictions. Otherwise, early and late predictions may cancel out each other and in that case, the prediction error will drop to very small values.

The key fact that must be considered regarding the results is that the predicted arc extinction time is always longer for $V_{snD^{Th}} = 0.1\%$ than for $V_{snD^{Th}} = 1\%$ which is because of the nature of the decaying exponential curve. Based on this fact, there are three sets of scenarios possible. In scenario A, the time difference obtained for $V_{snD^{Th}} = 1\%$ is positive, i.e., the predicted arc extinction time for $V_{snD^{Th}} = 1\%$ is later than the reality. In such a situation, the time difference obtained for $V_{snD^{Th}} = 0.1\%$ is definitely positive and longer based on the mentioned fact. Fault occurrence at 30% length of the untransposed line in absence of shunt reactor is an example of such a situation (see Table 5.1).

In scenario B, the time difference for $V_{snD^{Th}} = 0.1\%$ is negative, means the predicted time is earlier than the reality. What happens in this scenario is that the time difference for $V_{snD^{Th}} = 1\%$ will be more negative. In this case, the absolute value of the time difference obtained for $V_{snD^{Th}} = 1\%$ will be larger than for $V_{snD^{Th}} = 0.1\%$. Fault occurrence at 30% length of the untransposed line in presence of shunt reactor is an example of such a situation (see Table 5.1).

**Table 5.1: Average arc extinction prediction time error of the point-based method for an ideally-transposed/untransposed transmission line (ms).**

| Fault location | | 30% | 70% | 100% |
|---|---|---|---|---|
| Absence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 132 / 307 | 132 / 87 | 67 / 115 |
| | $V_{snD^{Th}} = 1\%$ | 57 / 127 | 57 / 59 | 45 / 63 |
| Presence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 46 / 83 | 46 / 111 | 117 / 194 |
| | $V_{snD^{Th}} = 1\%$ | 68 / 134 | 68 / 124 | 83 / 121 |

**Table 5.2: Average arc extinction prediction time error of the point-based method for an ideally-transposed/untransposed transmission line in percent of the real arc extinction time (%).**

| Fault location | | 30% | 70% | 100% |
|---|---|---|---|---|
| Absence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 49% / 87% | 49% / 28% | 28% / 41% |
| | $V_{snD^{Th}} = 1\%$ | 20% / 36% | 20% / 19% | 10% / 23% |
| Presence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 19% / 18% | 19% / 28% | 62% / 55% |
| | $V_{snD^{Th}} = 1\%$ | 29% / 29% | 29% / 31% | 41% / 34% |

There is also a scenario C possible in which the time difference for $V_{snD^{Th}} = 0.1\%$ is positive while it is negative for $V_{snD^{Th}} = 1\%$. In such a scenario, the predicted time for $V_{snD^{Th}} = 0.1\%$ is later than the reality while it is earlier for $V_{snD^{Th}} = 1\%$. In this scenario, the proposed method has the most accurate performance as the real arc extinction time is located between the predicted times for $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$. In that case, the absolute value of the time difference is rather small and is very close for $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$ as the prediction is slightly late for the first while it is slightly early for the second one. Fault occurrence at 65% length of the partially-transposed line in presence of shunt reactor is an example of such a situation in which the absolute values of the time differences are exactly equal for $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$ (see Table 5.3).

**Table 5.3: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line (ms).**

| Fault location | | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|
| Absence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 250 | 117 | 71 | 65 | 68 | 62 |
| | $V_{snD^{Th}} = 1\%$ | 97 | 51 | 47 | 52 | 58 | 42 |
| Presence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 94 | 42 | 54 | 73 | 22 | 31 |
| | $V_{snD^{Th}} = 1\%$ | 66 | 66 | 54 | 47 | 28 | 4 |

**Table 5.4: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line in percent of the real arc extinction time (%).**

| Fault | location | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|
| Absence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 83% | 39% | 24% | 22% | 23% | 24% |
| | $V_{snD^{Th}} = 1\%$ | 32% | 17% | 16% | 17% | 19% | 16% |
| Presence of shunt reactor | $V_{snD^{Th}} = 0.1\%$ | 31% | 14% | 18% | 24% | 7% | 12% |
| | $V_{snD^{Th}} = 1\%$ | 22% | 22% | 18% | 16% | 9% | 2% |

Average arc extinction prediction time error for ideally-transposed, untransposed and partially-transposed line simulated cases are shown in Figures 5.9 to 5.16. As observed, for the ideally-transposed cases, the error values associated with the threshold value of $V_{snD^{Th}} = 0.1\%$ is always higher than error values associated with $V_{snD^{Th}} = 1\%$. Also, the error values related to the two thresholds become closer for uncompensated line as the fault location becomes further from the relay location (at 0% distance). But the gap between the error values associated with the threshold values becomes deeper for further fault locations when the line is compensated.

For the untransposed line cases, there is no pattern observable, but for the partially-transposed line cases there is a very clear pattern. In such cases, both the error values and also the gap between the error values associated with the thresholds decrease for further fault locations.

Using all simulated results, average arc extinction prediction time error for ideally-transposed, untransposed and partially-transposed line configurations are 32%, 25.8% and 31%, respectively. Average prediction error of the proposed method in absence and presence of shunt reactor are also 35.9% and 25.2% , respectively. Therefore, the proposed method has a better performance for partially-transposed lines and in presence of shunt reactor. Finally, the proposed method is able to predict the arc extinction time with error as large as 27.7% averaging all the simulated cases.

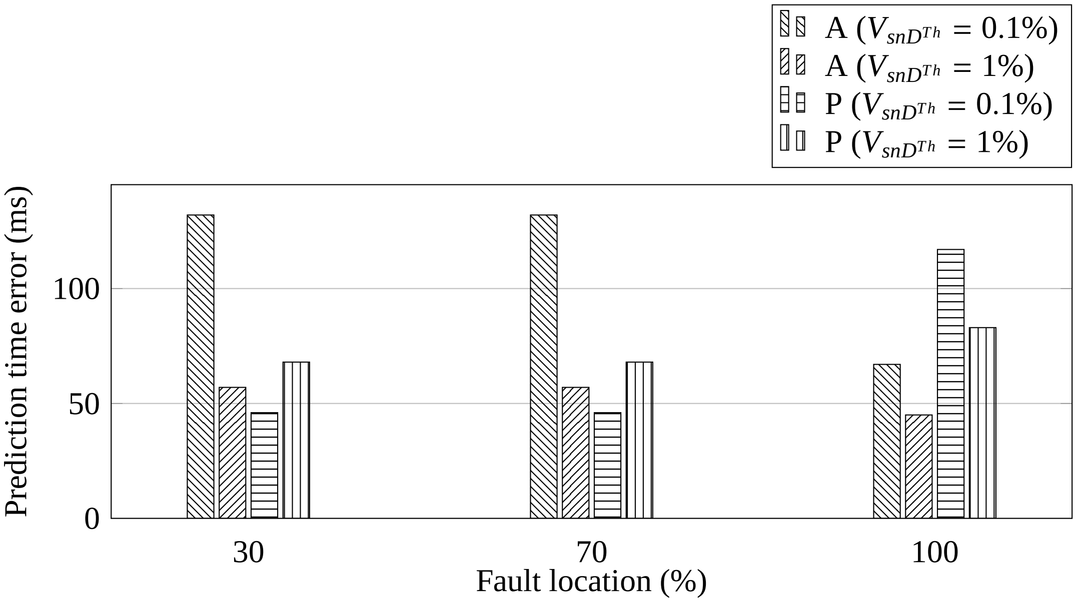

**Figure 5.9: Average arc extinction prediction time error of the point-based method for the ideally-transposed transmission lines in Absence (A) and Presence (P) of shunt reactor (ms).**

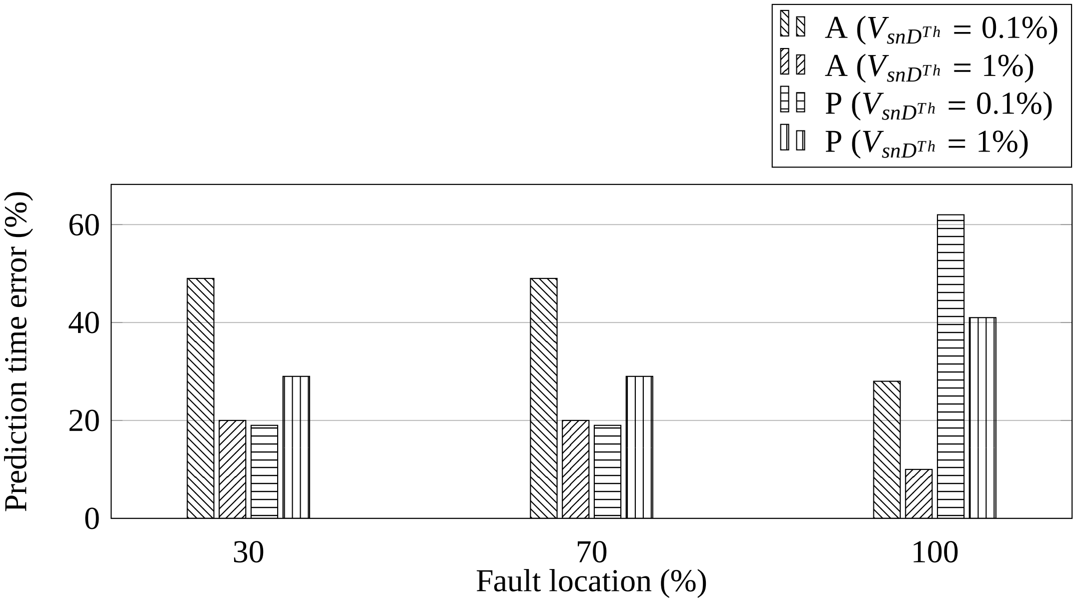

**Figure 5.10: Average arc extinction prediction time error of the point-based method for the ideally-transposed transmission lines in Absence (A) and Presence (P) of shunt reactor (%).**

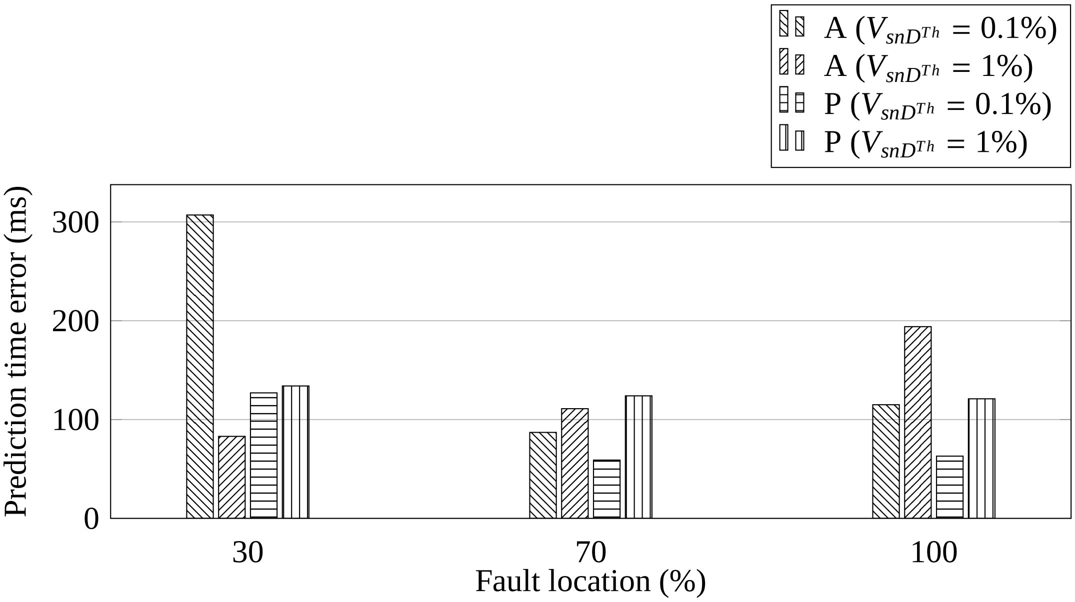

**Figure 5.11: Average arc extinction prediction time error of the point-based method for the untransposed transmission lines in Absence (A) and Presence (P) of shunt reactor (ms).**

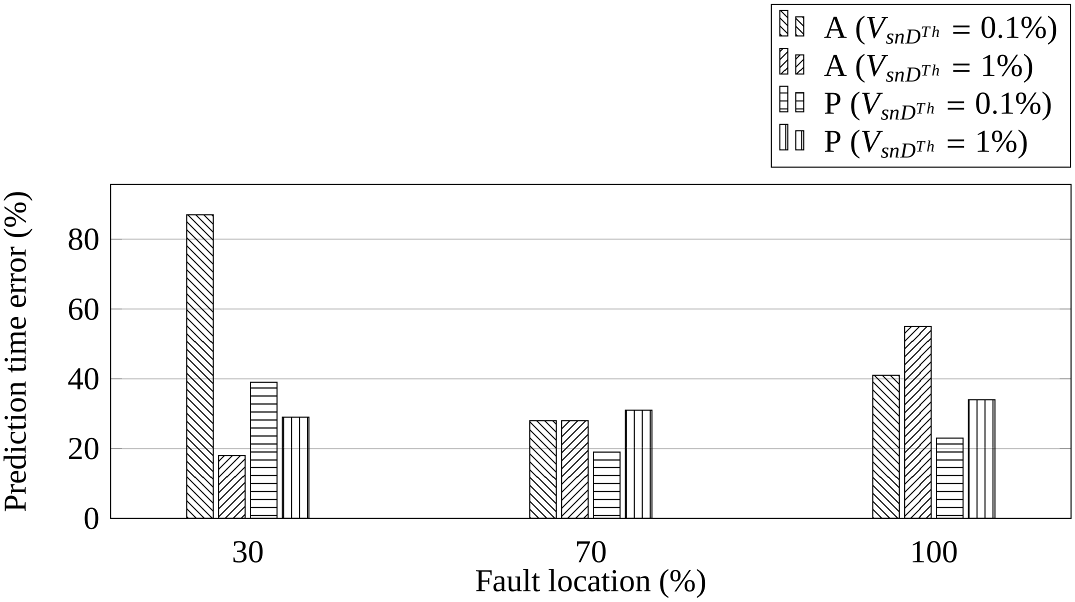

**Figure 5.12: Average arc extinction prediction time error of the point-based method for the untransposed transmission lines in Absence (A) and Presence (P) of shunt reactor (%).**

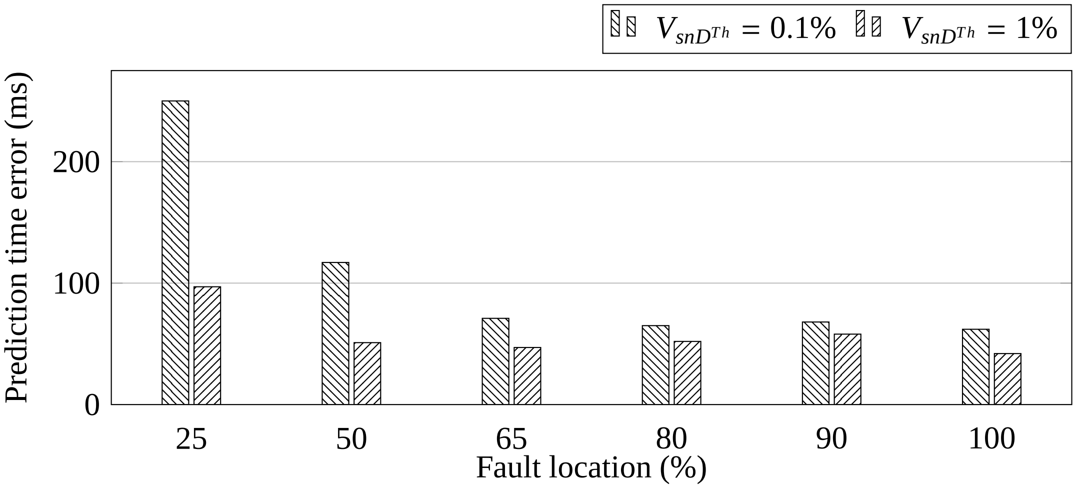

**Figure 5.13: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line in absence of shunt reactor (ms).**

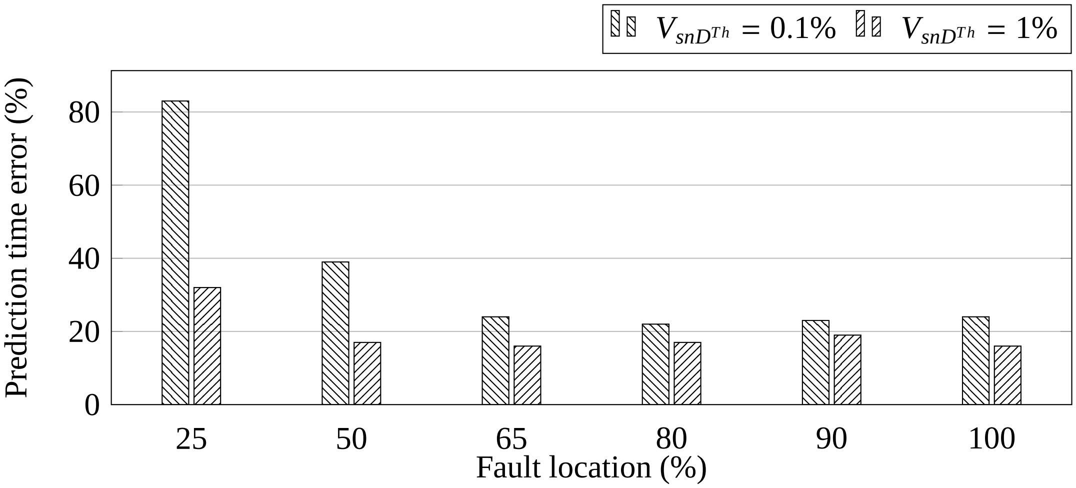

**Figure 5.14: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line in absence of shunt reactor, in percent.**

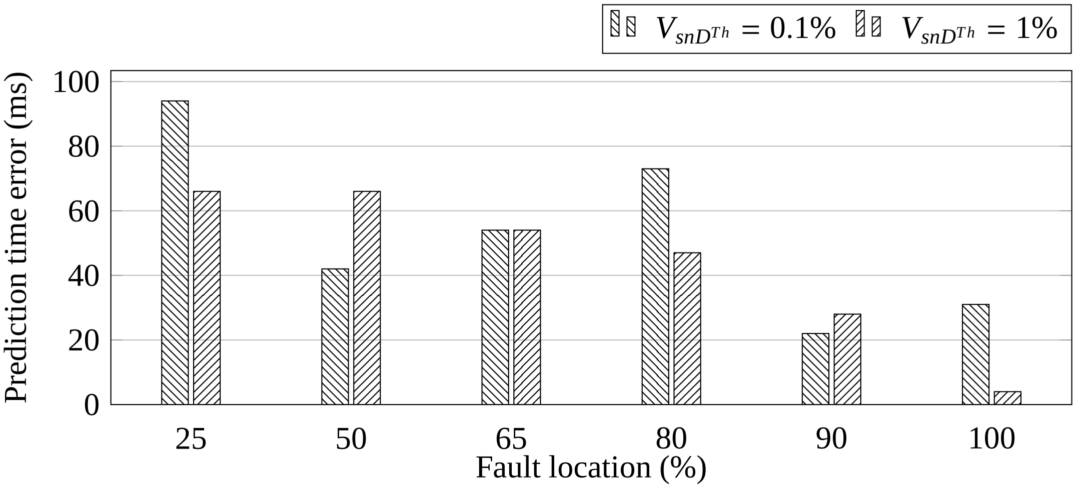

**Figure 5.15: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line in presence of shunt reactor (ms).**

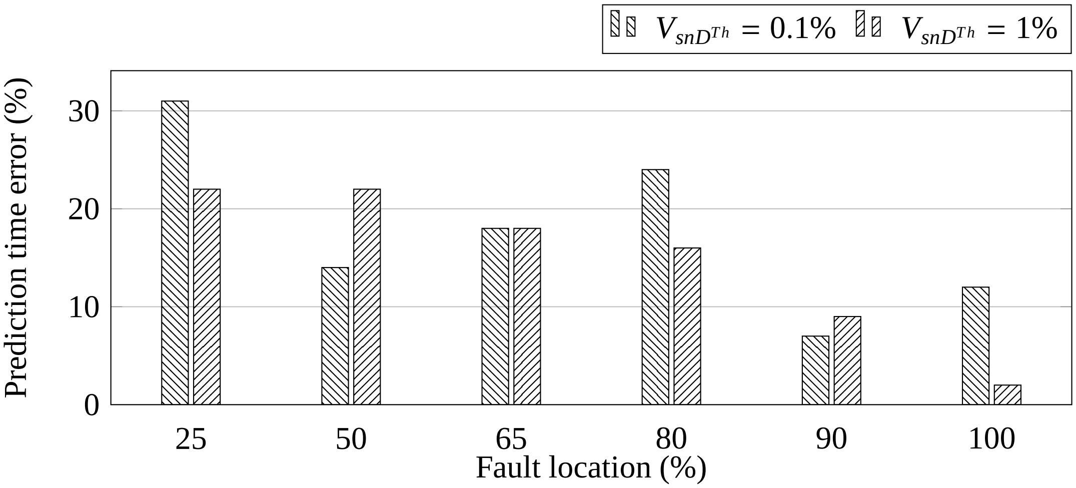

**Figure 5.16: Average arc extinction prediction time error of the point-based method for a partially-transposed transmission line in presence of shunt reactor, in percent.**

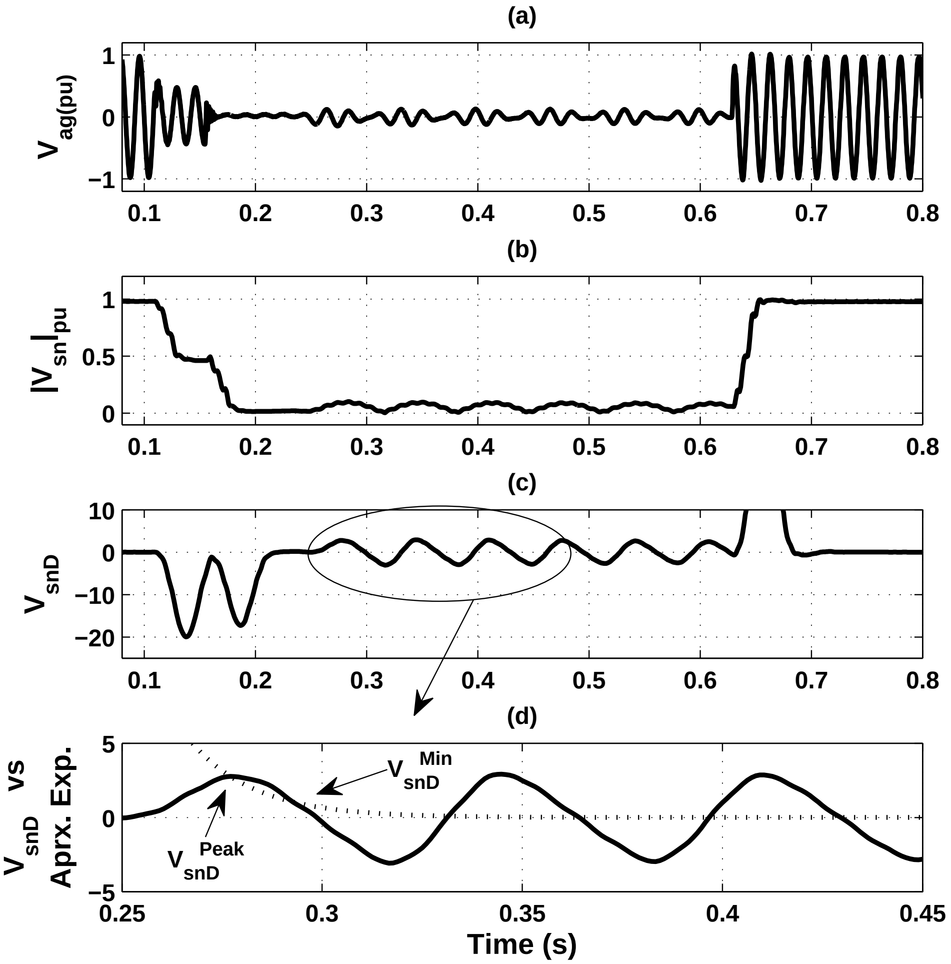

**Figure 5.17: (a) Normalized instantaneous waveform, (b) magnitude and (c) the first derivation of the faulted phase voltage, (d) the approximating exponential curve of the 765 kV faulted phase using the point-based method.**

Similar to Chapter 4, performance of the proposed arc extinction time prediction method is also evaluated using a field data, a temporary single-phase-to-ground fault in Rockport station in American Electric Power grid on a 765 kV untransposed line with shunt reactor only at one end [62]. Normalized instantaneous waveform, magnitude, the first derivation of the faulted phase voltage, and the approximating exponential curve are shown in Figure 5.17. According to the event recorder information, the fault inception time and the line single-phase isolation time are 100ms and 177ms, respectively and waveforms say that the arc extinguishes at around t=300ms. Therefore the arc extinction duration is 300ms-177ms=123ms. Based on the event recorder information, reclosing occurs at t=630ms.

As shown in Figure 5.17 (d), $V_{snD}$ waveform is approximated by the dotted exponential curve employing two points of $V_{snD}$ waveform, i.e., $V_{snD^{Peak}}$ and $V_{snD^{Min}}$. Using the approximating curve, the arc extinction prediction times are obtained as 404 ms and 367 ms for $V_{snD^{Th}} = 0.1\%$ and $V_{snD^{Th}} = 1\%$, respectively, both are much smaller than the practical reclosing time of 630ms. Therefore, the predicted arc extinction duration is obtained as 227ms and 190ms, respectively. Considering the real arc extinction duration of 123ms, the arc extinction time prediction error for the studied case is 84.6% and 54.5%, respectively. These error values although are higher than the average prediction error value of 31% related to simulation results of the untransposed line, they are still applicable for having an estimation for the arc extinction time well in advance.

### 5.3.2 Window-based method

Average prediction error of the window-based prediction method, i.e., the difference between the predicted values and PSCAD results for arc extinction duration are presented in Tables 5.5-5.7. Arc extinction duration is the time duration between the line single-phase isolation and the arc extinction moments. The error values, in both milliseconds and percent, are associated with the ideally-transposed, untransposed and partially-transposed line simulated cases. Format of the absolute error values is converted to percent form based on real arc extinction time durations resulted from PSCAD. It should be noted that the absolute error values are used in the averaging process so that early and late prediction results do not cancel out each other.

Regarding the overall performance of the window-based arc extinction time prediction method, average prediction error values for ideally-transposed, untransposed and partially-transposed line configurations are 17.7%, 18.6% and 9.9%, respectively. The average error values for compensated and uncompensated lines are also 15.3% and 13.7%. Therefore, the proposed method has a better performance for partially-transposed lines and in presence of shunt reactor. Considering all the simulated cases, the proposed method is able to predict the arc extinction time with average error as large as 14.9%.

**Table 5.5: Average arc extinction prediction time error of the window-based method for an ideally-transposed transmission line in (ms) and percent of the real arc extinction time.**

| Fault | location | 30% | 70% | 100% |
|---|---|---|---|---|
| Absence of shunt reactor | ($ms$) | 52 | 52 | 67 |
| | (%) | 17.3 | 17.3 | 25.3 |
| Presence of shunt reactor | ($ms$) | 41 | 41 | 62 |
| | (%) | 14.1 | 14.1 | 23.6 |

**Table 5.6: Average arc extinction prediction time error of the window-based method for an untransposed transmission line in (ms) and percent of the real arc extinction time.**

| Fault | location | 30% | 70% | 100% |
|---|---|---|---|---|
| Absence of shunt reactor | ($ms$) | 26 | 40 | 57 |
| | (%) | 8.2 | 12.7 | 18.7 |
| Presence of shunt reactor | ($ms$) | 66 | 84 | 59 |
| | (%) | 18.4 | 23.9 | 17.8 |

**Table 5.7: Average arc extinction prediction time error of the window-based method for a partially-transposed transmission line in (ms) and percent of the real arc extinction time.**

| Fault location | | 25% | 50% | 65% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|
| Absence of shunt reactor | ($ms$) | 36 | 3 | 22 | 43 | 49 | 37 |
| | (%) | 12.6 | 1.1 | 7.8 | 15 | 17.2 | 13.7 |
| Presence of shunt reactor | ($ms$) | 31 | 18 | 21 | 29 | 34 | 27 |
| | (%) | 11 | 6.5 | 7.4 | 10.2 | 12.3 | 10.1 |

The prediction error values resulted from the window-based method in both (ms) and percent are shown in bar charts of Figures 5.18 to 5.21. According to Figures 5.18 and 5.19, comparing bars IA and IP for ideally-transposed transmission lines, the window-based method is always more successful for shunt-compensated lines than for uncompensated ones, due to smaller prediction errors. But the prediction is generally more accurate in absence of shunt reactor than in its presence for untransposed lines, considering bars UA and UP, specially when the fault happens at the middle parts of the line. However, for partially-transposed lines, the prediction precision depends more on the fault location than the compensation condition of the line as seen in Figures 5.20 and 5.21. Eventually, the proposed method has a better performance for partially-transposed lines than for ideally-transposed and untransposed lines.

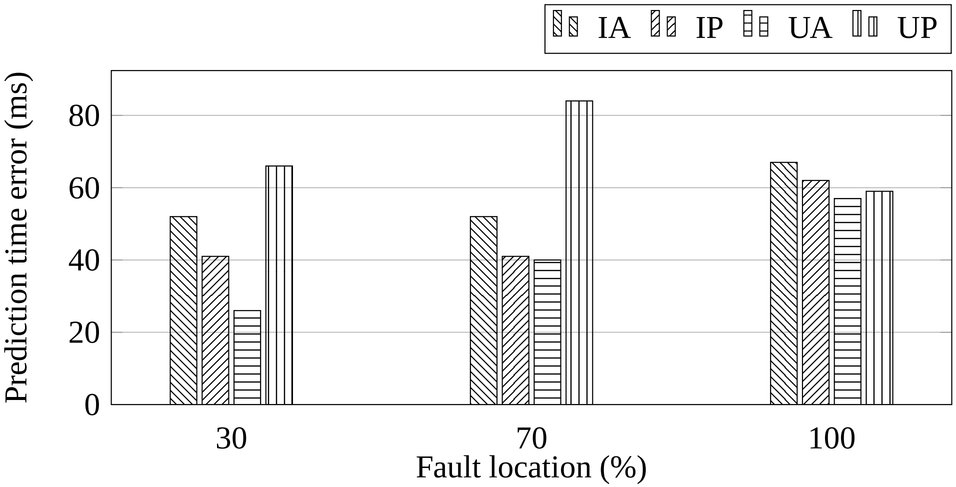

**Figure 5.18: Average arc extinction prediction time error of the window-based method for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Persence (P) of shunt reactor (ms).**

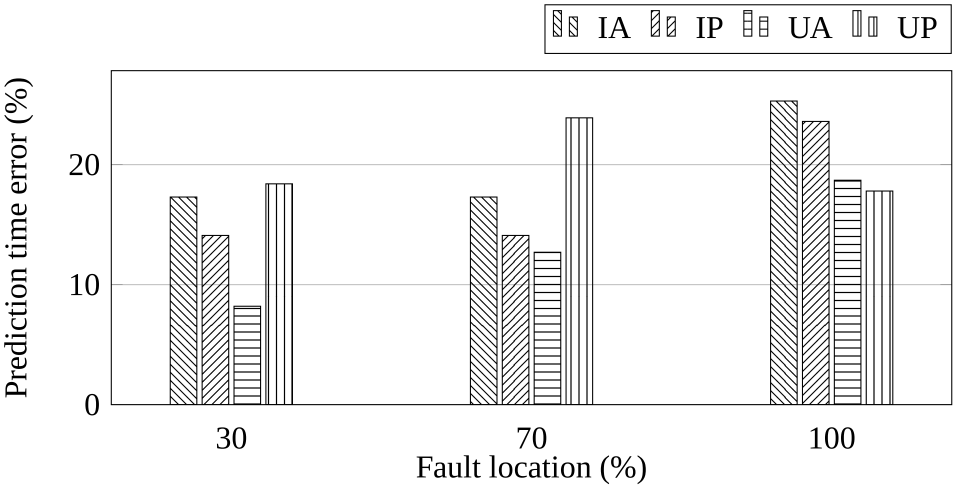

**Figure 5.19: Average arc extinction prediction time error of the window-based method for an Ideally-transposed (I) and an Untransposed (U) transmission lines in Absence (A) and Persence (P) of shunt reactor (%).**

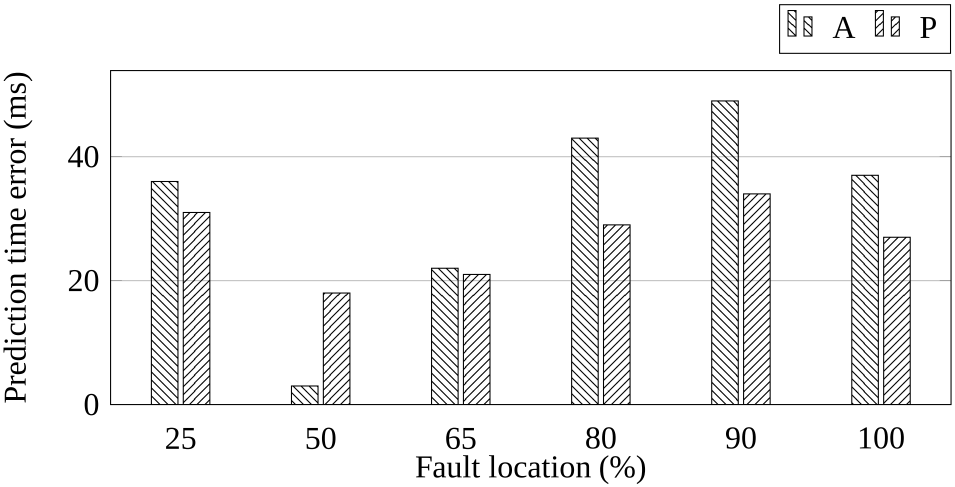

**Figure 5.20: Average arc extinction prediction time error of the window-based method for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor (ms).**

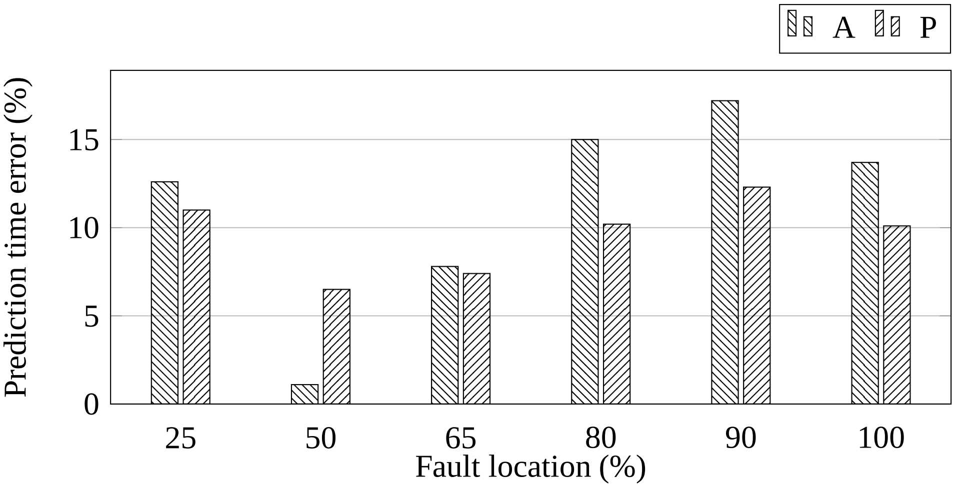

**Figure 5.21: Average arc extinction prediction time error of the window-based method for a partially-transposed transmission line in Absence (A) and Presence (P) of shunt reactor (%).**

Performance of the method proposed for arc extinction time prediction is also evaluated employing a filed recorded data of Rockport station which was a temporary single-phase-to-ground fault in American Electric Power grid on a 765 kV untransposed line with shunt reactor only at one end [62]. Normalized instantaneous waveform, magnitude, the first derivation of the faulted phase voltage and the approximating exponential curve associated with the field data are presented in Figure 5.22.

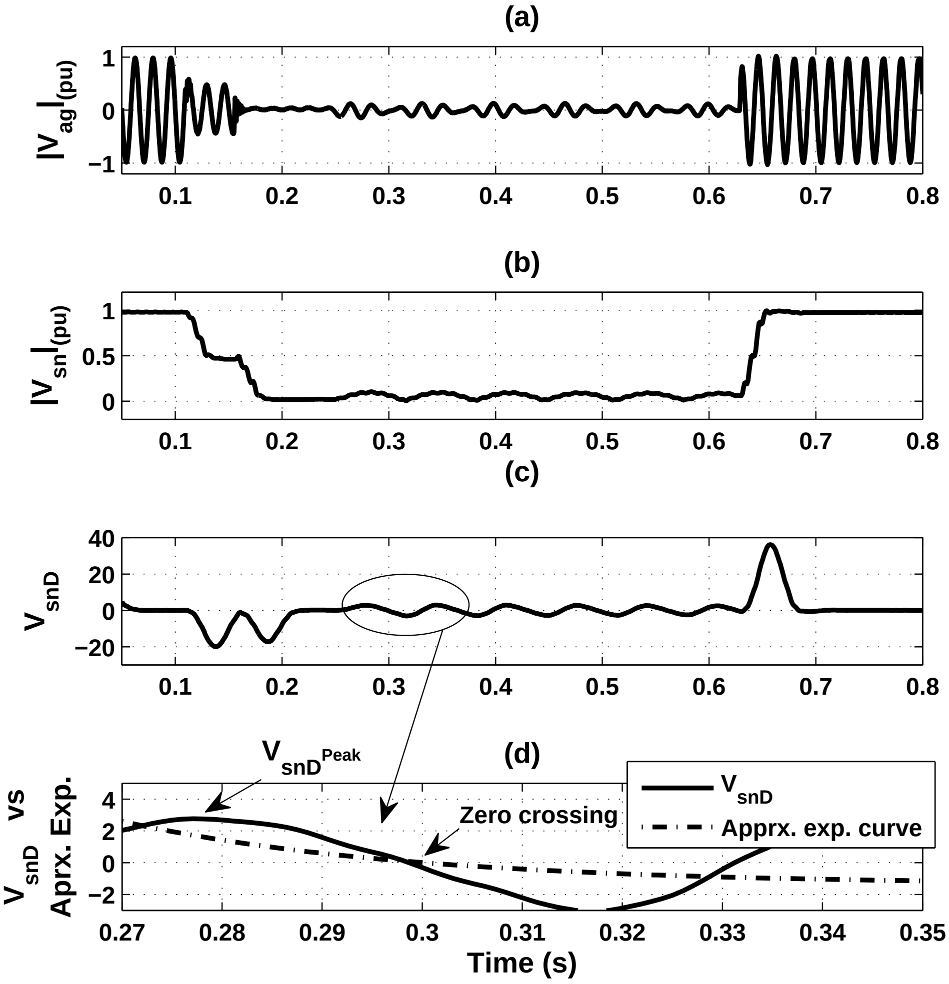

**Figure 5.22: Normalized instantaneous waveform, magnitude, the first derivation of the faulted phase voltage and the approximating exponential curve for the real temporary fault case using the window-based method.**

According to Figure 5.22 (d), exponential curve fitting is performed using a $V_{snD}$ data window of length of 100ms or six power system cycles starting from the peak point. As observed, the approximating exponential curve crosses the horizontal axis exactly at $t = 300$ms which matches the event recorder information and shows a negligible prediction error. Therefore, the proposed method has a perfect performance for the real analyzed temporary fault case.

### 5.3.3 Comparison of the prediction methods

The point-based prediction method is able to predict the arc extinction time with average error as large as 27.7%. The average error of this method for ideally-transposed, untransposed and partially-transposed line configurations is 32%, 31% and 25.8%, respectively. This method can also predict the arc extinction time by average error of 35.9% and 25.2% for transmission lines with and without shunt compensation, regardless of the transposition condition of the line.

Regarding the overall performance of the window-based method, average prediction error for ideally-transposed, untransposed and partially-transposed line configurations is respectively 17.7%, 18.6% and 9.9%. The average prediction error in presence and absence of shunt reactor is also 15.3% and 13.7%, respectively. Considering all the simulated cases, the proposed method is able to predict the arc extinction time with error as large as 14.9%. Therefore, compared to the results of the point-based method, there have been a significant improvement achieved in the precision of the prediction for the window-based method.

Considering the performance of the two proposed methods for the case of the temporary fault of the Rockport station, application of the point-based method has led to predicted arc extinction moments of t=404 ms and t=367 ms using two different criteria, or prediction error values as large as 84.6% and 54.5%, respectively, while the prediction error almost equals to zero for the window-based method. Therefore, the window-based method has a much better performance for the real temporary fault compared to the point-based method.

Finally, both methods has successful operation for simulation and test results while the prediction of the window-based method are so closer to the reality. But the point-based method is much easier to implement and needs much less processing power.

## 5.4 Summary

In this Chapter, two methods for the secondary arc extinction time prediction were proposed. The proposed methods are developed for being used in making a better decision on single-phase reclosing in transmission lines when the fault is temporary. The developed methods use the first derivative of the faulted phase voltage magnitude. The first method, namely the point-based method, uses only two point of the voltage derivative waveform, the peak and the minimum of the waveform in a predetermined time period, after single-phase isolation of the line. The second method, called the window-based method, uses a window of the voltage derivative data after the single-phase isolation of the line. Both methods had acceptable performances while the results obtained from the window-based method were more precise. In fact, the average prediction error of the window-based method was 14.9% versus 27.7% error for the point-based method. But the point-based method was much easier to implement and needed much less processing power.

# Chapter 6

# Conclusions

In this research study, the first aim was to develop an adaptive method for single-phase reclosing in high voltage transmission lines. The developed method must be able to recognize the fault type including permanent and temporary and also, to detect arc extinction for temporary faults. The method was also supposed to be local, i.e., to use only local measurement data of the substation. The other alternative is to be communication-based and therefore, to use measurement data associated with other substations of the power system. This was not a subject of this research work as communication facilities are not always available. The developed method had to be comprehensive as well, meaning it must be valid for transmission lines with different kinds of transposition conditions including ideally-transposed, untransposed and partially-transposed, and also for different compensation conditions including shunt compensated and uncompensated.

The second aim of the project was to propose a method to predict the arc extinction time well in advance. This way, when the arc extinction process is too slow, the protection system will have the option of issuing the three-phase trip signal instead of single-phase reclosing despite the temporary fault detection. The importance of this feature is the fact that during the system operation with one phase opened and two phases closed, negative sequence voltage/current components are injected to the system that can have harmful effects, such as overheating of the generators.

In the thesis, two adaptive reclosing methods were proposed for the first part of the project. The first proposed method, called the angle-based method, performed the reclosing task using phase angle of the faulted phase voltage. This variable was employed for both purposes of fault type recognition and arc extinction detection. The second proposed method, called the phasor-based method, used the first derivative of the faulted phase voltage magnitude for the fault type recognition, and the first derivative of both magnitude and phase angle of the faulted phase voltage for the arc extinction detection.

It was shown in Chapter 4 that both methods had successful operations for all 550 simulated cases, including lines with ideally-transposed, untransposed and partially-transposed configurations and also, for different transposition conditions including compensated and uncompensated. As a comparison of the performances of the proposed methods for the simulated cases, the phasor-based method had a better performance for permanent fault cases while performance of the angle-based method was more successful for temporary fault cases at both fault type recognition and arc extinction detection. Also, the angle-based method had a simpler algorithm as it uses only one variable, i.e., the phase angle of the faulted phase. In addition, the angle-based method was less sensitive to noise and fast transients as it uses the data itself and not the derivative of the data. Therefore, for selection of the more beneficial method a trade off must be made.

For the second part of research, two methods are developed for the arc extinction time prediction purpose. Both methods are using the first derivative of the faulted phase voltage magnitude. For this purpose, the derivative waveform was approximated by a decaying exponential curve for each method and the roots of the curves would be the predicted arc extinction time. The first method, called point-based method, uses only two points of the curve for the prediction task. The second method, i.e., window-based method, uses a long window of information for the prediction purpose. Both methods have local operations and therefore, no communication facilities are needed in the structures of the methods. Also, they both are comprehensive, i.e., are valid for transmission lines with different transposition and compensation conditions. Performances of the both methods were verified using 225 simulated temporary fault cases and a field recorded case where both methods had successful performances. As a comparison of the performances of the prediction methods, the output of the window-based method was closer to reality while the point-based method is easier to implement and requires less processing power.

Suggested future works:

Regarding continuation of the research, as a very immediate suggestion, the two proposed reclosing methods can be combined together to obtain one optimized reclosing method. The combined method will have the best performance for both permanent and temporary fault cases. The second suggestion is to implement the proposed methods in FPGA and other industrial hardwares and to evaluate their performances in terms of simplicity, processing time, etc.

Nowadays, application of single-phase auto-reclosing technique is more common in distribution systems than in transmission systems. The main reason for this is the fact that in transmission lines, the short circuit current level is much higher than the load current while they are almost at the same level in distribution networks. Therefore, there is no considerable demerit in applying the reclosing technique in distribution systems. Also, it will be more beneficial if the fault type is known before reclosing in distribution systems. Therefore, as the concepts of the developed reclosing methods in this research study are independent from the voltage level, one good suggestion for continuation of the research work is to apply the developed methods to distribution systems considering the required modifications.

The reason that the proposed reclosing methods were local was the fact that in many substations, communication facilities are not available. Therefore, the forth suggestion is to add communication facilities option to improve the performances of the methods. In this case, the improved methods will be applicable wherever the facilities exist. Although there are currently communication-based methods presented in the literature, but the reclosing methods proposed in this research operate almost at the same speeds. Therefore, adding communication facilities can improve the performances even further. However, there are restrictions mentioned in different documents such as IEC 61850 Standard regarding Communication Networks and Systems in Substations that must be considered for the improved methods.

The proposed arc extinction time prediction methods, specially the window-based method, are working based on some simplifications applied to the associated equations. Therefore, it is proposed to try different techniques for solving the equations and then compare the results.

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# Curriculum Vitae

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