UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA ELÉTRICA E DE COMPUTAÇÃO

UNICAMP

HOSSEIN YEKTAEI

COMPARATIVE ANALYSIS OF SINGLE-PHASE AND THREE-PHASE AUTO RECLOSING MANEUVER TO ELIMINATE LINE TO GROUND FAULT IN TRANSMISSION LINES

ANÁLISE COMPARATIVA DO DESEMPENHO DAS MANOBRAS DE RELIGAMENTO MONOPOLAR E TRIPOLAR PARA ELIMINAÇÃO DE FALTAS MONOFÁSICAS EM LINHAS DE TRANSMISSÃO

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Supervisor: Profa. Dra. MARIA CRISTINA DIAS TAVARES

Thesis presented to the School of Electrical and Computing Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Master in Electrical Engineering, in the area of Electrical Energy.

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ABSTRACT

An electric power system comprises of generation, transmission and distribution of electric energy. Transmission lines are used to transmit electric power to distant large load centers. The rapid growth of electric power systems over the past few decades has resulted in a large increase of the number of lines in operation and their total length. For EHV (extra high voltage) transmission levels, between 90–95% of all line faults involve only a single phase. Of these, more than 90% are temporary and can be cleared by three phase reclosing; consequently, phase-to-ground faults have received the most attention in system studies.

This project analyzes the transmission line entities resulting from elimination of a single-phase fault by using the SPAR (Single-Phase Auto-Reclosing) and three-phase auto-reclosing on the 400 kV transmission line. The project analyzes the influence of different system parameters like compensation level, line length and fault location together with the mitigation method. For the simulation study, PSCAD/EMTDC is selected as the simulation software.

Keywords: Single-Phase Auto-Reclosing; Three-Phase Auto-Reclosing; Transmission Lines; PSCAD/EMTDC; Single-phase fault.

RESUMO

Um sistema de energia elétrica compreende geração, transmissão e distribuição de energia elétrica. As linhas de transmissão são usadas para transmitir energia elétrica a centros de carga distantes. O rápido crescimento dos sistemas de energia elétrica nas últimas décadas resultou em um grande aumento do número de linhas em operação e seu comprimento total. Para níveis de transmissão EHV (extra-alta tensão), entre 90-95% de todas as falhas de linha envolvem apenas uma única fase. Destes, mais de 90% são temporários e podem ser compensados por três fases de religamento; Consequentemente, faltas fase-terra têm recebido a maior atenção em estudos de sistema.

Este projeto analisa as entidades da linha de transmissão resultantes da eliminação de uma falta monofásica usando o SPAR (Auto-Reclusão Monofásica) e o religamento automático trifásico na linha de transmissão de 400 kV. O projeto analisa a influência de diferentes parâmetros do sistema, como nível de compensação, comprimento da linha e local da falta, juntamente com o método de mitigação. Para o estudo de simulação, PSCAD / EMTDC é selecionado como o software de simulação.

Palavras chave: Religamento Trifásico; Religamento Monofásico; Linha de Transmissão; Curto-circuito; Compensação Reativa em Derivação; Reator de neutro;

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1. INTRODUCTION

Today’s electrical power system is growing in size and complexity in all sectors such as generation, transmission, distribution and load systems. Electrical power systems can be classified into generation, transmission, sub-transmission, and distribution systems. An overhead transmission line is one of the main components in the electric power system. The faults in power system network result in severe economic losses and reduce the reliability of the electrical system. Accordingly, when a fault occurs on an important transmission line, it is necessary to isolate the line from the network as soon as possible to prevent damages caused by short circuit currents [1, 2]. However, the transmission line disconnection from a network (even for a short period of time) may cause transmission lines cascade outages and overwhelming blackout due to power system severe stress [3].

A fault is defined as flow of a large current which could cause equipment damage. The faults in power system network result in severe economic losses and reduce electrical system reliability and availability. System faults usually, but not always, provide significant changes in the system quantities, which can be used to distinguish between tolerable and intolerable system conditions. These changing quantities include overcurrent, over- or under-voltage, power factor or phase angle, power or current direction, impedance, frequency, temperature, physical movements, pressure, and contamination of the insulating quantities. If the current is very large, it might lead to interruption of power in the network. Voltage will change, what can affect equipment insulation. Voltage below its minimum level could sometimes cause failure to equipment. The most common fault indicator is a sudden and generally significant increase in the current; consequently, overcurrent protection is widely used [4]. It is important to study a power system under fault conditions in order to provide system protection.

1.1 Justification

Faults usually occur in a power system due to either insulation failure, flashover, physical damage or human error. These faults may be either three phase in nature involving all the three phases in a symmetrical manner or may be asymmetrical where usually only one or two phases are involved. Faults may also be caused by short-circuits to the earth broken conductors in one or more phases or between live conductors. In some cases simultaneous faults due to involving both short-circuit and broken conductor (known as open-circuit faults) [5].

In many instances, the flashover caused by such events does not result in permanent damage if the circuit is interrupted quickly. A common practice is to open the faulted circuit, permit the arc to extinguish naturally, and then close the circuit again. Usually, this enhances the continuity of services by causing only a momentary outage and voltage dip. Typical outage times are in the order of 0.5 to 1 or up to 2 s, rather than many minutes and hours [4].

For EHV (extra high voltage) transmission levels, between 90–95% of all line faults involve only a single phase. Of these, more than 90% are temporary and can be cleared by three phase reclosing; consequently, single line to ground (SLG) faults have received the most attention in system studies. The fault arc will extinguish and the dielectric fault path will restore completely during the dead time of the breaker, usually for 25–30 cycles (0.5 – 0.6 s) in a 500 kV systems. Three-phase reclosing, however, may cause system instability and result in system breakup and outages. For such instances, single-phase reclosing provides an improvement, without causing system instability, to enhance transmission system availability [6].

If single-phase reclosing is used instead, then only the faulted phase is cleared. After a time delay, the breakers at each phase end are cleared. The two faultless (sound) phases remain connected and keep on carrying around 54 % of the pre-fault power [7, 8]. With single-phase switching, the energized phases inductively and capacitively couple energy into the faulted phase. This coupled fault current, which can sustain the arc, is usually called the secondary arc current. With relatively short transmission lines, the secondary arc current may be so low that the fault extinguishes quickly and reclosing can be accomplished after only a small delay. With longer lines, some type of action is needed to reduce the fault current. An accurate secondary arc representation is essential in determining the auto-reclosing performance of EHV transmission lines [6].

The arc starts by a single-phase fault, at any transmission line point. By the opening of faulted phase circuit breakers, the initial (fault) current is reduced from kA levels to the so-called secondary arc and rarely exceed 10^2 A (rms) in magnitude. Indeed, higher values of secondary arc may be observed in very long lines, with no intermediate substations and low compensations levels (or none) – a very rare configuration, only if adequate procedures to reduce secondary arc current are not taken [9].

Single-phase auto-reclosing (SPAR) is widely employed to eliminate single-phase to ground faults, which constitutes the overwhelming majority of faults at transmission lines. SPAR procedure can be summarized as: after Circuit Breakers (CBs) at faulted phase tripping, faulted phase relay is activated and the reclosing command is sent for the CBs after specified dead time. If the fault is transient and has extinguished within dead time, the line returns to its normal operation, otherwise three-phase tripping is implemented and the faulted line is disconnected from the network. Conventional SPAR assumes fixed dead time reclosure, that is, the breaker recloses after a defined period. However, if this period between the tripping operation and the reclosure of the faulted phase breakers is not optimized (or smartly adapted), it is possible that an unnecessary delay to reclose the phase after the arc extinction occurs or the phase may be reclosed with the fault still existing [3, 10].

As explained, using constant time delay for SPAR has some disadvantages. The main problems related to conventional reclosure scheme are: the risk of a fault restrike due to an insufficient time to extinguish the fault; the risk of a second shock to the system in the case of a permanent fault; and the possibility of greater oscillations. These problems could jeopardize the system stability and reliability and cause serious damages with negative impact on utility equipment [11].

Three-phase auto-reclosure is one in which the three phases of the transmission line are opened after fault incidence, independent of the fault type, and are reclosed after a predetermined time period following the initial circuit breaker opening. In three phase auto reclosing breaker closes more than once and this scheme is useful for semi transient faults for example a branch of tree falling over the line. More than two shots are rather meaningless and may cause extra wear and tear to breaker contacts. Three-phase reclosing may cause system instability and result in system breakup and outage.

1.2 Objective

Transient faults can be successfully cleared by the proper use of auto-reclosing. This maneuver de-energizes the line long enough for the fault source to pass and the fault path to de-energize, then automatically recloses the line to restore service.

The reasons for applying auto-reclosing function can be summarized as follows [12]:

- minimizing the interruption of the supply to the customer;
- maintenance of system stability and synchronism;
- restoration of system capacity and reliability with minimum outage and least expenditure of manpower;
- restoration of critical system interconnections;

- restoration of service to critical loads;
- higher probability of some recovery from multiple contingency outages;
- reduction of fault duration, resulting in less fault damage and fewer permanent faults;
- Relief for system operators in restoration during system outages.

The main objective of this research project is the analysis of SLG fault elimination through two methods: SPAR (Single-Phase Auto-Reclosing) and Three-Phase Auto-Reclosing (3PAR).

The system used is a 400 kV transmission system and the influence of different system parameters like compensation level, line length and fault location together with the mitigation method will be considered.

The project analyses the effect of variations parameters and the different method to clear fault and compare the results. This discussion aims to examine the severity of each procedure and the effect on system equipment, such as neutral reactor.

2. LITERATURE REVIEW

Electricity providers all over the world have in recent times been confronted with the challenging task of meeting the ever-growing demand for electrical power. This growing electrical power demand is a result of the increasing trend of industrialization and population growth. The massive load centers are concentrated in areas which are often distant from the generating stations, and thus require the building of transmission lines to transport the power. Not only must electricity providers be able to meet the growing need, they must also do so in a reliable, quality, economical, and secure manner [6].

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 [13].

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 was 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.

With regarding to the transmission of electric power to these load centers, electric power providers have these options: (a) Construction of new transmission networks, (b) Addition of another circuit to existing single transmission circuits, i.e. double-circuit lines, and (c) Upgrading of existing transmission networks; be it single or double-circuit, in order to operate at higher voltage levels. The option of constructing new transmission networks (a) has huge economic and environmental implications; the cost of new conductors, towers, insulators, protection equipment, the difficulty in acquiring new right-of-ways, and the environmental battles that must be fought. Option (b) seems worth considering, however, its implementation also comes with a cost. The cost mainly involves the reconfiguration or replacement of towers, and the acquisition of new conductors and insulators. The reversion to double-circuits will also demand changes in the existing protection system. [14, 15].

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 [13, 16]. In such a condition, first, reclosing is performed regardless of the fault type, i.e., permanent or temporary. Second, there is no guarantee that 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 [17, 18].

In [15] notwithstanding the financial gains in resorting to the upgrading of existing transmission lines, pushing more power through existing transmission systems threatens the marginal stability of the system. The problem of marginal stability, coupled with the frequent occurrence of faults on power systems poses serious threats to the quality, reliability of supply, and the overall security of the power system. The advent of auto-reclosures has brought a huge sigh of relief to electricity providers. The application of auto-reclosures to power systems improves marginal stability, power quality (voltage dips are avoided), security and reliability of supply. Auto-reclosures can be classified into conventional and adaptive auto-reclosures.

In [19] conventional auto-reclosures reclose a circuit after a fixed (dead) time, following a trip initiated by a fault, and can be single-pole or three-pole. This can lead to reclosure into permanent and transient faults, shock to system, and endangering of system stability. Properly designed adaptive auto-reclosures, owing to they being able to adapt reclosure times, overcome the aforementioned disadvantages.

Properly designed adaptive auto-reclosures provide a distinction between permanent and transient faults. Reclosure is inhibited when a fault is permanent and in the case of a transient fault, the optimal reclosure time is determined. Adaptive auto-reclosures can be classified into Adaptive single-pole or single-phase auto-reclosures (AdSPARs) and Adaptive three-phase auto-reclosures (AdTPARs).

In [20, 21] adaptive single-pole auto-reclosing is the auto-reclosing of one phase of a circuit breaker following a single-phase trip for SLG faults, with the auto-reclosing time based on existing specific conditions on the transmission line. In [22] adaptive three-phase auto-reclosing involves the auto-reclosing of all three phases of a circuit following a three-phase trip. Three-phase auto-reclosure failures however have more serious consequences to the power system than single-phase auto-reclosure failures.

Adaptive auto-reclosures can result in the following advantages to a power system [23, 24]:

- Improvements in transient stability.
- Improvements in system reliability and availability, especially where remote generating stations are connected
- To load centers with one or two transmission lines
- Reduction of switching overvoltages.
- Reduction of shaft torsional oscillation of large thermal units.
- High-speed response to a sympathy trip.
- Minimized unsuccessful reclosing.
- Reduction in system and equipment transients.

The successful development of an adaptive auto-reclosing technique is inhibited by factors such as the complex nature of the transmission network (line configuration, source parameters, system loadings, and system voltage), different fault types and locations, fault point on wave, and atmospheric conditions [15, 24].

Properly designed adaptive auto-reclosures are expected to meet the following requirements:

- Make a clear distinction between permanent and transient faults.
- Avoid reclosing into permanent faults.
- Determine the extinction time of a transient fault arc.
- Provide an optimal reclosure time.
- Perform satisfactorily under varying power system operating conditions such as loading, noise and atmospheric conditions.
- Less expensive and easy to implement.

These methods may utilize high frequency voltage or current signals to distinguish between permanent and transient faults and also predict optimal reclosure times [25-27]. In [25] while the algorithm makes use of busbar voltages and generator output currents to predict arc extinction times, the technique uses a spectral energy computation to detect the optimal reclosure time. On the other hand, the scheme in [27] predicts its optimal reclosure time by computing the transient energy of the power system. The proposed method in [26] however does not have arc extinction time determination capabilities.

The following limitations can be pointed out:

- The high cost of high frequency transient voltage detectors in [25].
- Difficulty in calculating the spectral and transient energies of a practical system.
- The many causes of faults and the interplay of several factors such as line construction, fault position, pre-fault loading, source parameters, and atmospheric conditions which influence the actual waveforms of the secondary arc voltage may hinder the effectiveness of these techniques [24] .
- These schemes are also limited in their ability to cope with previously unnamed situations and are also not robust in the presence of noise.

The method proposed in [28] utilizes an algorithm which is derived in the time domain and based on the differential equations describing the electromagnetic transients on overhead lines. The method is however only able to classify faults; it cannot determine the secondary arc extinction time.

In [29] another AdTPAR method has been proposed in the paper titled: "A New Adaptive Auto-reclosure Scheme to Distinguish Transient Faults from Permanent Faults". The proposed method is based on the carrier channel protection and modal analysis. However, like the scheme developed in [28], this method is only able to distinguish between faults. Likewise, the technique proposed in [26] provides only a partial solution to the three-phase auto-reclosure problem.

The method proposed in [30] which employed an artificial neural network has the ability to identify faults (permanent or transient) and also determine the secondary arc extinction time. The method was however developed for double-circuit transmission systems and will not work for single-circuit lines.

As regards adaptive three-phase auto-reclosure (AdTPAR) schemes there are some other proposals to distinguish between faults, and also determine the secondary arc extinguishing time for single-circuit transmission systems [22]. The difficulty in fulfilling these tasks is due to the fact that:

- There are lots of fault transient components before tripping which interfere in the arc fault characteristics.
- After three-phase tripping, the transmission line is separated from the power system, and the line voltage should be monitored. There is no data for line current.

Over the years analog and digital techniques have been extensively used by the researchers to predict system performance, but the main difficulty has always been the arc modeling during the secondary arcing phase with resultant uncertainty associated with the predictions of secondary arc extinction times and the empirical rules used as measures of acceptability and subsequent reclosing [31].

Such improved models allow to identify more precisely, whether it is necessary to have extra device or even if a special procedure is necessary to assure the SPAR success, while specifying its characteristics in practice, it means a more optimized line design as a whole (improving performance and reducing costs). The aim of analyzing fault data cases is to determine common parameters of interest, i.e., maximum and minimum values, in order to identify the features of each fault case.

In [32, 33] auto-reclosing is an efficient maneuver to mitigate the expected line fault growth caused by lightning strokes in compact line design due to its reduced insulation distances. An accurate representation of the secondary arc is essential in determining the auto-reclosing performance of EHV transmission lines. The arc dynamic behavior is basically presented by a time-varying resistance. The arc parameters such as time constants and arc length has great influence in the arc extinction time besides the capacitive and inductive coupling between the faulty and the sound phases. Parameters for the arc model have been extracted from staged fault tests records carried out on a double-circuit uncompensated 400 kV line.

In [34] the authors studied the importance of optimizing transmission system parameters from its conception, considering altogether the relevant options and possibilities, in order to have better cost-performance result. The presented results were obtained in the study of a real transmission system expansion, based on an 865 km long line. The single-phase auto-reclosing procedure was one of the aspects carefully studied. The secondary arc current was mitigated through the traditional solution of using the neutral reactor on the existing shunt reactor banks. The method of obtaining the optimized value for the neutral reactor was discussed. Several system elements were adjusted to improve the system performance.

In [35] the authors collected and analyzed several articles from the international publication about secondary arcs. They classified the parameters which influenced on the secondary arc extinction time into two groups. The first group parameter (line length, rated voltage, method of arc ignition, degree of compensation, location of shunt reactor and distance between arcing horn) is influenced by the network configuration and operation (at field test) or by the laboratory test circuits. The others (fault location, primary arc current and duration, wind, secondary arc resistance, recovery voltage and secondary arc current) are depending on atmospheric or other stochastic conditions.

In [36] the authors proposes an algorithm for AdSPAR based on processing the mode current signal using wavelet packet transform, which can identify transient and permanent faults, as well as the secondary arc extinction time. The studied method has been successfully tested under fault conditions on a 500 kV overhead line using EMTP. The algorithm does not need a case-based threshold level. Its performance is independent of fault location, line parameters, and pre-fault line loading conditions.

Many studies have been made based on measurements of secondary fault current and time for arc extinguishing on single-circuit and double-circuit lines. In [37] the authors reported the use of high-speed grounding switches. This is an effective method for extinguishing secondary arc current associated with single-pole switching. High-speed grounding switches are connected at each end of BPA's existing 500 kV transmission line, hence in parallel with the secondary arc, and will permit rapid circuit breaker reclosing.

In [38] the authors performed fault tests on a 528 km 500 kV single-circuit line. The tests were made at three different positions along the line. The line had reactive compensation. Although not specifically stated, it is expected that the shunt reactors were selected for optimum or near optimum compensation. The secondary arc current extinguished very quickly, probably because the line was well compensated and fault current (If) was low. The slope of the recovery voltage in the first few ms after the arc extinguished is very low. It was noted that the time until extinction was mainly dependent upon the DC offset of the secondary fault current, which was a function of the breaker opening time.

In [39] the results of a large number of single-phase reclosing experiments on two transmission lines were reported. The first line was a 243 km 765 kV line in the United States, and the second was a 417 km 750 kV line in the USSR. Reactive compensation with the usual neutral reactor was used on both lines, although various reactor configurations were used during the tests. Scherer, et al. indicates that the tests on the 765 kV line with the 4.2 m arc length support a TRV initial rate of rise of 10 kV/ms for successful extinguishing.

In [40] the authors presented on test results on the same 243 km 765 kV line as considered in [39]. It was noted that the arc resistance has a significant effect on the secondary arc current. It is also stated that the withstand rate of rise of the 4.2 m gap was about 10 kV/ms, and also that for this line the rate of rise was around 0.2 If.

Based on the results reported above, it would appear that for a 500 kV system, single-pole reclosing schemes have pre-set delay times (typically 0.4 to 0.5 s) that reclose the open circuit breaker phase whether the arc has extinguished or not. Successful reclosing will occur when the secondary arc self-extinguishes prior to the time of reclosing.

Considering the range of published reference data, the following values will result in successful reclosing for the majority of cases:

- The secondary arc current is less than 40 Arms.
- The rate of the recovery voltage after the arc clears is less than 10 kV/ms

In order to improve the stability of the system, it is desirable to restore the service as soon as possible; it is a common operating practice to reclose a circuit breaker a few cycles after it has interrupted a fault.

3. METHODOLOGY

3.1 Transmission Line

Transmission lines are sets of wires, called conductors that carry electric power from generating plants to the substations that deliver power to customers. At a generating plant, the voltage level is stepped up to several thousand volts by a transformer and delivered to the transmission line. At numerous substations on the transmission system, transformers step down to a lower voltage and deliver it to distribution lines. Distribution lines carry power to farms, homes and businesses. The type of transmission structures used for any project is determined by the characteristics of the transmission line's route, including terrain and existing infrastructure.

3.1.1 Type of transmission Line

1. ***Short Transmission Line:***

- Length is less than 80 km
- Capacitance effect is negligible
- Only resistance and inductance are taken in calculation

Short transmission line is modeled in Fig. 3.1:

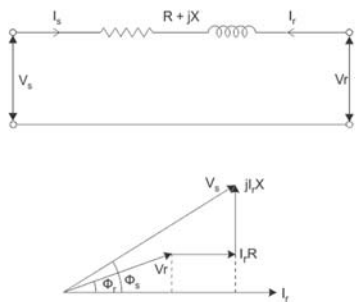


Fig. 3.1 Short Transmission Line

2. ***Medium Transmission Line***

- Length is about 80 km to 240 km
- Capacitance effect is present
- Distributed capacitance form is used for calculation purpose.
- Nominal π-circuit for medium transmission line is modeled in Fig. 3.2:

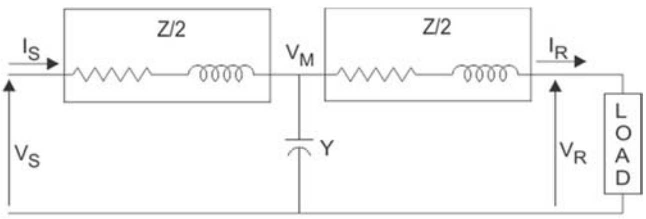


Fig. 3.2 T model -circuit

3. ***Long Transmission Line***

- Length is more than 240 km
- Line constants are considered as distributed over the length of the line.
- Long transmission line is modeled in Fig. 3.3:

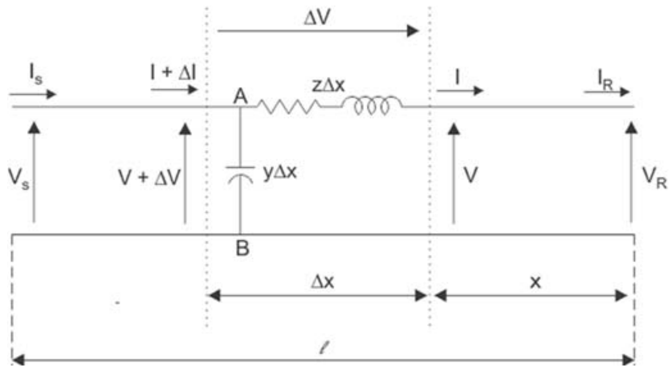


Fig. 3.3 Long Transmission Line

During normal operation, a power system is in a balanced condition. Abnormal scenarios occur due to faults. Faults in a power system can be created by natural events such as falling of a tree, wind, and an ice storm damaging a transmission line, and sometimes by mechanical failure of transformers and other equipment in the system. A power system can be analyzed by calculating system voltages and currents under normal and abnormal scenarios [41].

A power system is predominantly in steady state operation or in a state that could with sufficient accuracy be regarded as steady state. In a power system there are always small load changes, switching actions, and other transients occurring so that in a strict mathematical sense most of the variables are varying with the time.

A short circuit in a power system is clearly not a steady state condition. Such an event can start a variety of different dynamic phenomena in the system and to study this dynamic models are needed. A fault current consists of two components, a transient part, and a steady state part [42].

3.1.2 Network Models

All analysis in the engineering sciences starts with the formulation of appropriate models. A model, and in power system analysis we almost invariably then mean a mathematical model, is a set of equations or relations, which appropriately describes the interactions between different quantities in the time frame studied and with the desired accuracy of a physical or engineered component or system. Hence, depending on the purpose of the analysis different models of the same physical system or components might be valid. It is recalled that the general model of a transmission line was given by the telegraph equation, which is a partial differential equation, and by assuming stationary sinusoidal conditions the long line equations, ordinary differential equations, were obtained. By solving these equations and restricting the interest to the conditions at the ends of the lines, the lumped-circuit line models (π-models) were obtained, which is an algebraic model.

In principle, the complete telegraph equations could be used when studying the steady state conditions at the network nodes. The solution would then include the initial switching transients along the lines, and the steady state solution would then be the solution after the transients have decayed. However, such a solution would contain a lot more information than wanted and, furthermore, it would require a lot of computational effort. An algebraic formulation with the lumped-circuit line model would give the same result with a much simpler model at a lower computational cost.

In the above example it is quite obvious which model is the appropriate one, but in many engineering studies the selection of the "correct" model is often the most difficult part of the study (Fig. 3.4).

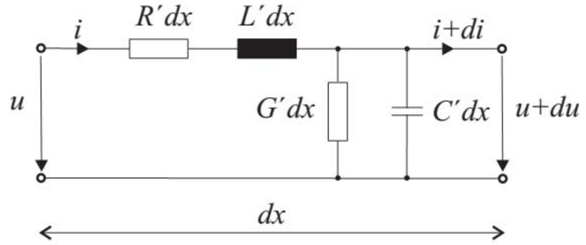


Fig. 3.4. Equivalent circuit of a line element of length dx

In the subsequent sections algebraic models of the most common power system components suitable for power flow calculations will be derived. If not explicitly stated, symmetrical three-phase conditions are assumed in the following.

Lines and Cables:

Transmission line parameters:

- An electric transmission line is modeled using series resistance, series inductance, shunt capacitance, and shunt conductance.
- The line resistance and inductive reactance are important.
- For some studies it is possible to omit the shunt capacitance and conductance and thus simplify the equivalent circuit considerably.

The general distributed model is characterized by the series parameters

R′ = series resistance/km per phase (Ω/km)

X′ = series reactance/km per phase (Ω/km)

And the shunt parameters

B′ = shunt susceptance/km per phase (siemens/km)

G′ = shunt conductance/km per phase (siemens/km)

As depicted in Figure 3.4. The parameters above are specific for the line or cable configuration and are dependent on conductors and geometrical arrangements.

This model is frequently referred to as the π-model, and it is characterized by the parameters (Fig. 3.5):

$Z_{km} = R_{km} + jX_{km}$ = series impedance (Ω) (1)

$Y_{km}^{sh} = G_{km}^{sh} + jB_{km}^{sh}$ = shunt admittance (siemens) (2)

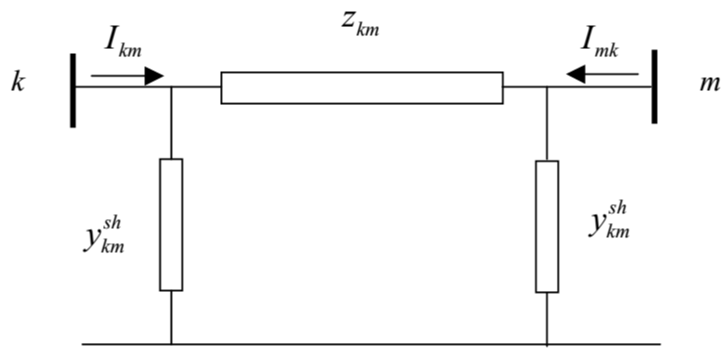


Fig. 3.5. Lumped-circuit model (π-model) of a transmission line between nodes k and m.

3.2 Fault in Transmission Line

A transient fault is a fault that is no longer present if power is disconnected for a short time and then restored. Many faults in overhead power lines are transient in nature. When a fault occurs, equipment used for power system protection operate to isolate the area of the fault. A transient fault will then clear and the power-line can be returned to service.

The fault analysis of a power system is required in order to provide information for the selection of switchgear, setting of relays and stability of system operation. A power system is not static but changes during operation (switching on or off of generators and transmission lines) and during planning (addition of generators and transmission lines).

Faults usually occur in a power system due to either insulation failure, flashover, physical damage or human error. These faults, may either be three phase in nature involving all three phases in a symmetrical manner, or may be asymmetrical where usually only one or two phases may be involved. Faults may also be caused by either short-circuits to earth or between live conductors, or may be caused by broken conductors in one or more phases. Sometimes simultaneous faults may occur involving both short-circuit and broken conductor faults (also known as open-circuit faults) [5].

There are two types of faults which can occur on any transmission lines; balanced fault and unbalanced fault also known as symmetrical and asymmetrical fault respectively. Most of the faults that occur on the power systems are unbalanced faults. In addition, faults can be categorized as shunt faults and series faults. Series faults are those type of faults which occur in impedance of the line and does not involve neutral or ground, nor does it involves any interconnection between the phases. In this type of faults there is increase of voltage and frequency and decrease of current level in the faulted phases. Example: opening of one or two lines by circuit breakers. Shunt faults are the unbalance between phases or between ground and phases. This research only consider shunt fault. In this type of faults there is increase of current and decrease of frequency and voltage level in the faulted phases [41].

3.2.1 Fault Level

In a power system, the maximum the fault current (or fault MVA) that can flow into a zero impedance fault is necessary to be known for switch gear specification. This can either be the balanced three phase value or the value at an asymmetrical condition. The Fault Level defines the value for the symmetrical condition. The fault level is usually expressed in MVA (or corresponding per-unit value), with the maximum fault current value being converted using the nominal voltage rating [5].

The Short circuit capacity (SCC) of a busbar is the fault level of the busbar. The strength of a busbar (or the ability to maintain its voltage) is directly proportional to its SCC. An infinitely strong bus (or Infinite bus bar) has an infinite SCC, with a zero equivalent impedance and will maintain its voltage under all conditions.

- **Symmetrical Three Phase Fault Analysis**

A three phase fault is a condition where either

(a) All three phases of the system are short-circuited to each other (Fig. 3.6a), or

(b) All three phase of the system are earthed (Fig. 3.6b).

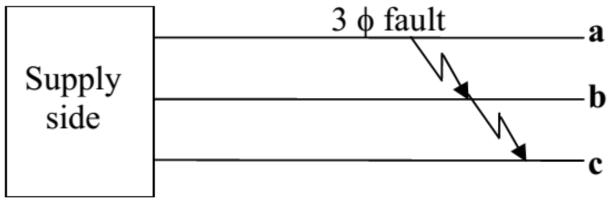


Fig. 3.6a – Balanced three phase fault

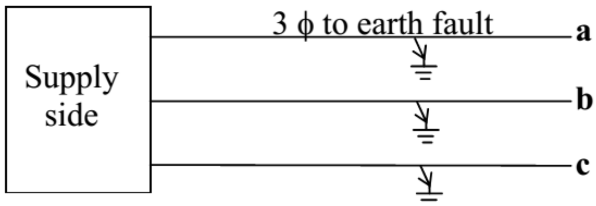


Fig. 3.6b – Balanced three phase fault

This is in general a balanced condition, and we need to only know the positive-sequence network to analyses faults. Further, the single line diagram can be used, as all three phases carry equal currents displaced by 120°. Typically, only 5% of the initial faults in a power system, are three phase faults with or without earth. Of the unbalanced faults, 90 % are line-earth and 15% are double line faults with or without earth and which can often deteriorate to 3 phase fault. Broken conductor faults account for the rest [5].

3.2.2 Asymmetrical Three Phase Fault Analysis

a) Assumptions Commonly Made in Three Phase Fault Studies

The following assumptions are usually made in fault analysis in three phase transmission lines.

- All sources are balanced and equal in magnitude & phase
- Sources represented by the Thevenin's voltage prior to fault at the fault point
- Large systems may be represented by an infinite bus-bars
- Transformers are on nominal tap position
- Resistances are negligible compared to reactance
- Transmission lines are assumed fully transposed and all 3 phases have same Z
- Loads currents are negligible compared to fault currents
- Line charging currents can be completely neglected

b) Basic Voltage – Current Network equations in Sequence Components

The generated voltages in the transmission system are assumed balanced prior to the fault, so that they consist only of the positive sequence component V_f (pre-fault voltage). This is in fact the Thevenin's equivalent at the point of the fault prior to the occurrence of the fault.

$$\begin{aligned} V_{a0} &= 0 - Z_0 I_{a0} \\ V_{a1} &= E_f - Z_1 I_{a1} \\ V_{a2} &= 0 - Z_2 I_{a2} \end{aligned} \qquad (3)$$

This may be written in matrix form as:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \qquad (4)$$

These may be expressed in Network form as shown in figure 3.7:

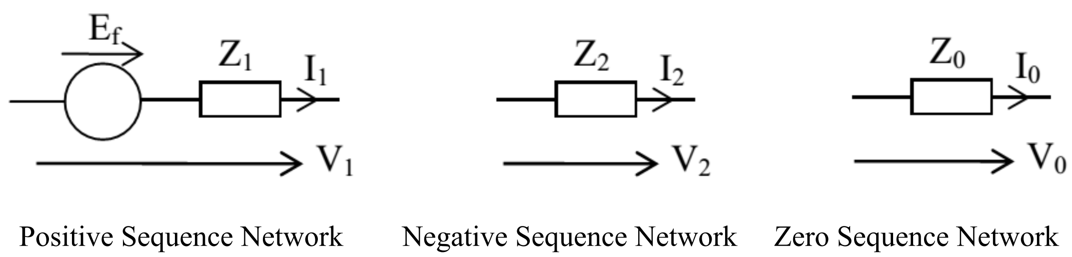


Fig. 3.7 – Elementary Sequence Networks

3.2.3 Analysis of Asymmetrical Faults

An asymmetric or unbalanced fault does not affect each of the three phases equally. The common types of asymmetrical faults occurring in a Power System are single line to ground faults and line to line faults, with and without fault impedance. The asymmetrical faults will have faulty parameters at random. They can be analyzed by using the symmetrical components. The standard types of asymmetrical faults considered for analysis include the following (in the order of their severity):

1) Line–to–Ground (L-G) Fault
2) Line–to–Line (L-L) Fault
3) Double Line–to–Ground (L-L-G) Fault

a) Single Line to Ground faults (L – G faults)

The single line to ground fault can occur in any of the three phases. However, it is sufficient to analyze only one of the cases. Looking at the symmetry of the symmetrical component matrix, it is seen that the simplest to analyze would be the phase a. Consider an L-G fault with zero fault impedance as shown in figure 3.8.

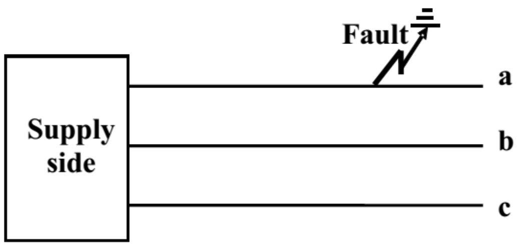


Fig. 3.8 – L-G fault on phase a

Since the fault impedance is 0, at the fault

$V_a = 0, I_b = 0, I_c = 0$ (5)

These can be converted to equivalent conditions in symmetrical components as follows.

$V_a = V_{a0} + V_{a1} + V_{a2} = 0$ (6)

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b = 0 \\ I_c = 0 \end{bmatrix} \quad (7)$$

And giving, $I_{a0} = I_{a1} = I_{a2} = I_a/3$ (8)

Mathematical analysis using the network equation in symmetrical components would yield the desired result for the fault current $I_f = I_a$.

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_f \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} = I_a/3 \\ I_{a1} = I_a/3 \\ I_{a2} = I_a/3 \end{bmatrix} \quad (9)$$

Thus $V_{a0} + V_{a1} + V_{a2} = 0 = -Z_0.I_a/3 + E_f - Z_1.I_a/3 - Z_2.I_a/3$ (10)

Simplification, with $I_f = I_a$, gives

$$I_f = \frac{3E_f}{Z_1 + Z_2 + Z_0} \quad (11)$$

Also, considering the equations

$V_{a0} + V_{a1} + Va2 = 0$, and $I_{a0} = I_{a1} = I_{a2}$ indicates that the three networks (zero, positive and negative) must be connected in series (same current, voltages add up) and short-circuited, giving the circuit shown in figure 3.9.

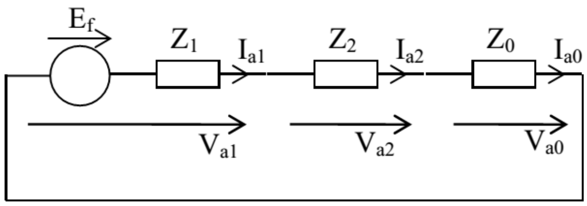


Fig. 3.9 – Connection of Sequence Networks for L-G fault with Zf = 0

In this case, I_a corresponds to the fault current If, which in turn corresponds to 3 times any one of the components ($I_{a0} = I_{a1} = I_{a2} = I_a/3$). Thus the network would also yield the same fault current as in the mathematical analysis.

b) Line to Line faults (L – L faults)

Line-to-Line faults may occur in a power system, with or without the earth, and with or without fault impedance.

1) L-L fault with no earth and no Z_f

Solution of the L-L fault gives a simpler solution when phases b and c are considered as the symmetrical component matrix is similar for phases b and c (Fig. 3.10). The complexity of the calculations reduce on account of this selection. At the fault,

$I_a = 0$, $V_b = V_c$ and $I_b = -I_c$ (12)

Mathematical analysis may be done by substituting these conditions to the relevant symmetrical component matrix equation.

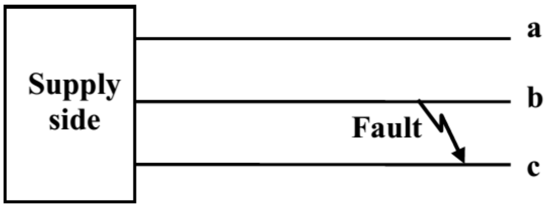


Fig. 3.10 – L-L fault on phases b-c

2) L-L-G fault with earth and no Z_f At the fault,

$I_a = 0, V_b = V_c = 0$ (13)

Gives:

$I_{a0} + I_{a1} + I_{a2} = I_a = 0$ (14)

And the condition, $V_{a0} = V_{a1} = V_{a2}$ (15)

These conditions taken together, can be seen to correspond to all three sequence networks connected in parallel (Fig. 3.11).

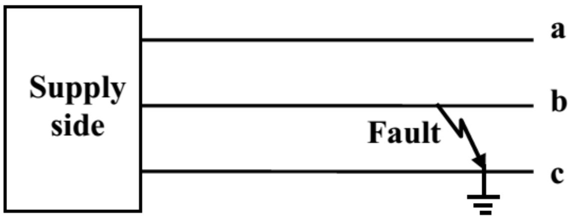


Fig. 3.11 – L-L fault on phases b-c

3) L-L-G fault with earth and Z_f

If Z_f appears in the earth path, it could be included as $3Z_f$, giving $(Z_0 + 3Z_f)$ in the zero sequence path (Fig. 3.12).

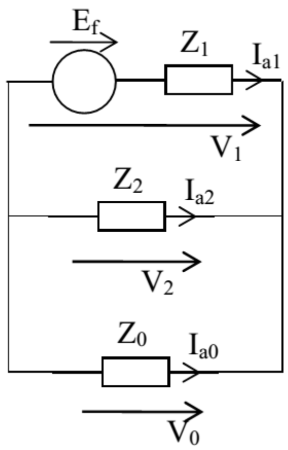


Fig. 3.12 – Connection for L-L-G fault

Transient faults can be successfully cleared by the proper use of tripping and auto-reclosing.

3.3 Auto-Reclosing

In auto reclosing whenever a fault occurs in transmission line, breaker trips and recloses after some time delay to clear the fault. About 80 to 90 % faults on transmission line are temporary faults and mainly due the lightning (over voltage induced in line due to static electricity of lightning may cause flash over across the insulator string), temporary contact with foreign objects which can be cleared by tripping and subsequent reclosing of the breaker [22]. Remaining 10 to 20% of faults are either semi-transient or permanent fault, like open conductor etc, which cannot be cleared by opening and subsequent closing of the breaker.

1) Single Phase Auto Reclosing
2) Three Phase Auto Reclosing

In the high voltage circuits where the fault levels associated are extremely high, it is essential that the system dead time be kept to a few cycles so that the generators do not drift apart. High speed protection such as pilot wire carrier or distance must be used to obtain operating times of one or two cycles. It is therefore desired that the reclosure be of the single shot type. High speed reclosure in high voltage circuits improves the stability to a considerable extent on single-circuit ties. On double circuit ties subjected to single circuit faults the continuity through the healthy circuit prevents the generators from drifting apart so fast and increase in the stability limit is thus moderate. Nevertheless, it is sometimes important. However, when the faults occur simultaneously on both the circuits the stability limit increases again considerably.

The successful application of high speed auto-reclose to high voltage systems interlinking a number of sources depends on the following factors.

a. The maximum time available for opening and closing the circuit breakers at each end of the faulty line, without loss of synchronism.

b. The time required to deionize the arc at the fault, so that it will not restrike when the breakers are reclosed.

c. The speed of operation on opening and closing of the circuit breakers.

d. The probability of transient faults, that will allow high speed reclosure of the faulty lines.

It will be seen that some of these conditions are conflicting, e.g., the faster the breakers are reclosed the greater the power that can be transmitted without loss of synchronism, provided that the arc does not restrike. But here the likelihood of arc restriking is greater. An unsuccessful reclosure is more detrimental to stability than no reclosure at all. For this reason the time allowed to deionize the line must not be less than the critical time for which the arc hardly ever restrikes. The reduction of reclosing time obtained by high speed relaying is however preferred as it reduces the duration of arc. Indeed, the increase in power limit due to reclosing is much greater with very rapid fault clearing than with slower fault clearing. For best results the circuit breakers at both ends of the faulty line must be opened simultaneously. Any time during which one circuit breaker is open in advance of the other represents an effective reduction of the breaker electrical dead time and may well jeopardize the chances of a successful reclosure.

For a single circuit interconnectors between two power systems, the opening of all the three phases of the circuit breaker makes the generators in each group start to drift apart in relation to each other, since no interchange of synchronizing power can take place. On the other hand SPAR is one in which only the faulted phase is opened and reclosed after a controlled delay period. For multiphase faults, all three phases are opened and reclosure is not attempted. In case of SLG faults which are in majority, synchronizing power can still be interchanged through the healthy phases.

In the case of SPAR each phase of the circuit breaker has to be segregated and provided with its own closing and tripping mechanism; this is normal with EHV air blast and SF6 breakers. Also it is necessary to fit phase selecting relays that will detect and select the faulty phase. The associated tripping and reclosing circuitry is therefore more complicated.

Thus SPAR is more complex and expensive as compared to 3PAR. When the former is used the faulty phase must be deenergized for a longer interval of time, than in the case of 3PAR, owing to the capacitive coupling between the faulty phase and the healthy conductors which tends to increase the duration of the arc. The advantage claimed for single-phase reclosing is that on a system with transformer neutrals grounded solidly at each substation, the interruption of one phase to clear a ground fault causes negligible interference with the load because the interrupted phase current now flows in the ground through neutral points until the fault current is cleared and the faulted phase reclosed. The main drawback is its longer deionizing time which can cause interference with communication circuits and, in certain cases misoperation of earth relays in double circuit lines owing to the flow of zero sequence currents [44, 45].

3.4 Shunt Compensation

As the volume of Power transmitted and distributed increases, so do the requirements for a high quality and reliable supply. Thus, reactive power and voltage control in an electrical power system is important for proper operation for electrical power equipment to prevent damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the system to withstand and prevent voltage collapse. As, the power transfer grow, the power system becomes increasingly more complex to operate and the system become less secure. It may lead to large power with inadequate control, excessive reactive power in various parts of the system and large dynamic swings between different parts of the system, thus the full potential of transmission interconnections cannot be utilized [46].

In power transmission, reactive power plays an important role. Real power accomplices the useful work while reactive power supports the voltage that must be controlled for system reliability. Reactive power has a profound effect on the security of power systems because it affects voltages throughout the system. Decreasing reactive power causing voltage to fall while increasing it causing voltage to rise. A voltage collapse occurs when the system try to serve much more load than the voltage can support. Voltage control and reactive power management are the two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission networks. Voltage is controlled by absorbing and generating reactive power. Thus reactive power is essential to maintain the voltage to deliver active power through transmission lines [46].

The shunt reactor is the most cost efficient equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables, which are the primary generators of reactive power. The reactor can be seen as the voltage control device which is often connected directly to the high voltage lines.

- Three-Phase Shunt Reactors

Three-phase shunt reactors (fig. 3.13) are widely used in transmission networks. They absorb (consume) reactive power by connecting them to the transmission line. Since they decrease the voltage, they are typically used during light load conditions. Shunt reactors are inductive loads that are used to absorb reactive power to reduce the over voltages generated by line capacitance. An inductive load consumes reactive power versus a capacitive load generates reactive power. A transformer, a shunt reactor, a heavy loaded power line, and an under magnetized synchronous machine are examples of inductive loads. Examples on a capacitive load are a capacitor bank, an open power line and an over magnetized synchronous machine. Although shunt reactors are inductive loads similar to transformers but they are different than transformers in terms of construction and some electrical characteristics [47].

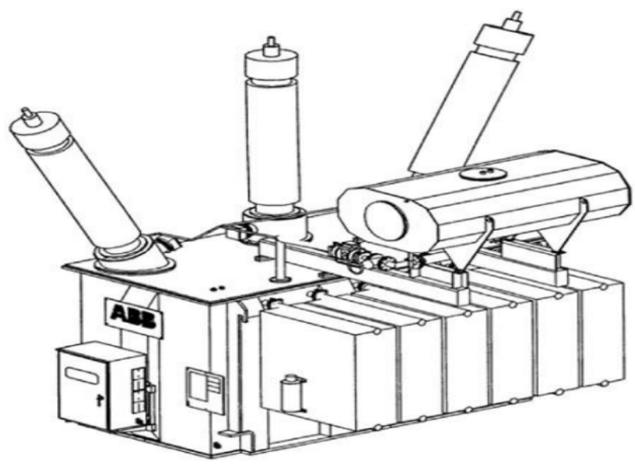


Fig. 3.13 Schematic of a three-phase shunt reactor

- Classification Of Shunt Reactors

Figure 3.14 shows the classifications of shunt reactors according to applications and design. Generally, there are two kinds of shunt reactors: dry-type reactors and oil insulated type reactors. Oil-immersed shunt reactors with an air-gapped iron core are widely used in transmission systems. For this type of reactor, the main winding and the magnetic circuit are immersed in oil. The insulation oil acts as the cooling medium, which can both absorb heat from the reactor winding and conduct the heat away by circulating the oil. The core of an oil-immersed reactor is made of ferromagnetic materials, with one or more built-in air gaps. These air gapped iron cores are designed to resist not only the mechanical stresses during normal operation but also withstand the fault conditions in the network [47].

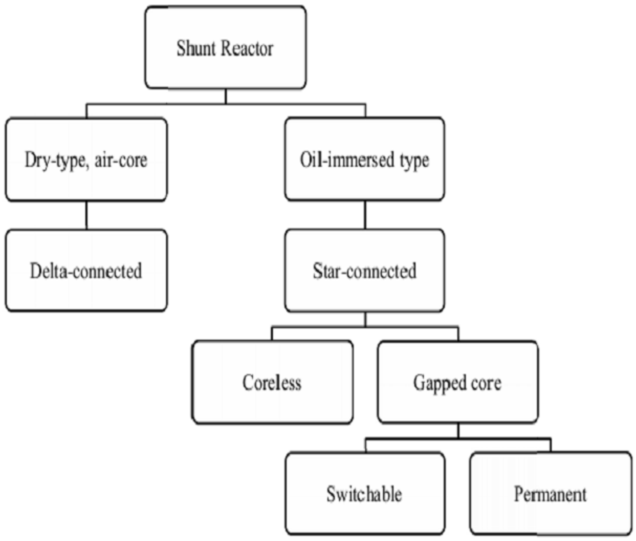


Fig. 3.14 Classification of shunt reactors

The characteristic and design construction of shunt reactors are more dependent on the applied voltage. The design of shunt reactors rated 60 kV to 245 kV is most commonly oil-filled and have three-legged gapped cores with layer, continuous disc or interleaved disc windings. At 300 kV to 500 kV, the design of shunt reactors can be single-phase or three-phase units with three-legged, five-legged or shell-type cores. For shunt reactors rated below 60 kV, the design is either oil-filled three-legged iron core types or dry coil types. Depending on the intended function, a shunt reactor can be designed to have either linear or adjustable inductances. As the name implies, linear shunt reactors have constant inductance within the specified tolerances. Conversely, a shunt reactor in which the inductance can be adjusted by changing the number of turns on the winding or by varying the air gap in the iron core is called an adjustable shunt reactor. The number of turns on a winding is changed by means of a tap changer. The service conditions are vital to the design and structure of the shunt reactor [47].

4. DESCRIPTION OF ANALYZED POWER SYSTEM

In this section, we present the data of system studied, specifically an 11-buses system, overhead transmission line, circuit-breaker, fault and shunt compensation.

The simulation program that will be used is PSCAD. PSCAD stands for Power Systems Computer Aided Design and is the graphical user interface, which allows the user to construct schematic circuits, run simulations, and analyze the result. In this project, the transmission line and fault will be simplified and incorporated as a custom component model in PSCAD. PSCAD is a graphical user interface (GUI) for EMTDC. PSCAD allows the user to graphically assemble the circuits, run the simulations, analyses the results and manage the data in a completely integrated environment.

The PSCAD component library has an extensive range of models for power system fault transient analysis purposes. These include programmable network faults and various network components such as transformer (with or without saturation effect). The following models in the PSCAD component library have been found very useful in this research work. The users are also allowed to rewrite the source code of an existing library model or build a new model with the users' own graphics and source code using FORTAN or "C" languages. The availability of extensive library components and advantage of creating customers own models facilitate the design of the fault identification and phase selection algorithm in this research work.

The simulated system is based on an actual Iranian power system were the nominal voltage is 400 kV, 60 Hz. The system is presented in Fig. 4.1, with the line were we applied the fault properly identified.

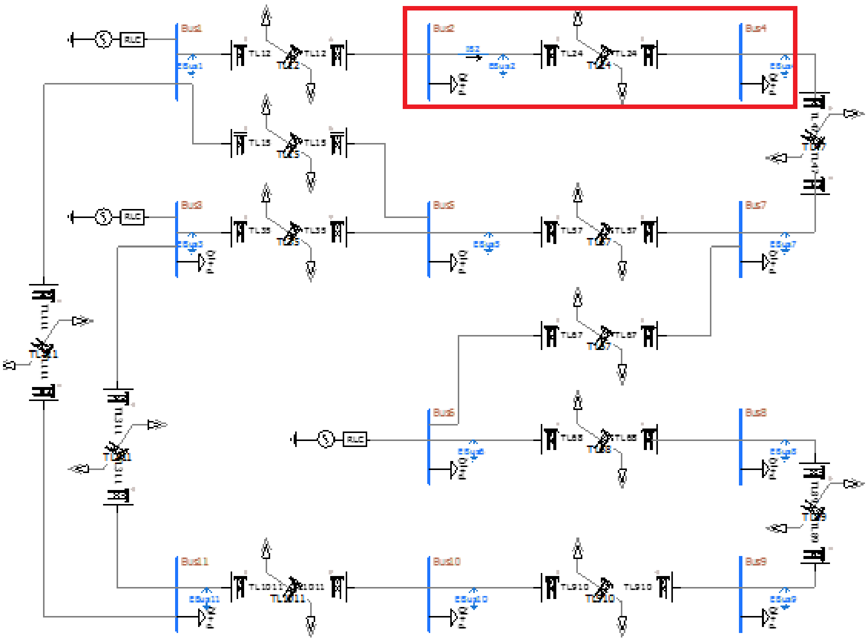


Fig. 4.1. 11-bus system

We consider the line between BUS2 and BUS4 (Fig. 4.2), we simulate system for two different length of this line (150 km and 350 km) in order to study the performance of SPAR and 3PAR for short and long compensated line.

BUS2: (Voltage = E2, Current = I2); BUS4: (Voltage = E4, Current = I4);

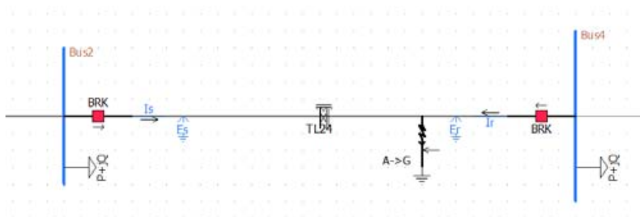


Fig. 4.2 Line with Fault

- **Compensation**

Here, we use simulate shunt compensation at both sides of transmission line (Fig. 4.3). Data of two compensation degree (70% and 90%) are presented on "Table 4.1".

En2: Natural voltage on compensation of BUS2

En4: Natural voltage on compensation of BUS4

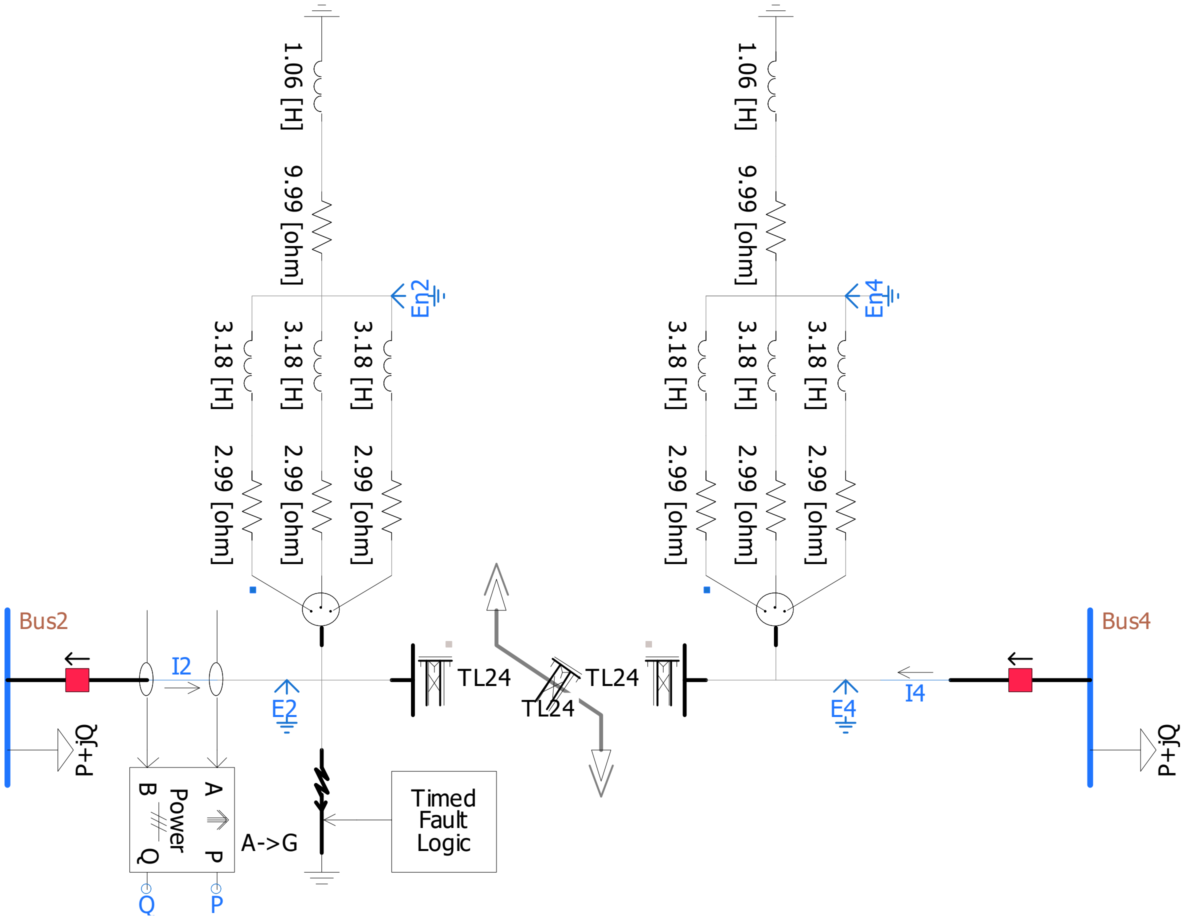


Fig. 4.3 Shunt compensation representation

Table 4.1 Data of Compensation

Comp. Degree	L_{phase} [H]	R_{phase} [ohm]	L_n [H]	R_n [ohm]
90 %	4.80	4.53	1.60	15.10
70 %	6.18	5.82	2.06	19.42

- **Overhead lines (Line 400 kV):**

Figure 4.4 shows the data of overhead line:

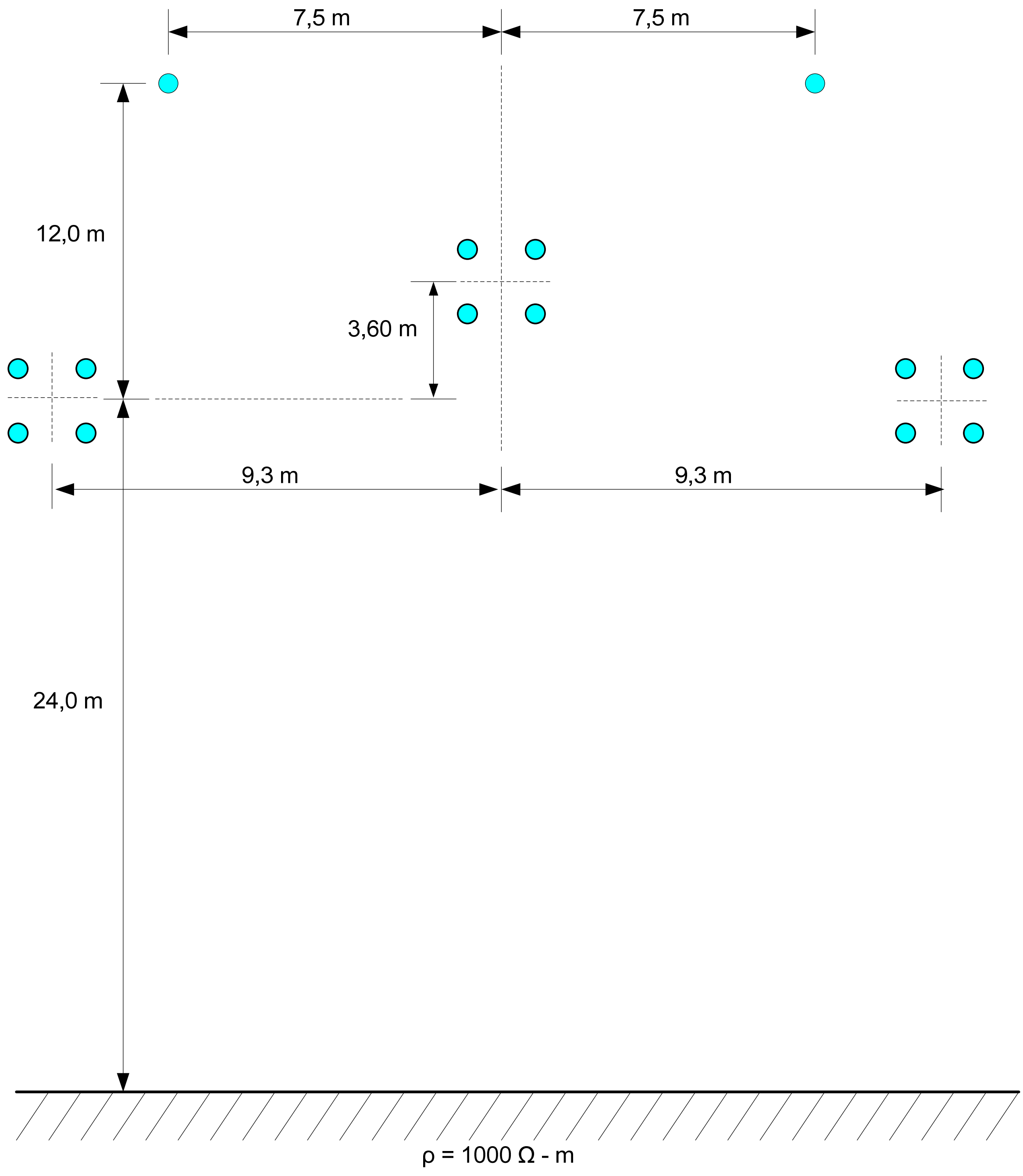


Fig. 4.4. Overhead line parameters

Data of conductor and ground-wire are presented in table 4.2 and 4.3.

Table 4.2 Data of Conductor

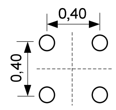
Conductor Type	**Grosbeak**
N° of Conductor	4
Distance (m)	
Conductor Outer Diameter (m).	0.02514
Conductor Inner Diameter (m).	0.00927
Resistance 60 Hz (Ω/km)	0.089898
Temperature (º)	75
Relative Magnetic Permeability	1
Relative Permittivity	1
Sag (m)	13.43

Table 4.3 Data of Ground-Wire

Cable Type	**EHS 3/8''**
Diameter of the conductor (m).	0.009144
Resistance a 60 Hz (Ω/km)	4.188
Temperature (º)	45
Relative Magnetic Permeability	70
Relative Permittivity	1
Sag (m)	6.4

- **Breaker and Fault:**

To model the fault and breaker we used "Timed Breaker Logic" and "Timed Fault Logic" (Fig. 4.5):

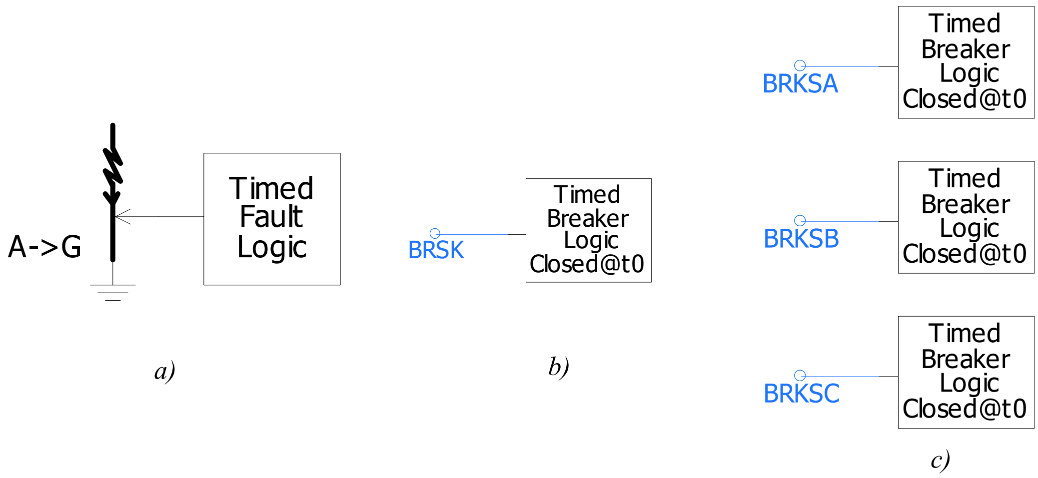


Fig. 4.5, Fault and breaker: a) fault with resistance 20 ohm, b) breaker for SPAR, c) breaker for three phase auto reclosing

To simulate fault in transmission line, we use "Timed Fault Logic". The time of applying fault is 100 ms, and duration of fault is 200 ms, and fault resistance is 20 ohm. Dead time of the breaker for this project is 500 ms. We use three "Timed Breaker Logic" at both sides of transmission line to simulate breaker for SPAR method and one "Timed Breaker Logic" at both side of transmission line for 3PAR method. For SPAR, at first, all phases will be closed, 50 ms after occurring fault in transmission line, the phase A of breaker at sending side of transmission line (first breaker) will be opened and others phases will be closed, time of second breaker operation is 650 ms. For three phase auto-reclosing, 50 ms after occurring fault, all phases of first breaker will be opened and time of second breaker is 650 ms.

A predefined amount of variations in the model are listed and changed. The variations being changed in the different cases are:

- Shunt Compensation (90% and 70%);
- Fault location;
- Line Length (350 km and 150 km);
- Fault - single line to ground.

5. RESULTS

In this chapter, we present and analyze results for different condition. We will analyze system for line 350 km at first and for two compensation degree and different fault location by using 2 methods to clear fault, single-phase auto reclosing and three-phase auto reclosing. A short line with 150 km is also analyzed. At the end of this chapter, we present and compare overvoltage for all conditions and both methods.

5.1 Case A: Line 350 km, Compensation 70%, and fault in Sending end:

For this case we simulated system when shunt compensation reactors with 70% compensation level are installed at both line ends, when fault occur in sending end. A neutral reactor was designed to minimize capacitive coupling, which will reduce secondary arc current.

For this case, highest overvoltage was for 3PAR at receiving side and 1.54 (p.u).

- Figure of waveform for case A:

Fig. 5.1 and 5.2, show the waveforms of the voltage of bus bar 2 (sending side), using SPAR and 3PAR:

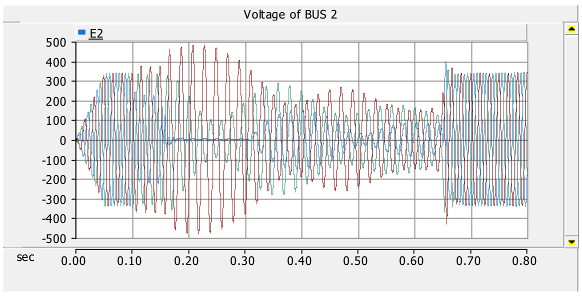


Fig. 5.1 The voltage at sending side, using three-phase reclosing for case A.

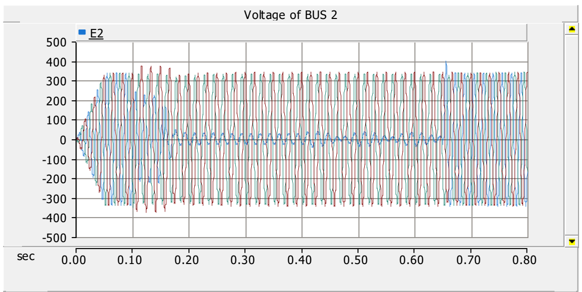


Fig. 5.2 The voltage at sending side, using SPAR for case A.

Fig. 5.3 and 5.4, show the waveforms of the voltage of bus bar 4 (receiving side), using SPAR and 3PAR:

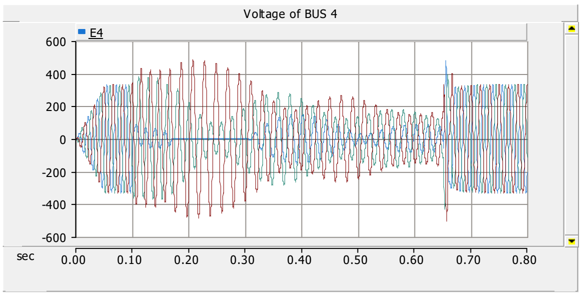


Fig. 5.3 The voltage at receiving side, using three-phase reclosing for case A.

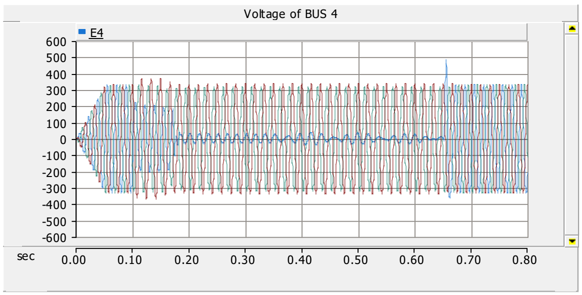


Fig. 5.4 The voltage at receiving side, using SPAR for case A.

We can see the difference between overvoltage due the SPAR and 3PAR and it is higher for the later. System will go back to normal operation earlier for SPAR. Also it is possible to observe the high overvoltage after line tripping in three-phase switching, whilst very small disturbance is observed in SPAR. During SPAR the healthy phases´ voltages will be unbalanced, but that will not have serious impact on the power system.

Fig. 5.5 and 5.6, show the waveforms of current at sending side, using SPAR and 3PAR for case A:

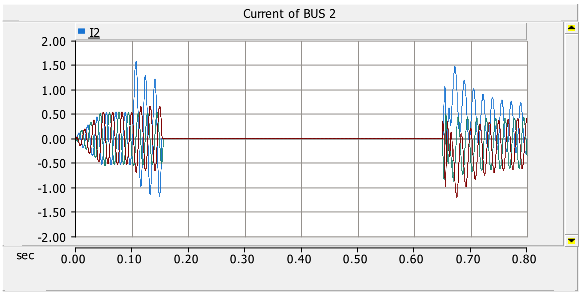


Fig. 5.5 The current at sending side, using three-phase reclosing for case A.

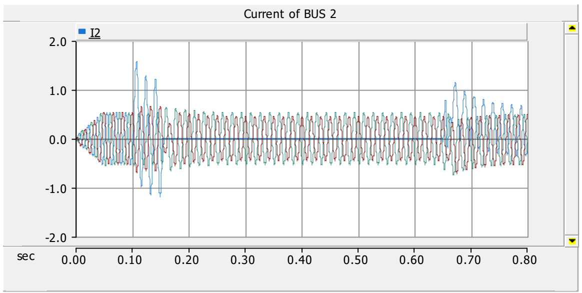


Fig. 5.6 The current at sending side, using SPAR for case A.

Fig. 5.7 and 5.8, show the waveforms of current at receiving side, using SPAR and 3PAR:

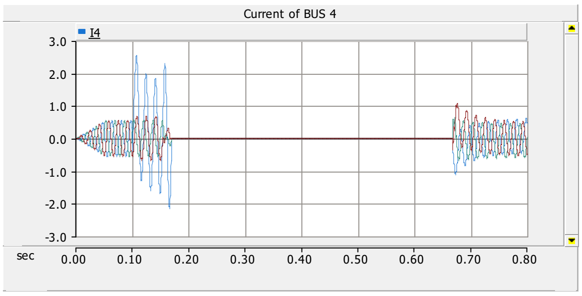


Fig. 5.7 The current at receiving side, using three-phase reclosing for case A.

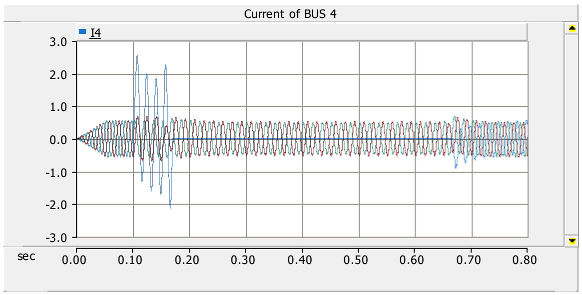


Fig. 5.8 The current at receiving side using SPAR for case A.

As figures show, there is no current flow during 3PAR, however current flows in phase B and C. After reclosing the overcurrent is higher in 3PAR than in SPAR, as well as the transient period is much small in SPAR, and system go back to normal operation earlier by using SPAR.

Fig. 5.9 and 5.10, show the waveforms of the neutral reactor voltage on compensation at sending side, using SPAR and 3PAR:

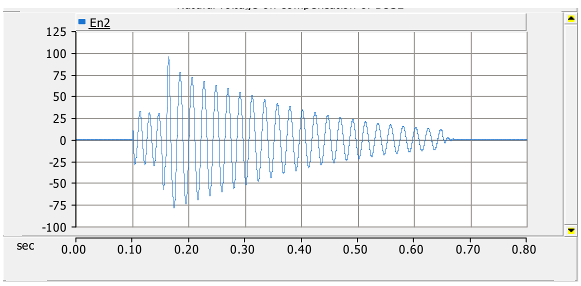


Fig. 5.9 The neutral reactor voltage on compensation at sending side, using three-phase auto-reclosing for case A.

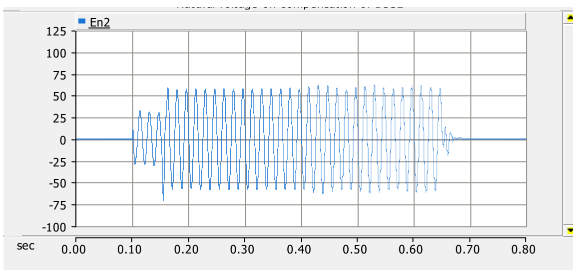


Fig. 5.10 The neutral reactor voltage on compensation at sending side, using SPAR for case A.

After 3PAR the voltage reaches very high values, considering that a 72 kV surge arrestor that has not been modeled would protect the neutral reactor. The reactor energy would reduce slowly and that would result in decreasing voltage until line is reclosed. For SPAR there is a 75 kV spike and after that the neutral reactor voltage magnitude stays almost constant around 60 kV. A small oscillation can be observed due to healthy phases´ unbalanced condition. After reclosing a small transient with short duration can be observed.

Fig. 5.11 and 5.12, show the waveforms of the neutral reactor voltage on compensation at receiving side, using SPAR and 3PAR. As the first CB to open was located at sending end the waveforms are different from the sending end ones.

For 3PAR as soon as the fault is applied a high overvoltage appears and starts to decrease continuously. This overvoltage is high and surge arrestor would operate if modeled. For SPAR the overvoltage reaches similar values and waveform until phase tripping, when its amplitude stayed almost constant and in the same range as the sending reactor one.

The energy absorbed by neutral reactor during SPAR will be larger than with 3PAR and that should be taken into account in project specification.

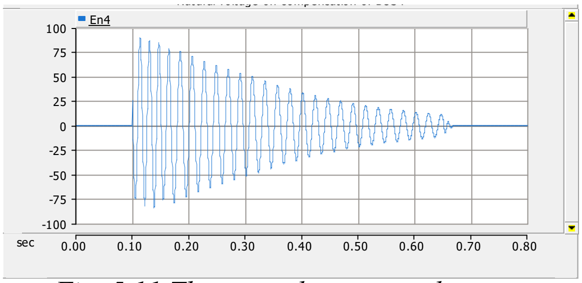


Fig. 5.11 The neutral reactor voltage on compensation at receiving side, using three-phase auto-reclosing for case A.

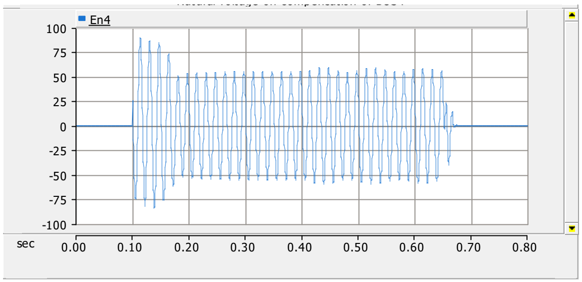


Fig. 5.12 The neutral reactor voltage on compensation at receiving side, using SPAR for case A.

Fig. 5.13 and 5.14, show the waveforms of power, using SPAR and 3PAR:

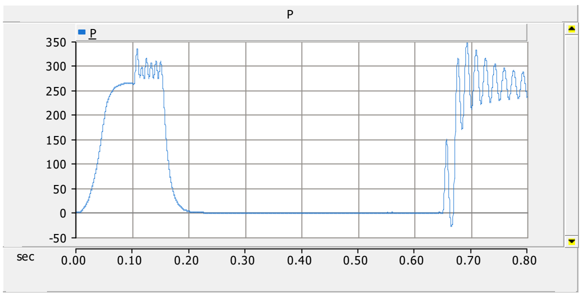


Fig. 5.13 Power, using three-phase auto-reclosing for case A.

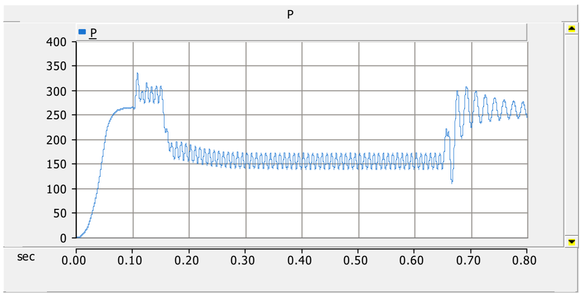


Fig. 5.14 Power, using SPAR for case A.

Fig. 5.15 and 5.16, show the waveforms of reactive power, using SPAR and 3PAR:

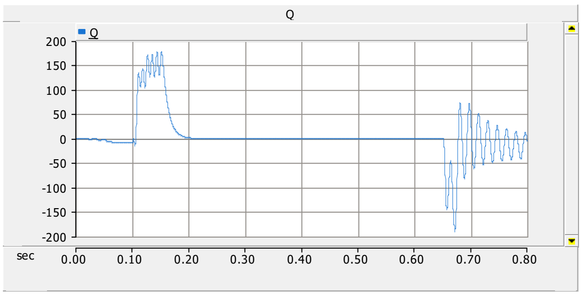


Fig. 5.15 Reactive Power, using three-phase auto-reclosing for case A.

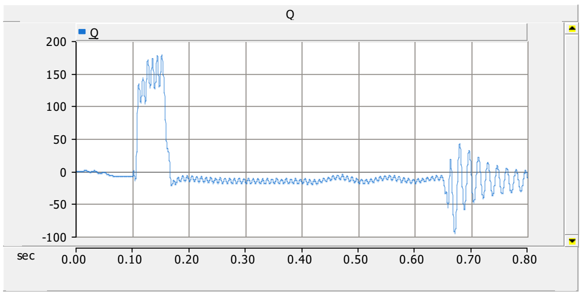


Fig. 5.16 Reactive Power, using SPAR for case A.

In single-phase reclosing, electrical power can be transferred by healthy phases while the faulted phase is open, but it is zero in the case of 3PAR.

5.2 Case B: Line 350km, Compensation 70%, and fault in receiving end:

Shunt compensation reactors, with 70% compensation level are installed at both line ends, when fault occur in receiving end. A neutral reactor can be designed to minimize capacitive coupling, which will reduce secondary arc current. For this case, highest overvoltage will be for 3PAR at receiving side and 1.54 (p.u).

For the tested system no important difference was observed when the fault location was varied (sending and receiving terminal). This is due to terminals network strength that in this case were similar.

- Figure of waveform for case B:

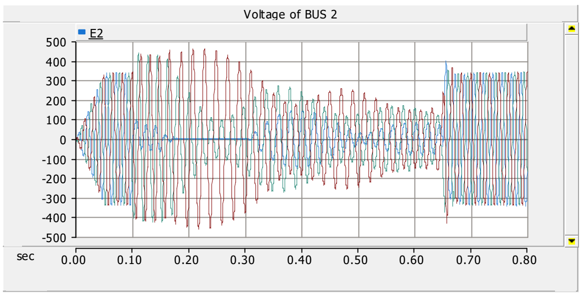


Fig. 5.17 The voltage at sending side, using 3PAR for case B.

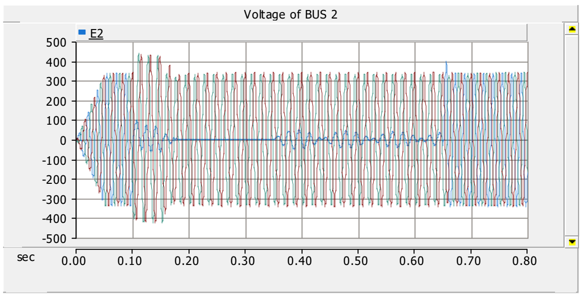


Fig. 5.18 The voltage at sending side, using SPAR for case B.

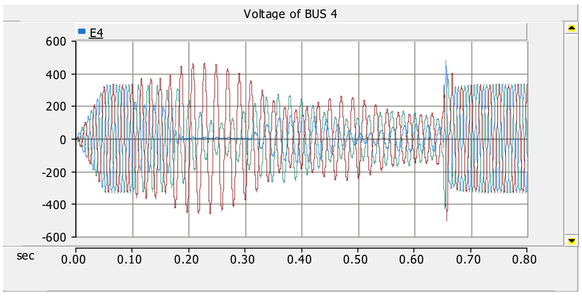


Fig. 5.19 The voltage at receiving side, using 3PAR for case B.

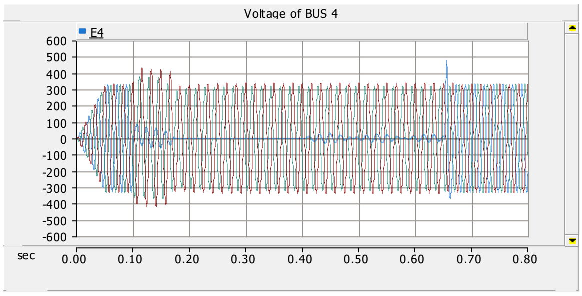


Fig. 5.20 The voltage at receiving side, using SPAR for case B.

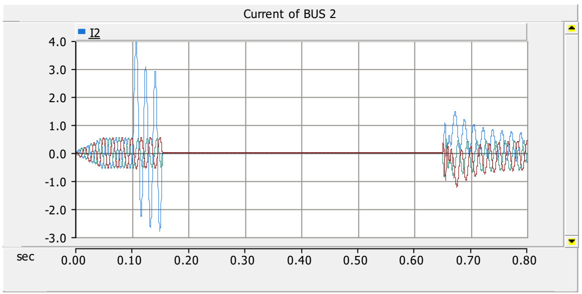


Fig5.21 The current at sending side, using 3PAR for case B.

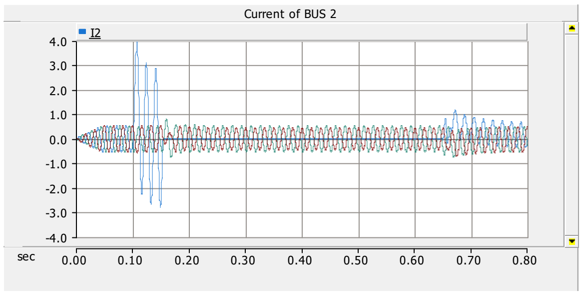


Fig. 5.22 The current at sending side, using SPAR for case B.

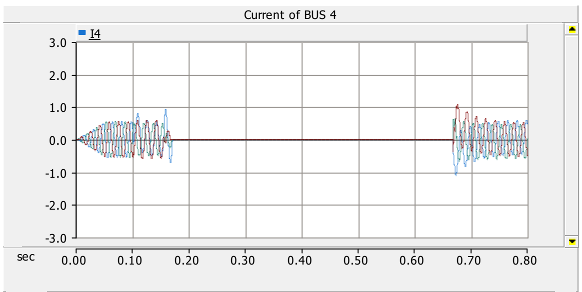


Fig. 5.23 The current at receiving side, using 3PAR for case B.

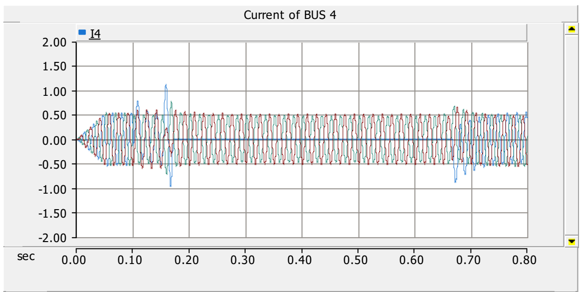


Fig. 5.24 The current at receiving side using SPAR for case B.

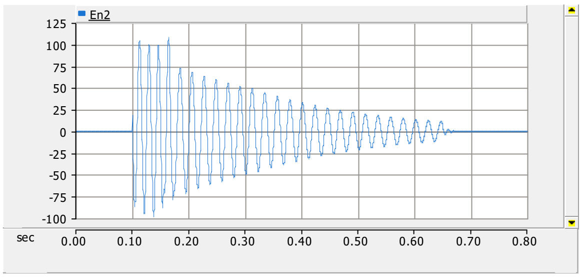


Fig. 5.25 The neutral reactor voltage on compensation at sending side, using 3PAR for case B.

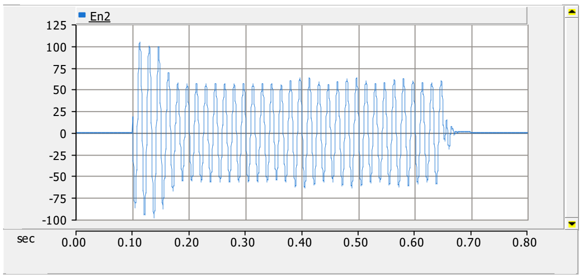


Fig. 5.26 The neutral reactor voltage on compensation at sending side, using SPAR for case B.

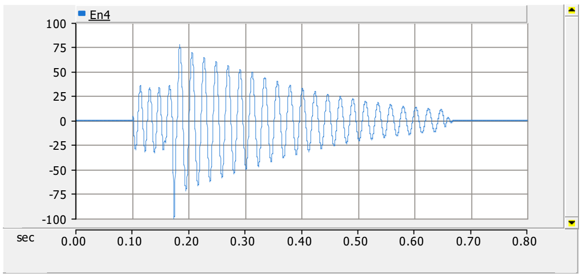


Fig. 5.27 The neutral reactor voltage on compensation at receiving side, using 3PAR for case B.

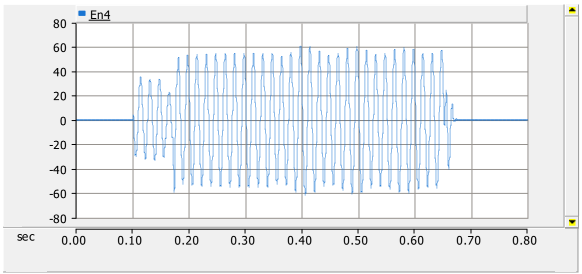


Fig. 5.28 The neutral reactor voltage on compensation at receiving side, using SPAR for case B.

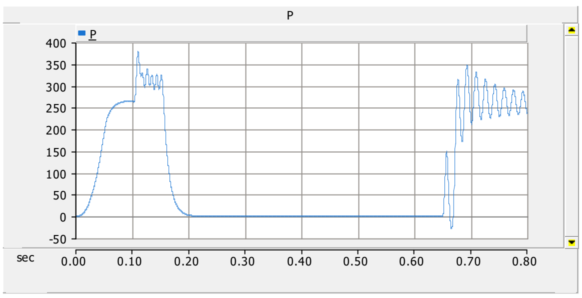


Fig. 5.29 Power, using 3PAR for case B.

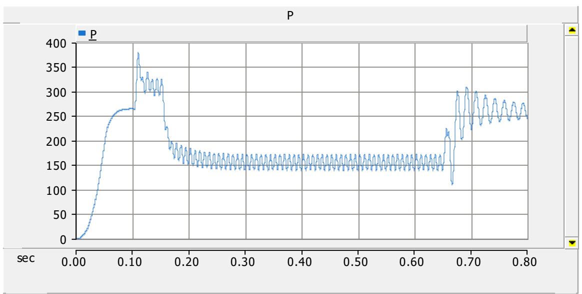


Fig. 5.30 Power, using SPAR for case B.

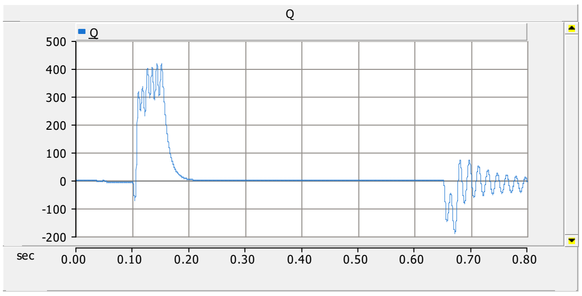


Fig. 5.31 Reactive Power, using 3PAR for case B.

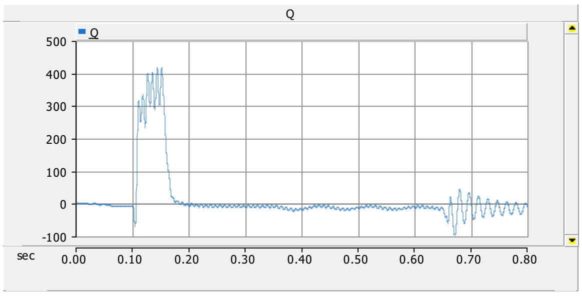


Fig. 5.32 Reactive Power, using SPAR for case B.

5.3 Case C: Line 350km, Compensation 90%, and fault in Sending end:

In this case a long line highly compensated is considered, specifically with 90 % compensation level. The neutral reactor was designed to minimize capacitive coupling, which will reduce secondary arc current. Fault is formerly positioned at sending end. For this case, highest overvoltage will be for 3PAR during reclosing at receiving side and 1.57 p.u.

It is important to observe the three distinct stages, specifically the fault occurrence, the tripping and reclosing. Before tripping process both methods present the same disturbance, as expected. However during tripping period 3PAR will produce overvoltages at healthy phases, due to a beat generated by interaction of line shunt admittance and shunt reactor. The overvoltage at one of the healthy phases reached very high value. This did not happen for SPAR, as the healthy phases are connected to the system, transmitting power. The healthy phases´ voltage will be unbalanced, but with no important overvoltages.

The overvoltages at reclosing will be more severe for 3PAR than for SPAR. For this case the highest overvoltage will be for 3PAR, at receiving side, 1.57 p.u, while the highest overvoltage for SPAR is 1.33 p.u. The 3PAR overvoltages may be very high depending on making instant.

For the tested system no important difference was observed when the fault location was varied (sending and receiving terminal). This is due to terminals network strength that in this case were similar. Similar results were also observed for different compensation level at 3PAR, but some difference was observed for SPAR, the lower the compensation the highest the overvoltage at receiving end.

It is very important to monitor the voltage at shunt reactor neutral for both methods. Waveforms are different for 3PAR and SPAR. The former shows an oscillatory decrease, whilst at SPAR a constant amplitude sinusoidal waveform is presented. The highest value is experienced for 3PAR and it is important to verify if the neutral surge arrester will be adequate. In the present simulations no surge arresters were represented to properly analyze the waveforms. The highest overvoltages are measured at neutral reactor near fault location for both methods.

- Figure of waveform for case C:

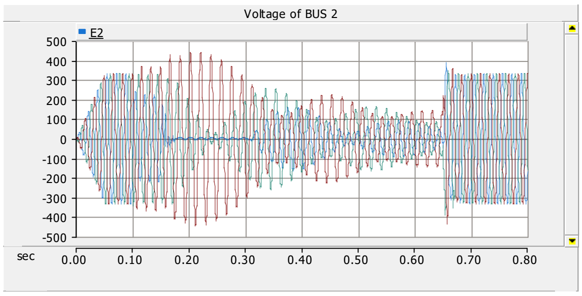


Fig. 5.33 The voltage at sending side, using 3PAR for case C.

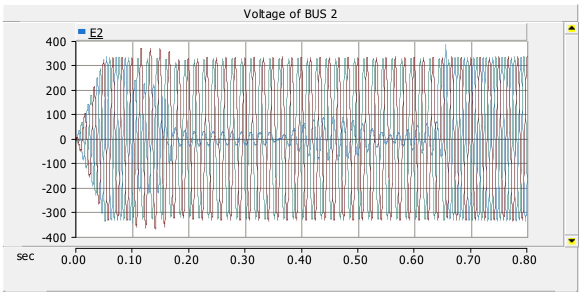


Fig. 5.34 The voltage at sending side, using SPAR for case C.

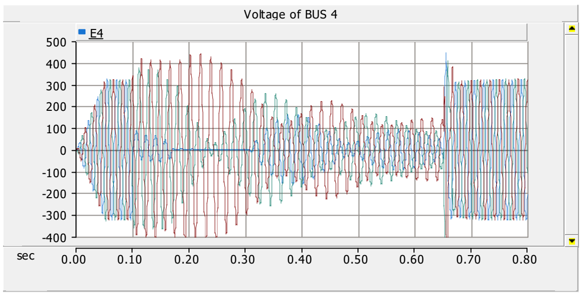


Fig. 5.35 The voltage at receiving side, using 3PAR for case C.

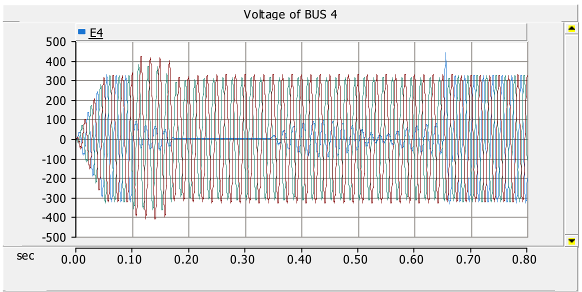


Fig. 5.36 The voltage at receiving side, using SPAR for case C.

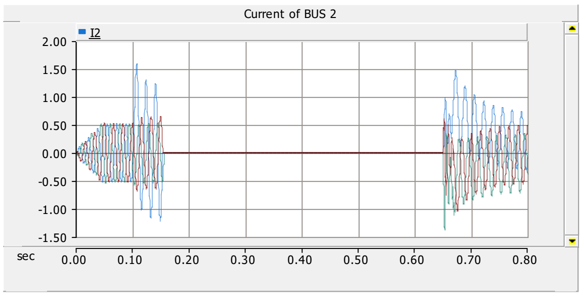


Fig. 5.37 The current at sending side, using 3PAR for case C.

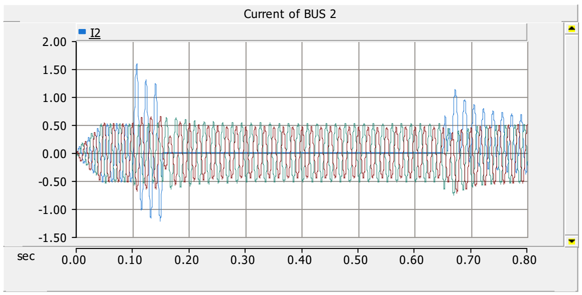


Fig. 5.38 The current at sending side, using SPAR for case C.

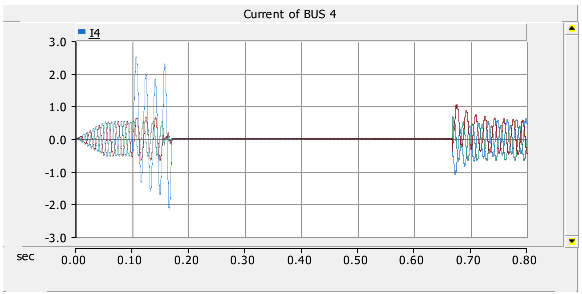


Fig. 5.39 The current at receiving side, using 3PAR for case C.

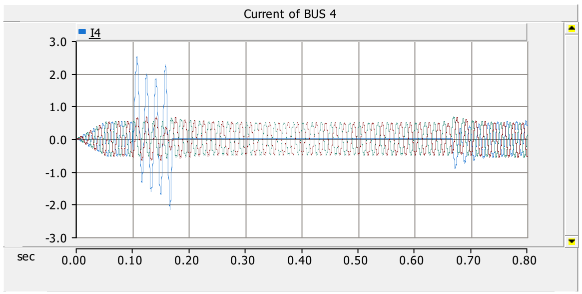


Fig. 5.40 The current at receiving side using SPAR for case C.

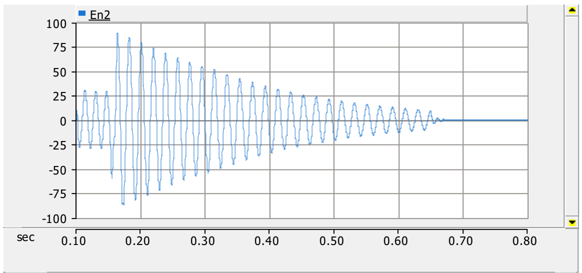


Fig. 5.41 The neutral reactor voltage on compensation at sending side, using 3PAR for case C.

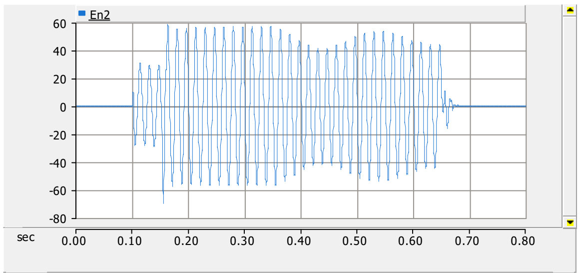


Fig. 5.42 The neutral reactor voltage on compensation at sending side, using SPAR for case C.

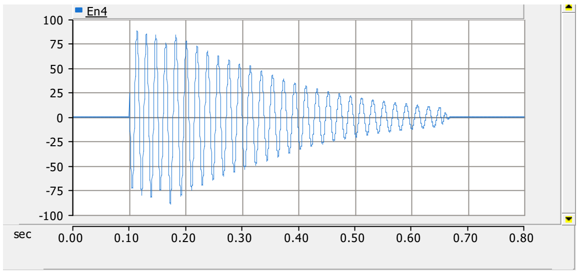


Fig. 5.43 The neutral reactor voltage on compensation at receiving side, using 3PAR for case C.

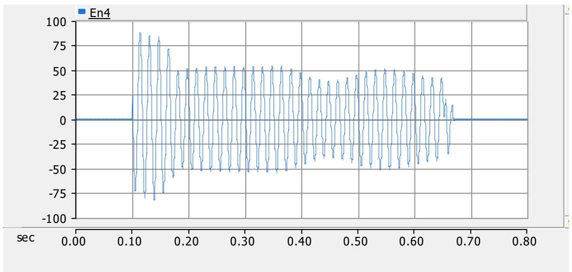


Fig. 5.44 The neutral reactor voltage on compensation at receiving side, using SPAR for case C.

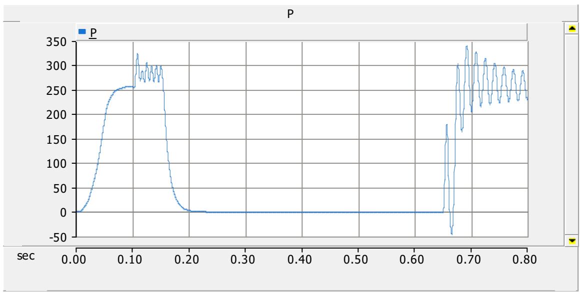


Fig. 5.45 Power, using 3PAR for case C.

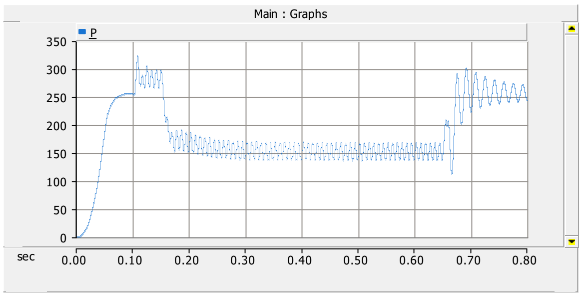


Fig. 5.46 Power, using SPAR for case C.

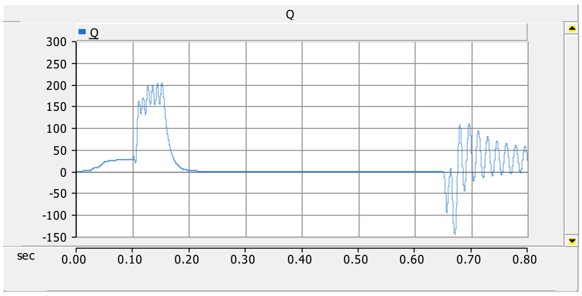


Fig. 5.47 Reactive Power, using 3PAR for case C.

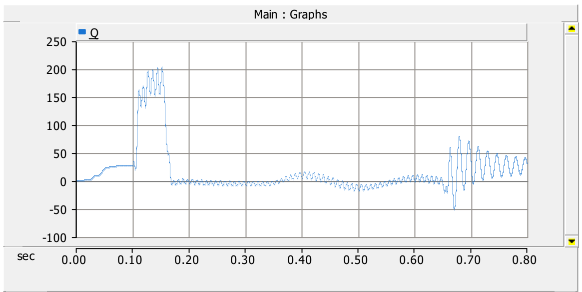


Fig. 5.48 Reactive Power, using SPAR for case C.

5.4 Case D: Line 350 km, Compensation 90%, and fault in receiving end:

In this case a long line highly compensated is considered, specifically with 90 % compensation level. Fault is positioned at receiving end. Again, highest overvoltage will be for 3PAR during reclosing at receiving side. For the tested system no important difference was observed when the fault location was varied (sending and receiving terminal). This is due to terminals network strength that in this case were similar. Similar results were also observed for different compensation level at 3PAR, but some difference was observed for SPAR, the lower the compensation the highest the overvoltage at receiving end.

- Figure of waveform for case D:

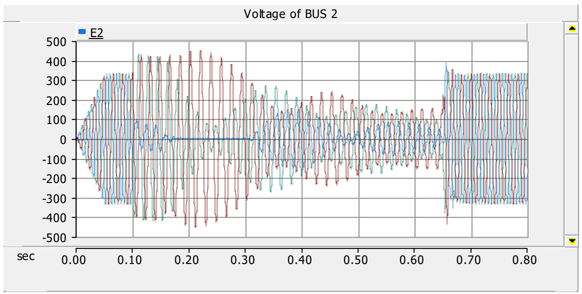


Fig. 5.49 The voltage at sending side, using 3PAR for case D.

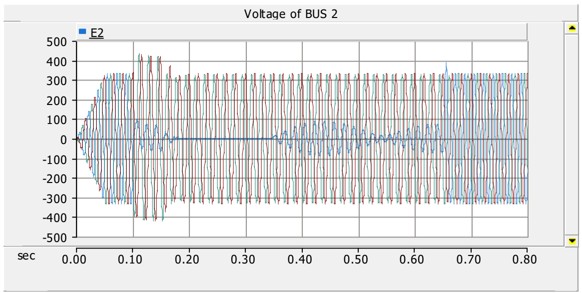


Fig. 5.50 The voltage at sending side, using SPAR for case D.

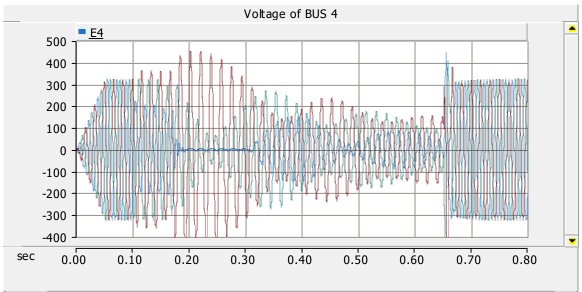


Fig. 5.51 The voltage at receiving side, using 3PAR for case D.

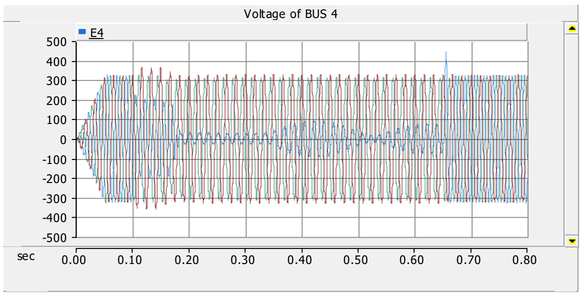


Fig. 5.52 The voltage at receiving side, using SPAR for case D.

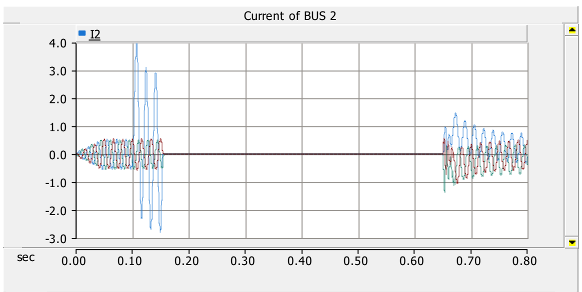


Fig. 5.53 The current at sending side, using 3PAR for case D.

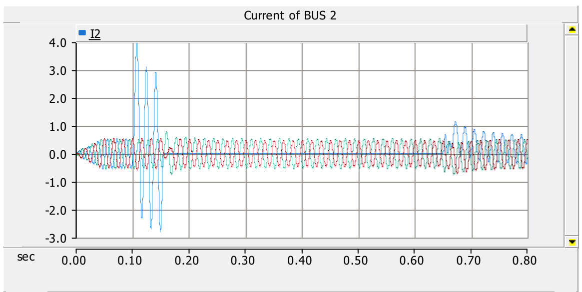


Fig. 5.54 The current at sending side, using SPAR for case D.

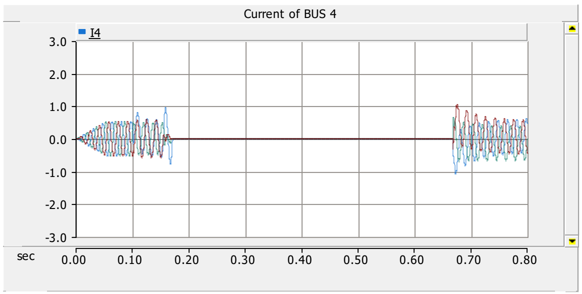


Fig. 5.55 The current at receiving side, using 3PAR for case D.

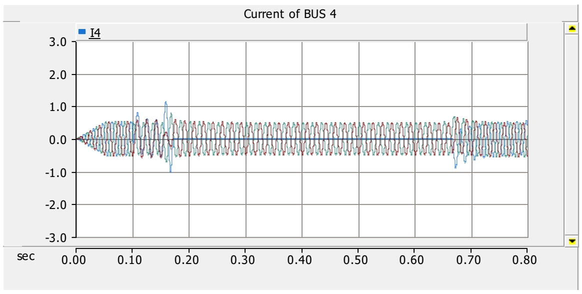


Fig. 5.56 The current at receiving side using SPAR for case D.

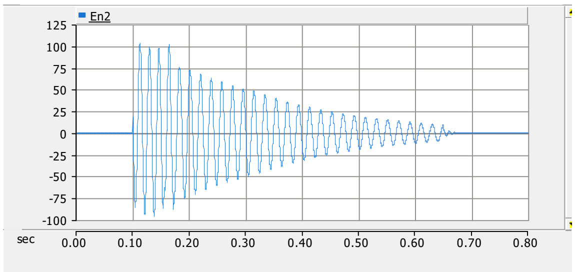


Fig. 5.57 The neutral reactor voltage on compensation at sending side, using 3PAR for case D.

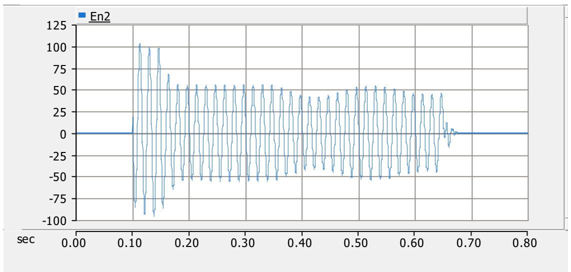


Fig. 5.58 The neutral reactor voltage on compensation at sending side, using SPAR for case D.

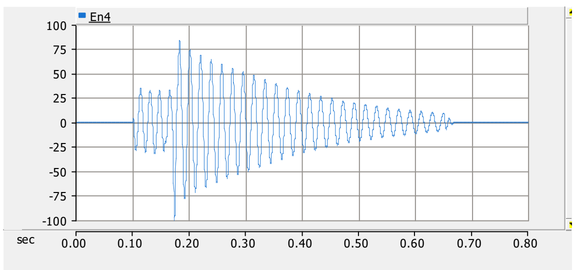


Fig. 5.59 The neutral reactor voltage on compensation at receiving side, using 3PAR for case D.

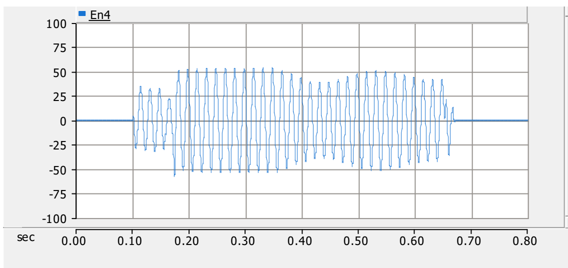


Fig. 5.60 The neutral reactor voltage on compensation at receiving side, using SPAR for case D.

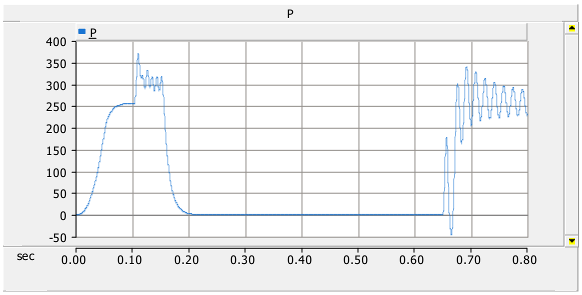


Fig. 5.61 Power, using 3PAR for case D.

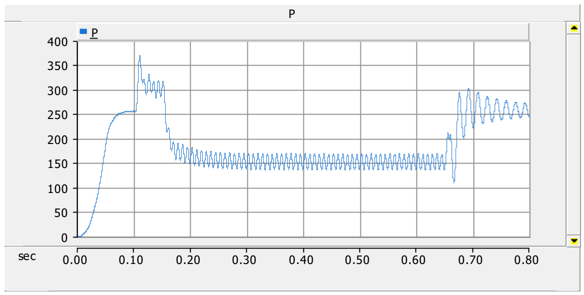


Fig. 5.62 Power, using SPAR for case D.

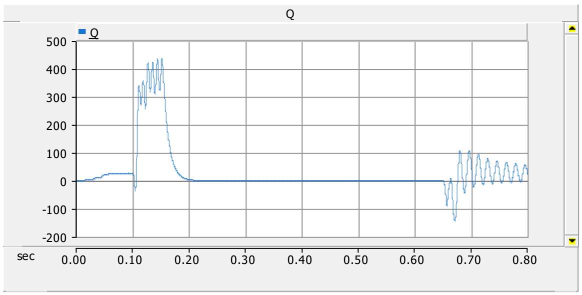


Fig. 5.63 Reactive Power, using 3PAR for case D.

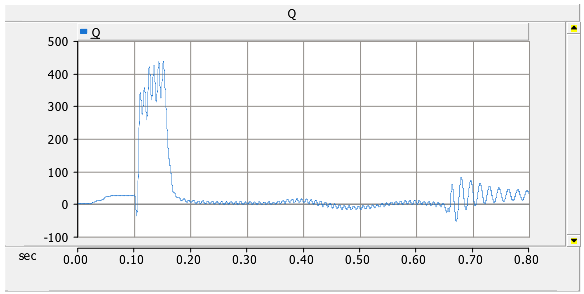


Fig. 5.64 Reactive Power, using SPAR for case D.

5.5 Case E: Line 150km and fault in sending end:

We analyze system for line 150 km, and for different fault location, fault at sending end, and fault at receiving end. For this case (Case E), highest overvoltage will be for 3PAR (1.52 p.u). The highest overvoltage for SPAR will be 1.33 p.u).

For this case the highest overvoltage will be for 3PAR, at receiving side, 1.53 p.u, while the highest overvoltage for SPAR is 1.33 p.u. No overvoltages are experienced during tripping at 3PAR, as there is no beat as at compensated line. The healthy phases´ voltages continuously decrease whilst the faulty phase voltage is very small. Regarding SPAR, no important difference is observed among compensated or short line. Reclosing overvoltages are higher for 3PAR than for SPAR. The 3PAR overvoltages may be very high depending on making instant. For the tested system no important difference was observed when the fault location was varied (sending and receiving terminal). This is due to terminals network strength that in this case were similar.

- Figure of waveform for case E**:**

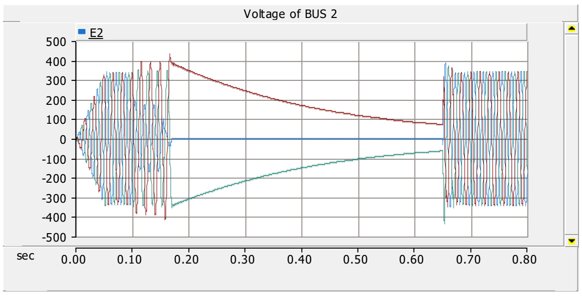


Fig. 5.65 The voltage at sending side, using 3PAR for case E.

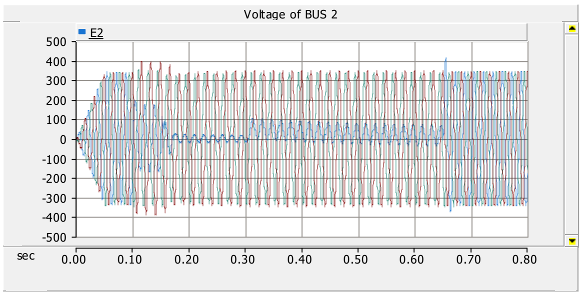


Fig. 5.66 The voltage at sending side, using SPAR for case E.

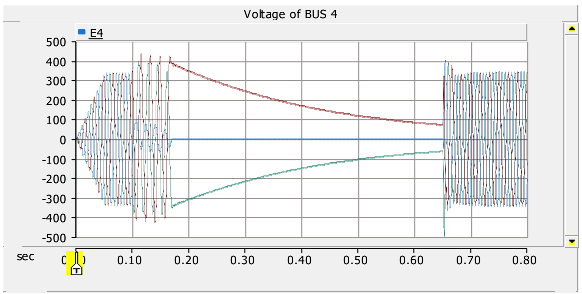


Fig. 5.67 The voltage at receiving side, using 3PAR for case E.

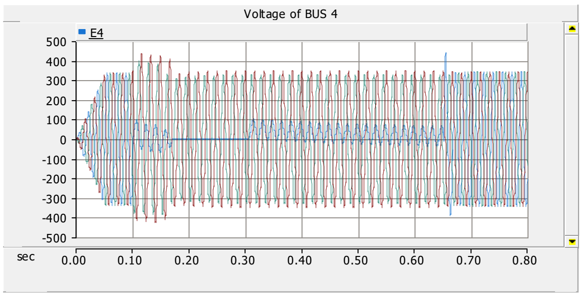


Fig. 5.68 The voltage at receiving side, using SPAR for case E.

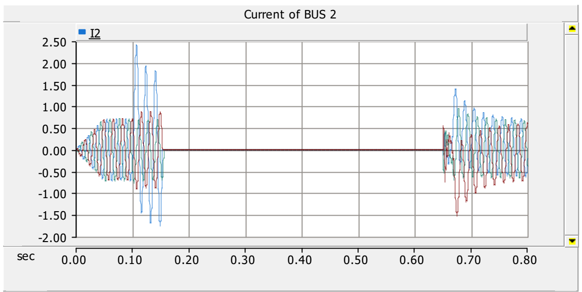


Fig. 5.69 The current at sending side, using 3PAR for case E.

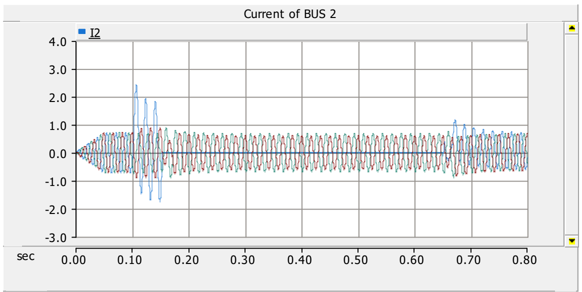


Fig. 5.70 The current at sending side, using SPAR for case E.

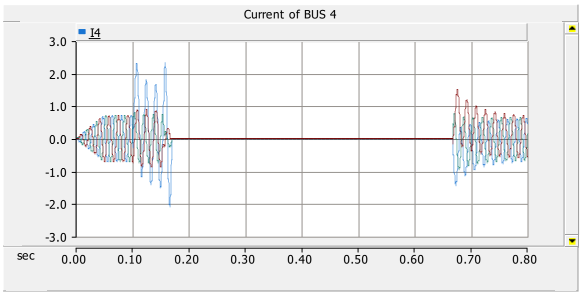


Fig. 5.71 The current at receiving side, using 3PAR for case E.

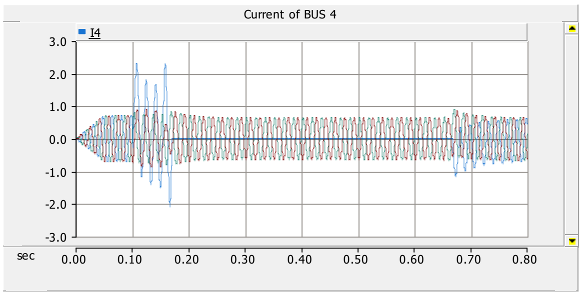


Fig. 5.72 The current at receiving side using SPAR for case E.

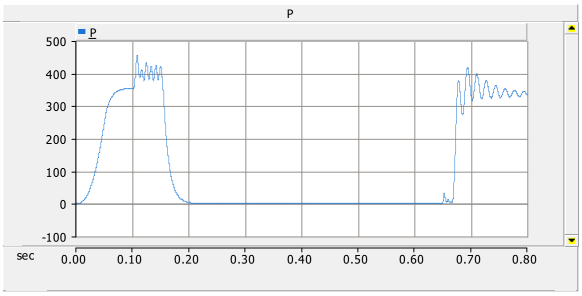


Fig. 5.73 Power, using 3PAR for case E.

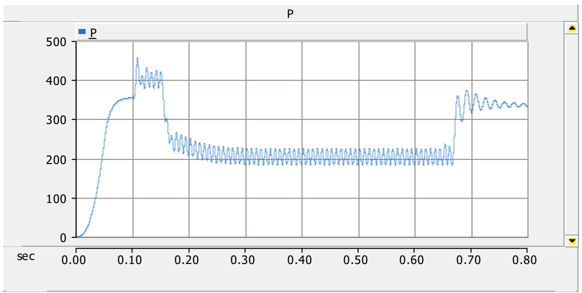


Fig. 5.74 Power, using SPAR for case E.

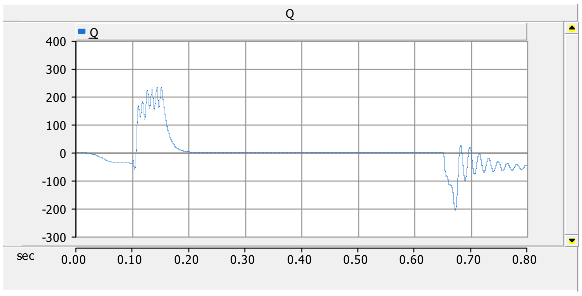


Fig. 5.75 Reactive Power, using 3PAR for case E.

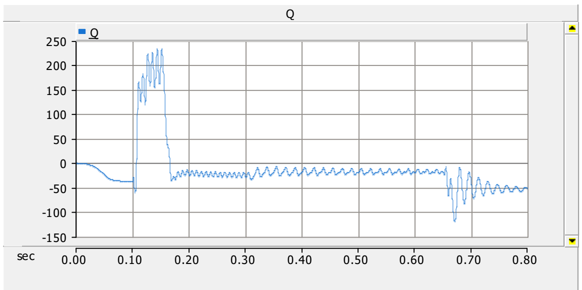


Fig. 5.76 Reactive Power, using SPAR for case E.

5.6 Case F: Line 150 km and fault in receiving end:

The fault location did not provoke important difference when compared to previous case. Again 3PAR reclosing overvoltages were more severe than the one with SPAR. During SPAR the system was connected and power was transferred.

- Figure of waveform for case F:

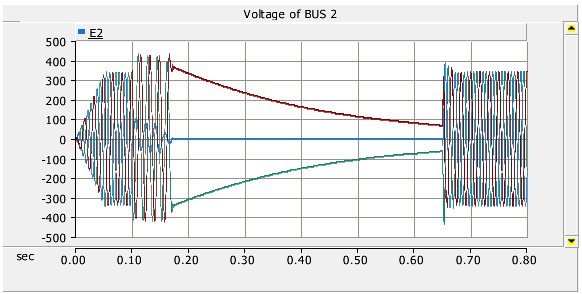


Fig. 5.77 The voltage at sending side, using three-phase reclosing for case F.

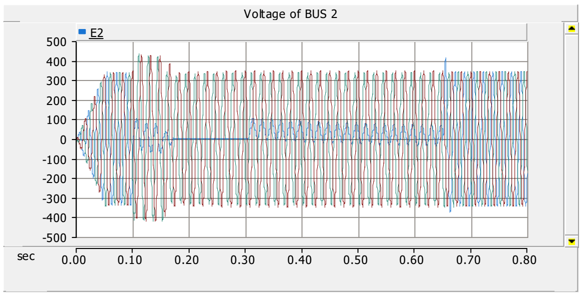


Fig. 5.78 The voltage at sending side, using SPAR for case F.

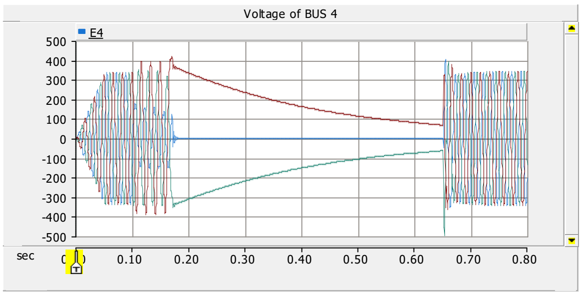


Fig. 5.79 The voltage at receiving side, using three-phase reclosing for case F.

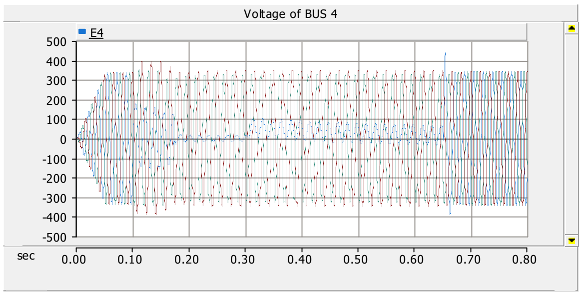


Fig. 5.80 The voltage at receiving side, using SPAR for case F.

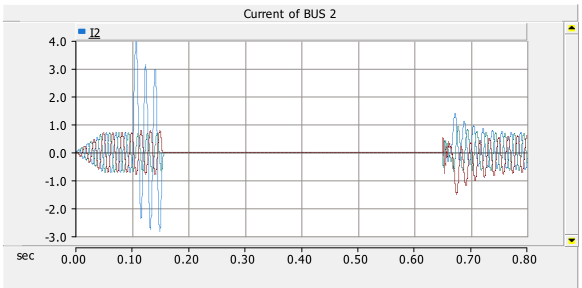


Fig. 5.81 The current at sending side, using three-phase reclosing for case F.

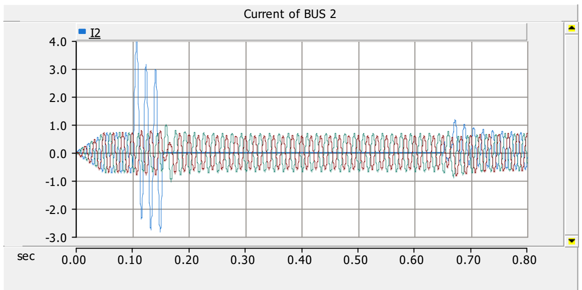


Fig. 5.82 The current at sending side, using SPAR for case F.

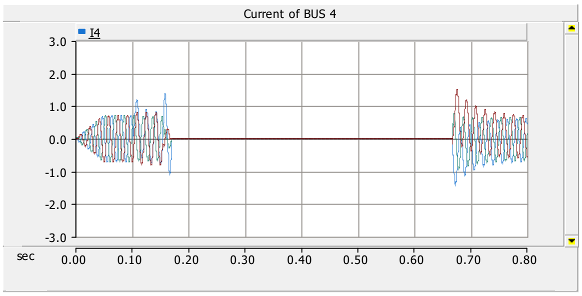


Fig. 5.83 The current at receiving side, using three-phase reclosing for case F.

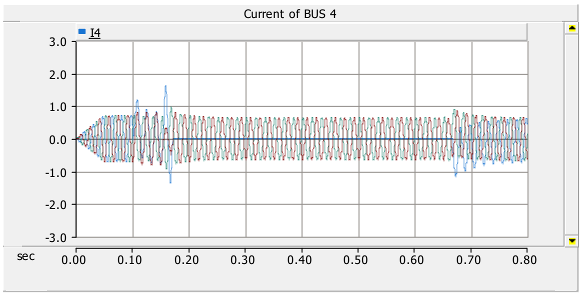


Fig. 5.84 The current at receiving side using SPAR for case F.

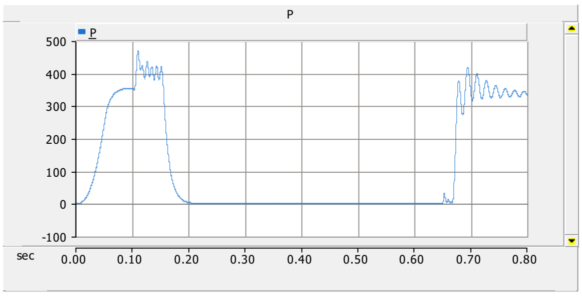


Fig. 5.85 Power, using three-phase auto-reclosing for case F.

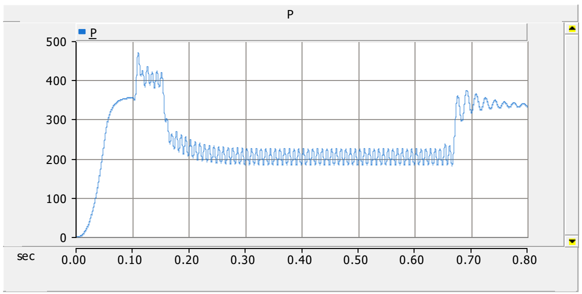


Fig. 5.86 Power, using SPAR for case F.

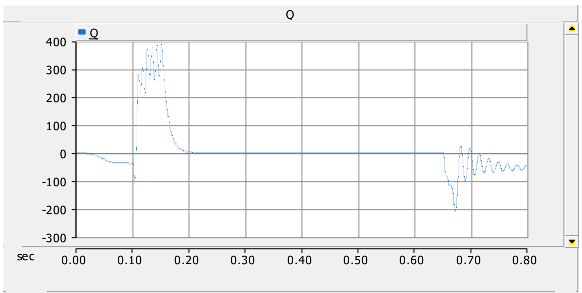


Fig. 5.87 Reactive Power, using three-phase auto-reclosing for case F.

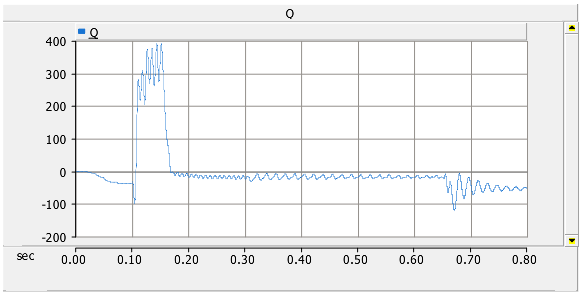


Fig. 5.88 Reactive Power, using SPAR for case F.

We present the overvoltage for different cases in table 5.1 and 5.2, the highest overvoltage is for 3PAR, with compensation degree 90% and fault at sending end (1.57 p.u). The overvoltage for SPAR is lower than 3PAR for all cases. For line 150 km, the worst case is for 3PAR and fault at receiving end where overvoltage is 1.53 p.u.

Table 5.1 Overvoltage for line 350 km

		Overvoltage at Sending Side (p.u.)		**Overvoltage at Receiving Side (p.u.)**	
Compensation	**Fault Location**	**PAR**	**3PAR**	**PAR**	**3PAR**
70 %	Sending end	***.21***	***1.30***	***.45***	***1.54***
	Receiving end	***.22***	***1.31***	***.46***	***1.54***
90 %	Sending end	***.17***	***1.33***	***.34***	***1.57***
	Receiving end	***.18***	***1.31***	***.35***	***1.55***

Table 5.2 Overvoltage for line 150 km

	Overvoltage at sending side (p.u)		***Overvoltage at receiving side (p.u)***	
Fault Location	***SPAR***	***3PAR***	***SPAR***	***3PAR***
Sending end	***1.26***	***1.33***	***1.33***	***1.52***
Receiving end	***1.26***	***1.33***	***1.33***	***1.53***

6. CONCLUSIONS

This project analyzes the transmission line entities resulting from elimination of a single-phase fault by using the SPAR and 3PAR on the 400 kV transmission line. The project analyzes the influence of different system parameters like compensation level, line length and fault location together with the mitigation method.

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. 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 transferred through the non-faulted phases while the faulted phase is open. During fault clearance in a single-phase reclosing, due to capacitive and also inductive coupling of the phases, there is an induced voltage in the de-energized line. Although distorted, the voltage is maintained in the healthy phases throughout the fault elimination process in SPAR. The system is back to normal operation much faster when SPAR is applied, what increases power system equipment lifetime.

For long lines the neutral reactor voltage shall be monitored and may experience high overvoltage for three-phase tripping and not for SPAR.

For long line, the recovery overvoltage is smaller for SPAR than for 3PAR, the same happening with the transient duration. Also it is possible to observe the high overvoltage after line tripping in 3PAR, whilst very small disturbance is observed in SPAR. During SPAR the healthy phases voltages will be unbalanced, but that will not have serious impact on the power system due to the small protection dead time. For 3PAR and for long line, as soon as the fault is applied a high overvoltage appears and starts to decrease continuously, this overvoltage is high. For SPAR the overvoltage reaches similar values and waveform until phase tripping, when its amplitude is reduced.

For short line and 3PAR, the voltage starts to decrease and drops very fast. The reclosing overvoltage can reach important values. For SPAR the open phase voltage is very low and reclosing overvoltage is much smaller than in 3PAR. For 3PAR, there is no current flow during 3PAR but two healthy phases are transferring power during SPAR method.

For both, short or long lines, reclosing overvoltage for 3PAR is higher than SPAR. The overvoltage for compensation 90% is higher than overvoltage for compensation 70%. For the analyzed system there was no important difference considering the fault location (sending or receiving terminal).

SPAR should be applied for long and short lines as the disturbances are much smaller and there is no power flow interruption. This will result in longer lifetime to equipment and higher reliability to power system.

Future Studies:

Several aspects should be studied for both fault elimination methods:

- Undesired trip;
- Reclosing onto fault;
- Short circuit level at terminal busbar;
- Representation of phase compensation as saturated element;
- Variation of system frequency to identify resonant conditions.

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