

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**SINGLE PHASE AUTORECLOSING IN 735 KV TRANSMISSION
SYSTEM**



M.Sc. THESIS

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Department of Electrical and Electronics Engineering

Electrical Engineering Program

MAY 2019

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To my parents,

FOREWORD

I sincerely thank to my supervisor, Prof. Dr. Ömer Usta, for guidance, helping and encouragement in carrying out this project work. Also, I wish to avail myself of this opportunity, express a sense of gratitude and love to my kind parents for their support, strength, help and for everything.

May 2019

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ABBREVIATIONS

SGL	: Single Line To Ground Fault
PLC	: Power Line Carrier
App	: Appendix
CB	: Circuit Breaker
GOV	: Governor
AVR	: Automatic Voltage Regulator
DG	: Distributed Generator
Mbps	: Megabits per second
WAN	: Wide Area Network



SYMBOLS

C : Capacitance

L : Inductance

t : Time

X_C : Capacitive reactance

X_L : Inductive reactance

G : Generator

H : Henry



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SINGLE PHASE AUTORECLOSING IN 735 KV TRANSMISSION SYSTEM

SUMMARY

In trendy tangled power systems, close to 80% of faults in HV transmission lines are essentially transient. The fast progression of the protection equipment is done due to the prerequisite of high speed fault clearing. Moreover, require for solid supply of loads has driven to advancement in single stage auto-reclosing equipment.

HighVoltage (HV) and Extra-High-Voltage (EHV) transmission lines face with genuine problems in fundamental transmission systems by happening the fault in these systems.

This enforce severe circumstances for protection and control systems, which must quickly clear the faults to preserve the system stability. It is beneficial to detect the fault location on a transmission system, as this is intensively advantageous during maintenance that may be necessary in the fault following. distance relays may set a flag as a indicator for the zone which fault is detected, but this kinds of fault location estimation is insufficient in subsistence. There are some procedures used for estimation of the fault location, which rely on the fault establishing a enduring cutoff on the line, which at that point can be demonstrated by controlling the inactivated transmission line to interjected traveling waves.

On HV and EHV transmission lines single-phase-to-ground faults are in the majority and being eliminated by automatic reclosure. In this case, the line is detached so let the arc to extinguish, and after the dead time the line can be reclosed to restore routine supply.

During occurrence of a single phase-to-ground fault on an empowered transmission line, the faulty phase is detacehd and after an applicable dead time automatically reclosed . All the settings of the equipment will reset if the fault clears. The sounded phases and faulty phase will be tripped if the fault is still on the line and the autorecloser willbe lokedout. For the multi-phase faults, all the phases is tripped and due to the scheme programing conditions the breakers and autoreclsoers can be loced out or autoreclosed.

The main intention of this thesis is about single phase auto reclosing in 735 KV EHV transmission system. The autorecloser has been integrated with distance protection and overvoltage relay by using SIEMENES 7SA522 relay to detect and distinguish fault occurrence.

First chapter addresses the advantages and disadvantages of autoreclosing and different requirements for system stability and load stability.it also describes about circuit breakers are needed in to use in transmission systems.

Second chapter involves history of reclosing and different methods of reclosing and IEEE committee guides for proper autoreclosing and operation considerations.

Third chapter refers to the various types of faults in transmission systems.

Moreover, the fundametal basis of the distance protection incluce fault impedance and span measuring, power swing characteristics ,busbar protection and methods of

settings calculation ,stepped zone of protection , Mho and Quadrilateral characteristics and pilot distance protection are mentioned in this chapter. In fourth chapter, a 735 KV transmission system is modeled in DIgSILENT Power Factory 15.1. First load flow calculation is simulated and system behavior during normal operation is assessed. Then distance protection system's performance is evaluated by short circuit analysis for various fault locations in the transmission line. Distance protection for single-phase and three phase faults detecting is implemented at each terminal of the both lines with two independent distance protections with same relays.a communication channel is established to the remote relay for the purpose of transmitting system data and signals and protection of the system is validated. The autoreclosing simulation is carried out in different fault location to verify the successful operation of the single phase autoreclosing in EHV transmission lines. As stated in results of the fourth chapter, high speed single phase auto reclosing is needed in EHV systems to back the system to the normal operation and keep the synchronism and serving the load continuously.



735 KV İLETİM SİSTEMİNDE TEK FAZLI OTOMATİK TEKRAR KAPAMA

ÖZET

Enterkonnekte modern güç sistemlerinde, yüksek gerilim iletim hatlarındaki arızaların yaklaşık % 80'i temelde geçicidir. Generatörlerin senkron çalışmasının kaybolmasına yol açabilecek (kararlılık problemi oluşabilecek) arızalar meydana geldiği durumlarda, acil durum manevraları ile elektrik enerji sisteminin bir bütün halinde işletilmesi sağlanamayabilir ve sistem yaygın büyük ölçekli bir kesinti yaşayabilir. Elektrik sisteminin çalışma bölgelerine kontrollü olarak ayrılmasının bir diğer yararı ise sistemde meydana gelecek arızalarda kısa devre akımlarının sistemde yer alan teçhizatın dayanım sınırlarının altında kalmasının sağlanması olarak verilebilir. Ayrıca kısa devre akımlarının azaltılması, sistemde meydana gelen arıza akımlarının sistem donanımı üzerinde yarattığı yaşlandırıcı etkilerinin de azaltılmasına yol açacaktır.

Koruma sistemi sayesinde arıza hızlı bir şekilde temizlenerek şebekenin geri kalan kısmının düzgün şekilde işletilmesine devam edilebilmektedir. Sürekli bir kısa devrenin şebekenin genel işletmesi ve özellikle kararlılığı üzerindeki etkilerini ortadan kaldırmak için hatalı eleman olabildiğince çabuk devre dışı edilmelidir. Bu sayede generatör, transformatör, kablo, hat gibi şebeke elemanlarının birinde kısa devre veya izolasyon hatası sonucunda oluşabilecek arıza akımlarının veya aşırı gerilimlerin yol açabileceği zararlar sınırlandırılmaktadır. Güç sistemlerini yukarıda bahsedilen olumsuz durumlara karşı röleler korur.

Koruma röleleri, işletme esnasında oluşabilecek arıza veya aşırı yüklenme durumunda büyük çapta hasarların oluşmasını önleyici rol üstlendiklerinden dolayı büyük önem taşımaktadır.

Koruma sisteminin görevi, işletme elemanları ile elektrik tesis ve şebekelerinde ortaya çıkan hataları ve bunların çeşitlerini ölçülen elektriksiz büyüklükler yardımıyla çabuk ve güvenilir bir şekilde tespit etmek ve gerektiğinde arızalı elemanı (generatör, trafo, hat vb.) devre dışı bırakarak enerjinin mümkün olduğunca sürekli olmasını sağlamaktır.

Admitans, reaktans ve dört kenarlı çeşitleri olsa da mesafe koruma röleleri, çoğunlukla, gerilim ve akım ölçü trafosundan aldıkları bilgileri kullanarak bir empedans değeri hesaplamakta ve böylece, bu degerin değişimine ve önceden ayarlanmış belli gecikme parametrelerine uygun bir koruma uygulaması gerçekleştirilmektedir. Bu yüzden empedans rölesi olarak da adlandırılırlar. Korunması istenen iletim hattının empedans degerinin genellikle %80-85'i ile 1. koruma bölgesi tanımlanmaktadır. Koruma süresince izlenen empedansdegerinin, ayarlanan bu degerin altına düşüp düşmediğine uygun bir koruma uygulaması gerçekleştirilir.

Koruma sistemi generatör, transformatör, kablo, hat gibi şebeke elemanlarının birinde kısa devre veya yalıtım hatası sonucunda oluşabilecek arıza akımlarının veya aşırı gerilimlerin yol açabileceği zararları sınırlandırmaktadır.

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Güç sistemlerinin kısa devre arızalarından zarar görmemesi adına yapılan çalışmalar uzun yıllardır süregelmektedir. Bu çalışmalarda genel öncelik kısa devre akımının sınırlandırılması ve generator çıkış geriliminin arıza öncesi değerine yükseltilmesidir. Çünkü yüksek kısa devre akımı güç sistemlerindeki yalıtım elemanlarına, koruma elemanlarına, sistem yüklerine zarar verebilmektedir. Diğer yandan ise düşen gerilim yerel ölçekli bir sorun olsa dahi uzun süre devam eden arıza durumunda global ölçekli bir sorun haline dönüşebilmektedir. Yüksek hızlı arıza giderme zorunluluğundan dolayı, koruma ekipmanlarının hızlı bir şekilde geliştirilmesine katkıda bulunmuştur. Ayrıca, güvenilir yük temini ihtiyacı, tek fazlı otomatik yeniden kapama ekipmanında gelişmeye neden olmuştur. Yüksek Gerilim (HV) ve Ekstra Yüksek Gerilim (EHV) iletim hatlarında meydana gelen arızalar, temel iletim ve dağıtım sistemlerinde ciddi sorunlara yol açmaktadır. Bu, sistemin kararlılığını korumak için arızaları hızlı bir şekilde izole etmesi gereken koruma ve kontrol sistemleri için zorlayıcı koşulları zorunlu kılar. Bir iletim sisteminde arıza yerini tespit etmek, arıza sırasında gerekli olabilecek bakım için avantajlıdır. mesafe röleleri, arızanın tespit edildiği bölge için bir işaret olarak işaretleyebilir, ancak bu tür arıza yeri tahminleri bakım çalışmalarında yardımcı olmak için yetersizdir. Arıza lokasyonunun tahmini tespiti için kullanılan teknikler vardır, ve bu teknikler hattın üzerinde arıza tarafından yaratılan kalıcı bir kesiklikliği kullanarak arızanın yerini tespit ediyorlar.

HV ve EHV iletim hatlarında arızaların çoğu tek fazdan toprağa olan arızalardır ve otomatik tekrar kapamayı kullanılarak giderildiler. Bu durumda, hat ayrılır, böylece arkın sönmeye izin verilir ve ölü zamandan sonra ki bu zaman ark yolunu uygun şekilde deiyonize etmek için gerekli olan zamandır, sistemin normal çalışmasına yardım etmek için hat tekrar kapatılabilir. Enerjiye sahip bir iletim hattında tek fazdan toprağa bir arıza meydana geldiğinde, arızalı faz tetiklenir ve uygun bir ölü zaman sonunda otomatik olarak tekrar kapatılır. Arıza giderildiğinde her şey sıfırlanır. Faz tekrar kapatıldığında hala sistemde arıza varsa, üç fazın tümü tetiklenir ve daha fazla tekrar kapama meydana gelmez. Enerji ileten bir iletim hattında herhangi bir türde çok fazlı bir arıza görüldüğünde, üç fazın hepsi tetiklenir ve fazlar devre dışı olur. Bu halde, programın nasıl programlandığına bağlı olarak, kesiciler kilitlenebilir veya uygun bir ölü zamandan sonra hatta yeniden kapatılabilir.

Bu tezin amacı, 735 KV EHV iletim sisteminde tek fazlı otomatik tekrar kapama ile ilgilidir. Otomatik tekrar kapama, arıza oluşumunu tespit etmek ve ayırt etmek için SIEMENS 7SA522 rölesini kullanılarak mesafe koruma ve aşırı gerilim röleleri ile entegre edilmiştir.

Tekrar kapama uygulamasının amacı sistem kararlılığı ile senkronizasyonunu muhafaza etmektir. Bu nedenle ilk olarak sistem kararlılığının kaybolmaksızın tahammül edilebilen sistem bozunum zamanı tespit edilmelidir. Bunun için söz konusu güç sistem konfigürasyonu ve arıza şartlarıyla ilgili olarak kararlılık analizinin yapılması gerekir.

Birinci bölüm otomatik tekrar kapamanın avantajlarını ve dezavantajlarını ve sistem kararlılığı ve yük kararlılığı için farklı gereksinimleri anlatmaktadır. ayrıca iletim sistemlerinde kullanılmak için ihtiyaç duyulan devre kesiciler hakkında da bilgi verir. İkinci bölüm, yeniden kapama tarihçesini ve farklı yeniden kapama yöntemlerini ve IEEE komitesinin uygun otomatik kapama ve çalıştırma hususları için içermektedir.

Üçüncü bölüm, iletim sistemlerindeki çeşitli arıza türlerine değiniyor. Ayrıca iletim hatlarında en çok tercih edilen mesafe korumanın temel prensipleri, arasında arızaya olan mesafenin ölçülmesi, koruma bölgeleri ve kademelerin hesaplanması , Mho ve Quadriateral karakteristikleri ve yedek aşırı akım rölelerin ayarlanması, pilot mesafe koruması yer almaktadır.

Dördüncü bölümde, DIGSILENT Power Factory 15.1'de bir 735 KV iletim sistemi modellenmiştir. İlk yük akış hesaplaması simüle edilir ve normal çalışma sırasındaki sistem davranışı değerlendirilir. Ardından, mesafe koruma sisteminin performansı iletim hattındaki çeşitli arıza yerleri için kısa devre analizi ile değerlendirilir. Tek faz arızalarına karşı temel koruma, her iki hattın iki tarafında olan terminalalarında aynı röleleri kullanarak iki bağımsız mesafe korumasını gerçekleştirerek ve bu korumaları iki farklı iletişim kanaliyle irtibatlarını sağlayarak kurulmuştur ve mesafe koruma sisteminin doğru çalışması onaylanmıştır. Otomatik kapanma simülasyonu, EHV iletim hatlarında tek fazlı otomatik kapanmanın başarılı bir şekilde çalıştığını doğrulamak için farklı arıza yerlerinde gerçekleştirilir. Dördüncü bölümün sonuçlarında belirtildiği gibi, EHV sistemlerinde, sistemi normal çalışmaya geri döndürmek ve senkronizasyonu sürdürmek ve yükü sürekli olarak hizmet etmek için yüksek hızlı tek fazlı otomatik tekrar kapama gereklidir.

1. INTRODUCTION

Contemporary man has been able to develop advanced technological means to further extract natural resources' energies and employing them for his own convenience and happiness and Power Systems play a significant role in this respect. Power systems with their ever-increasingly sophisticated constructs, produce electrical power in power stations, transmit it to various destinations and distribute it to power supply the electrical consumers. Obviously, many challenges should be resolved before the above said mission could be accomplished. Over distanced locations for example, the supply of electrical power through transmission lines to the consumers without the inception of short-circuit disturbances constitute a major challenge (Glover, Sarma, & Overbye, 2011).

The main aim of the present paper is adopting adaptive methods for the fault type recognition — permanent and/or temporary faults— and making the final appropriate remedial decision accordingly. As for the permanent faults, a suitable decision making would be initiating a three-phase trip signal, while for the temporary faults the proper decision would be reclosing the breakers following the detection of extinction. In cases where the system is facing a too slow arc extinguishment, a better approach would be preferably issuing a 3-phase trip signal meanwhile avoiding reclosing due to the fact that prolonged keeping the system in unbalanced conditions would be detrimental to it. Hence a predetermined extinction time is a must, to which this paper will deal with.

1.1 Single-Phase Reclosing

Statistics show that the most part of the short-circuit faults occurring in high voltage transmission grids are of temporary fault type (Esztergalyos-Chairman). Addressing the temporary type of transmission line faults, often simultaneous with electric arcs, one probable mitigating approach is temporarily isolating the fault affected line, with the following delayed or prompt re-energization called as reclosing technique (Esztergalyos-Chairman).

An arc-associated temporary fault could be safely extinguished through 3-phase reclosing, as with all three conductors isolated, there remains no further voltage source, feeding the arc. But the drawback of the above method is that it can be detrimental for the system stability since the two ends of line shall remain disconnected for a relatively long time. Similarly, as for the single-phase-to-ground transient fault type, using single-phase reclosure could be an optimal option (Robinson & Spurgeon, 1929).

1.2 Single-Phase Reclosing Advantages

1.2.1 System stability

Studies have demonstrated that keeping the transfer impedance among the systems low, the synchronous stability of interconnected generating plant will improve. To achieve this goal, two sound phases are kept in working order when a single-phase to ground fault is the case and besides, the transmission burden of the system is increased at no additional expense. Similarly, if the interconnection is comprised of several parallel lines, the continual service of as many phases available while a line fault occurs would result in the increase of transmission capacity. Enhancing the system synchronous stability during a single-phase fault was the main cause of adopting single-phase auto reclosing.

1.2.2 Stability of the load

Although maintaining the system loads stability in a line fault is critical, but the single-phase reclosing effect has not been comprehensively considered in this regard. Obviously reducing the transfer impedance through single phase reclosing can significantly enhance the synchronous motor loads' stability, similar the way it acts for the synchronous generators. But due to the inappropriate load angle, synchronous motors often cause more frequent stability problems compared to the generators, and hence the suitably employed single-phase reclosing assumes greater contribution in this regard; the pumped storage plant in the pumping mode operation is a typical example to mention in this respect.

1.3 Single-Phase Reclosing Drawbacks

1.3.1 Complexity and cost

No doubt the three-phase reclosing offers a much more convenient method than resorting to relaying and circuit breaker controls. Here the phase selection and selective tripping requirement issues are propounded. As was expected, primarily these issues arose resistance among the field personnel who were sufficiently overburdened by the complicated controls and protective measures. Afterwards their worries were eased, and the new scheme's fundamentals were identified and trained, the mentioned personnel showed their full support of the scheme as a result of their actual field experience, while the increased costs of relaying did not exceed any further than 20%.

1.3.2 Circuit-breakers

Power engineering and protective standards require that circuit-breaker mechanisms are equipped with 3 autonomous tripping systems. The encounter shows that at higher voltage levels, meeting the bursting capacity necessities is a must while this measure dictates no additional investment. The only 132kV circuit breakers and low rupturing capacity breakers (2500MVA) require increased investments. Also mounting circuit-breaker at both ends of the line as well as any Tee points on the spiral circuits is compulsory, and this would require higher investment. Comparing with the need for provisioning replicate superfluous line to improve supply continuity, stability, etc., this increased amount of investment however is still negligible.

1.3.3 Negative sequence currents

During one phase opening, the negative and zero sequence currents would increase over the dead time which cause over-heating of the rotary parts of the machines. Although the inception of dead times does not go beyond 1 or 2 seconds, and hence the resulting over-heating, dissipated across the whole system is not significant by any means.

1.3.4 Zero sequence currents

Small but longer telephone interference may also occur due to zero sequence component which is negligible compared with the magnitude of this interference occurring during actual short-circuit faults. Directional analogy and inverse-time ground overcurrent relaying may also be affected by the zero sequence current to which we will deal with in the following relevant section.

1.4 Problem Definition

With the conventional single-phase reclosing methods, the isolation of short-circuited single-phase must immediately occur which is followed by issuing the reclosing signal after the lapse of a delayed dead-time. The conventional single-phase reclosing method however suffers from two drawbacks:

- The actual duration of the fault —whether temporary or prolonged—is not known, and the reclosing signal is issued without regard to the fault type and duration;
- Assuming that the fault type is a temporary one, the actual reclosing may occur before the extinction of arc, and this is a major problem, as reclosing before the extinction of arc initiates arc re-striking, leading to unsuccessful reclosing and the immediate damages to the whole system.

Another important problem refers exclusively to the temporary short fault instances. As for the permanent faults, the preferable decision would be immediate initiating of the 3-phase trip signal. Regarding temporary faults however, the reclosing would be bound to detecting the time of arc extinction after which the reclosing signal should take place. Since arc extinction time in some temporary fault instances could be longer than the usual, the suitable decision for such cases thus could be initiating the 3-phase tripping signal.

Considering the proposed methods, it would be preferable that local voltage measurements' data are used for the reclosing operation because the communication means might not be immediately available. Moreover, the proposed method must prove reliable for any transposition and compensation conditions.

1.5 Literature Review

Statistics show that almost the best part of the short-circuit faults (over 80%) of the overhead grids are of temporary type, often single-phase-to-ground faults .

The reason why aforesaid faults are of temporary type lies in that they frequently occur due to the overvoltage resulting from the lightening, and transient contact between the phase and ground wires, often because of the falling branches of the trees or the flying birds. Due to the temporary nature of the faults that makes them capable of being cleared autonomously, a practical solution can be the single-pole auto-reclosure (SPAR) of the pertinent phase (IEEE Power System Relaying Committee, 2003). The mentioned solution, if correctly implemented, can remedy the faulted phase and shortly put it back into operation, leading to the improvement of the system reliability and stability (Ahn, Kim, Aggarwal, & Johns, 2001). Experimental data show that about 58% of the line capacity is available during the single-phase tripping of the faulty phase circuit breaker due to the presence of the other two operational phases (Jamali & Parham, 2010).

Considering the single-phase auto-reclosing (SPAR) in conventional systems, the reclosing operation occurs afterwards the opening of faulty phase following a pre-specified time-lagging, namely dead-time (IEEE Power Systems Relaying Committee, 1984). In this circumstances, firstly, the fault type (temporary or permanent) is not a decisive factor for the reclosing operation, and secondly, regarding the temporary fault instances, no guarantee can be given that the reclosing would suppress the arc and it would be 100 percent extinguished. Hence there would be chance of restriking of the arc in temporary fault cases and reclosing on-fault in permanent fault cases. Both the above unsuccessful reclosing attempts have potential risks for the power system and its equipment (Jamali & Parham, 2010), (Mohd Hasan Ali, Murata, & Tamura, 2008)- (M Mohammed Eissa & Malik, 2002) and the following frequent reclosing attempts will put the whole system even under higher potential risks (S. P. L. Blond & R. Aggarwal, 2012; S. P. L. Blond & R. K. Aggarwal, 2012; Websper, Johns, Aggarwal, & Dunn, 1995). In (Aboreshaid, Billinton, & Faried, 1998) (Bowler, Brown, & Walker, 1980; Fotuhi-Firuzabad, 2000) (El-Serafi & Faried, 1994) Recently some researchers have introduced and practically installed three-phase four-legged shunt reactors with inductively grounded neutral on both transmission line ends to minimize the dead-time (Reid,

1981)-(Sherling & Fakheri, 1979). Proper selection of neutral reactor would help limiting the voltage of the arc so that the dead-time is reduced. The method has proved effective when integrated in transposed transmission lines, while it was applied also in extra high voltage grids using shunt reactor switching scheme at the end of line (Fakheri, Ware, & Shperling, 1978).

In order to neutralize the bilateral capacitance among the two sound phases and the faulted phase, a four-legged reactor installed on the line side of a circuit breaker or capacitance which are mounted placed parallel with the circuit breaker can be deployed. To implement such reactors three type of designs can be followed:

- Employing a four-legged reactor of identical reactance for compensating the bilateral coupling of a transposed transmission line
- Employing one four-legged reactor for compensating the impacts of an untransposed

transmission line (Mohd H Ali, Murata, & Tamura, 2006).

The quick discharge of secondary arc after the isolation of faulty phase is important for which the High Speed Grounding Switch (HSGS) method is employed. Using this system, both ends of the open line are earthed using resistors with no delay after the isolation of the faulted phase, so that the stimulating voltage supporting the secondary arc is eliminated. When the secondary arc is extinguished, the switching resistors are opened before the circuit breakers reclose (Peterson, 1981). The application of the above explained method is restricted for the uncompensated transmission line (Turnip, 1995).

As was discussed above, the conventional SPAR suffers a number of problems for which some adaptive reclosing methods have been introduced to overcome. The major goal an adaptive single-phase reclosing approach is trying to achieve is quick identification of a perpetual fault and detection of the arc annihilation during momentary fault instances (Moustafa Mohammed Eissa & Malik, 2000). The study (Tsuboi, Takami, Okabe, Aoki, & Yamagata, 2013) investigated 27 cases of real temporary faults affecting the 550 kV transmission lines on the basis of voltage shapes. In another study (Mestas, Tavares, & Gole, 2011), the zero reclosing point of the voltage is used as a basis for the enhancement of reclosing performance. The studies conducted in (Tuan Tran-Quoc, Hadj-Said, Sabonnadiere, & Feuillet, 2000)

and (T Tran-Quoc, Huy, Duong-Lan, Hoang, & Tran-Dinh, 1998) the frequency features of the current are employed for the reduction of dead-time of reclosing.

The study described in (Nagpal et al., 2016) conducted by Canadian investigators in the field of single-phase reclosure, proposed a structure of detection of arc extinction on the basis of the faulty phase voltage behavior.



2. AUTO RECLOSING AND PROTECTION

2.1 Reclosing Technology Background

Reclosing solution was first used at the start of 20s for the spiral feeders in over-current relays and fuses were mounted for protecting the distribution systems. Investigation demonstrated that the antecedent reclosing model system was successful in 73 to 88% of the fault events.

In early 1930's the inverse-time relays equipped with tripping parts were employed in power systems. Inverse-time relays could coordinate among fuse systems. At that time, the auto-reclosing approach was used primarily for the after a pre-determined lag for the sake of deionization of the arc course as well as the mechanical reset of the relay. If the relay tripped within 30 seconds after the first trip, the lockout operation would occur. In fact, the constancy of supply service was considered the primary goal of the reclosing technology.

Afterwards the circuit breaker of the transmission was invented and employed in the power system. It featured high mechanical performance and could reduce the fault clearance time through faster operating the new designed breakers and guaranteed faster reclosing resulting in higher stability of the power system. The investigations also led to the invention of flash-over probability in insulators, enabling the minimum reclosing time possible and provisioning the compulsory time for deionization of the course of arc.

At first, the auto-reclosing was employed for the faulted lines with more than two installed terminals. For the purpose of circuit completion, the system was designed to perform a delayed reclosing across all terminals, with the precondition that the first reclosing is successful. However, obviously the best reclosing technique was multi-shot reclosing from the continuity of service perspective.

During the recent decade however the power industry witnessed the transformers failures due to the reclosure of distribution substation feeders. Another drawback was the potential of the increased stress on shafts operating between the turbines and

generators. It's worth noting that the issues were explained in report by a study in 1940. The conclusion was that in spite of the presence of transient power limits, the use of single-pole switching might be inevitable.

Abundant improvements of mechanisms designs, operational reliability and speed have been achieved in relation to the high voltage circuit breakers. These achievements together with protection systems developments have made rapid reclosing technically possible and practical.

Based on the recent accomplishments in digital advances, using one reclosing relay per breaker has been propounded once again, in which a logic system or reclosing mainframe may be employed for setting up of each individual breaker. The processor can then check the energizing or de-energizing state of the grid lines, buses and positions of the circuit-breakers selector as well as the control switching, closing control voltage, etc. Since due to the advances of the communication and data acquisition systems greater number of stations has been available in a grid system, awareness of the conditions across substations has become more local than central. The reclosing systems controlling however should remain locally at the substation.

2.2 IEEE Guides for Auto-Reclosing

2.2.1 Principals and utilization

The basics of auto-reclosing are explained regarding circuit breakers of distribution and transmission lines. Normally the reclosure of breakers happen afterwards of the trip function of the protection system. If the fault is of temporary type happening in line or substation bus, the isolated fault line can be put in operation once again and hence, and the system will be capable of carrying full active / reactive power. Obviously, the increment of the system stability margins and thereby more reliability of service for the consumers will be provided.

2.2.2 Auto-reclosing task performed by a reclosing relay

Traditionally the auto-reclosing is performed through reclosing of the relays, an operation that is customary pertaining to a number of specifically designed circuit breakers. However, the reclosing can be performed on any number of mechanisms having an input to get, whether the condition of the breaker and without regarding

the applying of the tripping signal. The auto-reclosing can be applied if one of the below conditions is satisfied:

- Cycle situation: The CB is located in open state and the auto-reclosing function is timed for closing the breaker. One other potential for this condition is when the breaker is switched after an auto-reclosing operation is successfully performed; following which the timing for returning to the reset condition is performed.
- Lockout condition: The auto-reclosing mechanism is in closed and locked status because the reclosure has occurred at most one time before but the relay has reconstituted the tripping signal. Hence, the breaker will be locked and the reclosing operation is unable to be effected. In this situation, the only solutions for reclosing the breaker are either through local or distanced manual operation (local-manual or remote-manual).
- Reset condition: The CB is initially in a close state. The auto-reclosing mechanism rests until getting the timing signal for performing reclosure afterwards the breaker opening.
- Power-up condition: The input signals and the breaker status are read by the relevant relay to identify the actual condition and thus the system moves to the determined condition. For instance, when then the system is in natural conditions and no particular input signal has been inserted, in case the breaker is in normal position, it will be moved to the lockout status, and when the breaker is closed, the accurate condition will be 'reset'/ Again, when the auto-reclosing is in the reset conditions, this operation can be executed with two possibilities in order to start to the first try formed on the logic scheme or the device design:
 - Detecting the breaker's opening, resulting in the start of the first reclose/open interval timing, or
 - Detecting the tripped status of the breaker by the protecting device, and confirming the following breaker opening, which will initiate the first reclose/open interval timing.

While the breaker is in controlled opening operation, the reclosure protection device starts timing to return to the first auto-reclosing attempt. This move from timing to

the initial auto-reclosing position causes the reclosing function to shift from reset situation to cycle condition.

During the completion of this delay, the protection device of reclosing begins closing the output contact in order to initiate closing of the breaker and confirms that the breaker has been closed as a result of a change of condition of input of breaker status. In case the breaker is unable to perform the closure within preset amount of time, the reclosing protection mechanism may change status to lockout condition and keeps asserting to closing the output or let off the closing output, according to the the reclosing protection mechanism program design.

When the breaker is in close state, the reclosing protection mechanism starts the reset timer which is called the reclaim timer. But when the CB remains closed, this means that a fault of temporary type has been identified; the protection then will reset timing. After the reset time-delay has been accomplished, the auto-reclosing function returns to the reset condition and stays unchanged as long as the breaker remains closed.

As for the no fault clearance cases, the protective mechanism demonstrates a second tripping signal, the resetting timer will stop and performs reset, and the reclosing protection mechanism will start timing to a second auto-reclosing trial, conditional on the relay is set or programmed for additional auto-reclosing trial.

Afterwards any auto-reclosure attempt, if the breaker remains closed, as long as the reset timer delays, the reclosing relay turns back to the reset position. On the other hand, concerning permanent fault cases, in case the number of resetting the auto-reclosing trials ends, the following condition of the relay is locked as long as the breaker remains open. The condition of reclosing function will remain unchanged until the breaker is closed through other methods (manual, etc.)

2.3 Auto-Reclosing for Transmission Systems

2.3.1 An overview of the transmission systems

Reliability of power systems is of utmost importance and loosing a transmission grid line will considerably affect such reliability. Auto-reclosing is predicted for a line to minimize this adverse effect. For this purpose, time-delayed and high-speed reclosure solutions are widely applied in power industry.

The intelligent systems and SCADA with their provisioning huge amount of data, enable more selective reclosing functions which will turn the reclosing system into a successful solution and reduce the damage to the power system by reclosing the faulted line. The applicability of adjusting reclosing techniques, controlled CB closure and single-phase trip operation have improved the system reliability and reduced the negative impacts of auto-reclosing failures.

Moreover, in addition to the auto-reclosing methods, there exist other elements to address pertinent to their influence on the reclosing applicability. For instance, in a grid line needing reclosure surveillance by sync check . Regarding the system aftermath mitigation, reclosure may be employed only to one end of the line. Other elements affecting the reclosing mechanism include the transformers, capacitors , motors, reactors ,generators, multiple-terminal lines, etc. to which we will deal with in the following section.

2.3.2 Auto-reclosing methods

High-speed auto-reclosing

Automatically closing a circuit breaker without the need for a pre-specified delay time larger than what is suitable for deionization of the arc can be achieved using a high –speed auto- reclosing scheme. To perform successful operations on auto-reclosing trials for momentary faults, considering the high-speed auto-reclosing methods is recommended.

Some of the advantages of the application of high-speed reclosing include reduction of outage time, enhancement of system security and integrity, greater potential of recovery from multiple contingency outages and maintaining stability of the machinery.

Dealing with the high-speed reclosing, there are a number of restrictions on the equipment, operations and configurations to be considered:

- The system configuration must be able to keep the angle difference of the two sides of the opened CB with proper variability.
- The fault must not be preserved by the injected voltages from the parallel circuits.
- As for the durable faults, the system should be balanced after high-speed reclosure.
- All terminals of the line must be equipped with high-speed protection for all fault instances simultaneously to supply adequate time for arc path deionization.

- Assessment of damages to the rotational power equipment must be considered.

In order to a high-speed reclosing to be successful, the arc route should be deionized enough so that the insulation properties before the re-energization of the transmission line may be re-established.

The factors influential on successful high-speed reclosure include:

- Transmission line structure and design,
- Fault clearance time,
- Fault current magnitude,
- Transmission linelocation compared with natural or human-made sources of risks,
- Climatic conditions,
- Various components of lightning stroke,
- Capacitive and inductive pairing with the circuits in parallel connection,
- Spontaneous value of voltage at the line re-stimulation moment,

2.3.3 Auto-reclosing settings

2.3.3.1 Number of reclosing attempts

Auto-reclosing function constitutes the simplest case relative to the number of trials in single-shot reclosing; that is, reclosing breaker only one time. Single-shot reclosing can be executed in two forms: delayed or at high speed.

Another option is executing the reclosure for more than 1 time, namely the multiple-shot reclosing. In order to perform multiple-shot reclosure, numerous factors are involved including: system stability, potential failure of system equipment emanating from currents of the fault, possible harms to the consumer facilities and the like.

2.3.3.2 Dead-time

When initiating the reclosing attempts, a number of considerations are involved, especially when the relay issues the trip signal.

But for a too early reclosing attempt in a temporary fault occurrence, there is the potential for the associated arc not to be extinguished and hence, the reclosing attempt fails with the subsequent restrike of the arc.

When an arc restrike occurs, with the course of arc not deionized, it re-conducts following a failed reclosing attempt. The time interval required for the deionization

depends upon the distance among the conductors, voltage value, climatic conditions and fault current magnitude (Winegartner & Bonheimer, 1949).

The equation (2.1) can give a practical value of minimum required time-delay for avoiding the arc restrike:

$$t = 10.5 + VL/34.5 \quad (2.1)$$

Where t is the time delay of the power system cycles, and VL is the line voltage rated in kV .

Regarding any types of circuit breakers, there is a requirement for adding a delay to the auto-reclosing time or the circuit breaker time so that the arc deionization time is attained. For example, some circuit breakers are capable of reclosure in 2 or 3 cycles, for which a delay time must be added to avoid reclosing in case of resisting of the arc.

Still the arc deionization time may heighten even further should the single-phase tripping is applied and if the phases maintain the arc on or if a parallel line is able to support the arc to maintain its live energy.

2.3.3.3 Auto-reclosure reset-time/lockout

Following a outstanding auto-reclosing, the protection mechanism is required to be reset and be prepared for the following potential fault occurrence. This has to be effected via a timer called the reset timer. Also the reclosure protection mechanism returns back to the reset state afterwards the reset time. Selection of the reset time relays on the type of the fault and nature as well as the fault clearance time expected. For instance, the potential for re-skipping and hence, another reclosing attempt will reduce in case of selecting a longer reset time-delay . On the other hand, should the reset time is too lengthy, some lockout tasks may incur and hence, the additional reclosure may be avoided.

If the auto-reclosure attempt is successful, the protection mechanism will move to the lockout status to prevent the interruption system from executing automated closure. After the programmed attempts for the line re-energization is completed unsuccessfully, the auto-reclosing is either locked out or terminated. Lockout position may be helpful to avoid excessive wear on relay as the result of too many operations due to the frequent line temporary faults resulting from unwanted causes like falling broken branches of trees, etc.

It's worth mentioning that there are auto-reclosing mechanisms able to be programmed for preventing from sequential auto-reclosing attempts through provisioning lockout conditions if the number of faults gets to a pre-specified value during a time span. For instance, a three-shot auto-reclosing may be programmed to lockout if seven faults happen in a 30-min time span.

A further advantage of the lockout is preventing a relay from undesirable auto-reclosing when the closed status has been manually applied to the line. The mentioned status will apply automatically in case the CB is manually closed either locally or distanced. Here the CB stays closed for pre-specified time. Hence, no fault will happen during the breaker closing time.

2.3.3.4 Blocking of auto-reclosure

Auto-reclosing operation is interrupted and blocked in case one of the below conditions exist:

- Tripping by the operators: in the case of opening the circuit breaker manually or by remote control at the distanced station. The preference in such a situation is the system being subject to the operator to close.
- Line voltage supervisory monitoring: Auto-reclosing can be blocked in case the line is live by the existing voltage. This happens often when the line is connecting to the power generators, large electric motors or the like solid sources. Using the voltage supervisory monitoring, the auto-reclosing is blocked when such sources on the downstream side preserve voltage on the line to prevent potential damages to the pertaining rotary equipment.
- Onset of fault on an buried cable, a high voltage transformer or bus: This type of fault is often of sustain type and an auto-reclosing by a breaker can severe the damages to the consumption equipment. Hence, the auto-reclosure advantages and risks against blocking the auto-reclosing should be taken into account.
- Voltage unbalance: During an unbalance occurrence in the substation voltage the auto-reclosing can be blocked. A tripped phase for example on the source side can result in such unbalance. Recovery of service when the condition is unbalanced may contribute incurring damage to the consumption facilities.
- Protecting the circuit breaker: Failure protection of the circuit breaker mainly performs tripping all the breakers which are directly connect to the bus with

the bus differential protection .CB's auto-reclosing is blocked until the failed breaker is isolated and the bus is restored.

- In case the breaker closure is failed: If the breaker is not closed after an auto-reclosure attempt (auxiliary contact 52), the closure time then lasts more than the expected time, or an open circuit (discontinuity) is detected, the auto-reclosing is blocked so that incurring more damages to the equipment is prevented.
- Faults resulting from high-current: in order to block the auto-reclosing of high-current faults, an instantaneous overcurrent may be installed. This type of blocking could be applied in case the fault attains the rating that can incur damage to the generator transformer or the equipment else. The type of fault here is often of permanent type occurring in the outlet cables or substation equipment.
- Lockout of the aggregate operations: This is applicable for the cases when the fault duty attains a predetermined rating of circuit breaker to block an auto-reclosing afterwards of a preset number of operations, until the required maintenance or inspection is performed.
- Receiving a transfer trip: Every now and then it happens that a timer is triggered when a signal of trip is received. In such instances, if the timer's time-out is reached, the reclosing sequence operation is blocked.
- Backup tripping: A distance zone (overreaching zones) mounted for backup protection may be utilized for disabling of reclosing function in case it demonstrates a protection failure for the other zone.

2.3.4 Operation considerations

2.3.4.1 Underground lines

In respect of the underlying cables, the faults are often of stable type and the auto-reclosing mechanism should be installed in accordance with the following guidelines. Grid lines partially using underground cables represent especial concerns relative to the consumption utilities, and that must be addressed through auto-reclosing system. In case the cables is thoroughly made of cable, an auto-reclosure system must not be used (in accordance with the IEEE Power System Relaying Committee guidelines) because it will put the cable and equipment such as the substation power transformer,

circuit breakers, buses and other power system parts to high potential risk of damages and stresses .

Depending on the location and length of the faulted portion of the cable, the utilities often assume this type of feeder as totally overhead line and implement their particular auto-reclosure scheme while others may treat it as a single-shot auto-reclosing in order to consider the line status as momentary fault or some other circumstances that would eventually consequent malfunction of the relay. One other possible solution is using a sectionalizer for isolating the faulted cable section to apply a modification of the auto-reclosing schemes. In case of compromising the line in overhead and ground cable portions, the auto-reclosure mechanism can be implemented in case fault refers to the overhead section and not the cable portion .

Also it should be determined that which of the two ends of the faulted combined line must be closed-in as the initial auto-reclosing attempt. Another practice might be the need for overvoltage investigation using a transient network analyzer to ensure a safe auto-reclosure of the line. For the cases of connection of a shunt reactor to the line, conducting such investigations is of utmost importance to control the impacts of capacitances of the cable, leading to the increased line voltage, namely the Ferranti effect .

2.3.4.2 Bus faults and the subsequent auto-reclosure

In some cases, after the onset of fault on bus the auto-reclosing can be deployed for the bus system recovery. In such cases, the basic consideration for decision making pertaining to the application of auto-reclosing scheme depends on a arrangement among the reclosing aftermath to a bus fault and the extended bus outage impact. Since the power system busses commonly terminate to a couple of elements, not only the bus fault, but also the outage of bus may produce dramatic reaction on the security and operability of the power system in question. The competence of the bus auto-restoration following a momentary fault is generally assessed against the potential risks to the power system if the fault was originally of a permanent type of fault. In that case, the possible damages to the fundamental elements of the system would include the turbo generators, transformers, etc. as well as the stability of the power system.

Regarding substations of outdoor type, the auto-reclosing on the breaker of a bus is performed if the protection mechanism serves for the fault of bus. Normally the

delay of auto-reclosing is set for a specified amount of time, e.g. for 5 seconds, no additional monitoring is maintained unless the busses are connected to other sources including the ones distributable over the transmission line or those feeding other transformers. Hence the auto-reclosure can be supervised using an under-voltage relay. Some other settings of the system may require auto-reclosure blocking including under-frequency, transformer differential, CB failure, etc.

Bus systems like outdoor open rigid bus, similar to overhead distribution or transmission lines are vulnerable in the face of faults of external reasons such as flash-over of the insulator, birds, lightning, etc. when they use open-air insulation medium. If cleared instantly, then a successful reclosing without the need for inspection can probably take place. The distances among the conductors—which depend upon the voltage levels of the bus— can affect the above mentioned reclosing probability. The temporary faults caused by an animal occur with greater probability in power distribution networks than other sources of faults. Open-air busses are not accessible due to the substation protective surrounded barriers.. But such accessibility is lower for transmission lines; hence, the deployment of reclosing on outdoor busses would pose higher threat for public than transmission line reclosure mechanism.

Reclosing of open-air busses poses a further risk potential for the substation personnel working during maintenance duties and other daily routines. The further danger said above can be mitigated through the use of the function of reclosing cut-off and blocking the auto-reclosure mechanism during routine tasks in substations. This approach is similar to the maintenance of live-line routinely implemented for the transmission and distribution circuits.

Using a suitable insulation method, it would be possible to protect a bus system from exterior interferences. To name some examples of this type of insulation, the detched phase bus, SF6 switchgear, metal-clad switchgear and insulated cable can be mentioned. The ionization of bus as a result of fault could not be cleaned up by naturally and applying auto-reclosure to these types of busses is way off from the benefit.

Where auto-reclosing system is employed for a faulted bus, there is the possibility to apply a single-shot reclosing protection mechanism for a CB having been connected to the bus, to execute CB reclosure in the case that dead-bus-live-live condition is represented. Practically, it is customary to select a breaker to perform the testing with

the lowest impact on the bus system in permanent fault cases. Mostly the live circuit has the lowest short-circuit potential. The differential relay of the bus however must have the required sensitivity to the downgraded level of fault current in a way that for the permanent fault cases, tripping could be initiated. As one solution for this purpose, reduction of pickup current threshold for a short time span during de-energization of the bus can be effected.

One other solution is designing an instantaneous over-current relay tasked with reclosure. To achieve a suitable level of sensitivity for protective reclosure of the bus, the impact of inrush currents supplied by CVTs and other bus equipment should be considered. During the reclosure of the breakers connecting to one single bus, in case of successful reclosing of the first breaker, auto-reclosing can be carried out for the remaining breakers meanwhile considering the standard constraints and authorizations required for the live-bus situations.

2.3.4.3 Adaptive auto-reclosing

Today many reclosing methods can be implemented to address different conditions such as time of the day, overloading or weather prediction. Most of the mentioned methods rely on both the last consumer and type of the system. Some examples of the installed adaptive reclosing methods are given below:

- 1) A method of enabling or disabling fuse savings through operating multiple-shot reclosure on weekends and evenings. For an industrial consumer, the worst thing is frequent power interruptions of the factory machinery and facilities. Hence, fuse savings are not allowed during production hours.
- 2) In this example the operators may enable or disable auto-reclosing based on the weather conditions. The historical data of utilities show that the best part of the successful auto-reclosure operations are those operated during thunderstorms.
- 3) Control of the auto-reclosure sequence on a line with the downstream reclosures included, through the use of overcurrent element. In this method, when the current level attains a value associated with the downstream fault current, an overcurrent relay contact is closed. If this contact is closed. This means that the downstream reclosure has performed the expected operation. This will lead the reclosure relay to skip from the initial reclosing attempt if finally the breaker is called on to carry out the fault interruption.

- 4) Applying the overcurrent element for detecting the load level in order to demonstrate whether or not a consumer has started a large motor. It is desirable to ensure that the reclosure is not operating for the condition described above.
- 5) Applying an impedance element or a high-set overcurrent element for determining any fault occurrence in the cable part of the line existing between the transition to overhead and the breaker. The reclosing must be avoided for such a case.
- 6) Trip circuit monitor alarm or breaker failure trip alarm. If a relay is activated to issue a tripping signal and the breaker fails to open during the time span in which it is expected to open, (e.g. 6-10 cycles) the auto-reclosure must preferably be blocked. It is also preferred that an alarm of trip signal monitor is used so that the reclosing function is blocked in case the trip circuit continuity is detected by a logic circuit.
- 7) If a circuit breaker fails to close. If an auto-reclosing attempt happens but the breaker remains open during the pre-specified closing time, then more attempts for reclosing must be prevented.
- 8) Delaying the auto-reclosure following extinction of arc. This requires the use of line-side voltage transformers (S. P. L. Blond & R. Aggarwal, 2012).
- 9) The auto-reclosure methods must be preferably avoided regarding multi-phased faults.
- 10) In case of the onset of unwanted tripping, immediate performing of reclosing is a must. Rapid reclosing initiation can be executed through the use of a substation SCADA computer in case the fault data illustrates the presence of an incorrect operation of relays.
- 11) In case of using a sync-check for reclosing, the sync-check angle must be changed. Such an angle is to set in case there is a relatively high disturbance in the system. However, there is the possibility for failure of the algorithm to carry out fast angle calculation when the system conditions are rapidly changed (S. P. L. Blond & R. Aggarwal, 2012).

With the use of smart breakers, it is preferable to adjust the number of authorized reclosing attempts or reclosing time delay through utilizing the operations data of the breaker. For example, if there are abundant numbers of operations in a short time interval, it can be preferable to increase the length of delay time or block reclosure. For faults of smaller currents however, shorter delays could be considered. As for the faults with high resistances, it would also be better to block the reclosing. The

computerized program could be used for rotating the reclosure function based on ‘breaker-and-a-half’ and ‘ring bus’ structures.

Through adaptive reclosure, it would be possible to adjust reclosing of different lines. Also using wide area network (WAN), the dispatcher of the load can develop communication with other substations and execute the online reclosing adjustment, in other words, the use of current status data of the system.

2.3.4.4 Time-delayed auto-reclosing

Regarding time-delayed reclosure, the application of some points can be considered as shown below:

- Reducing the probability of fault arc re-establishment by the increment in pre-specified time delay.
- Time-delayed reclosing can be useful conditional to the proper protection mechanism cannot be applicable for all transmission line terminals.
- The desirable re-establishment time of the system circuit, specifying the number of terminals of the line, stability studies, system requirements, loads types and the system damping factors.

In case the sync-check for unusually long fault-clearance time is required, load-flow and stability studies must also be performed. In some instances, double-checking of the phase difference and the existence of synchronous condition prior the application of the reclosing function is not necessary because of the number of parallel paths of the faulted line.

Given time-delayed reclosing through the application of fastest reclosing schemes, often only one of the line terminals at a time is reclosed for re-energization of the line. Additionally, relays of voltage monitoring are often considered for determining the system voltage existing on one of the breakers. Hence, the user can primarily choose and determine the system voltage conditions. In some cases, the user allows a delayed reclosure only when the phase difference among the open breaker contacts lies within a predefined range and remains synchronous during a desired time span, performed by sync-checks.

Switching surges

In case the transient analysis results performed on the voltage demonstrate that there is the possibility for switching surge of higher than the design values of the device, then the high-speed auto-reclosing technique must not be used.

Time considerations

In general, and without regard to the series capacitor deployments, the initial dead time of the 3-phase reclosing methods amounts to 0.5 to 10 seconds depending on the actual system conditions. In power grid transmission, the time delay of reclosing usually is calculated by the specialist engineers. To this aim, stability analysis should be taken into account in a way that the probable system oscillations after disturbances are damped. Additionally, auto-reclosing mechanism must be able to cover transient stability issues.

Single-shot and multiple-shot auto-reclosing

Single-shot reclosing can either mean high-speed or time-delayed reclosure of the breaker during one-time reclosing time span. The other possible choice for multiple – shot reclosure is reclosing circuit breaker during the specified duty cycle for above 1-time reclosing.

A normal reclosing on a terminal of a line involves a high-speed reclosure which is not monitored by sync-check or dead-line relaying, a delayed reclosure supervised by dead-line protection mechanism. A successful reclosure allows closing of other line terminals by a time-delay, monitored by sync-check protection mechanism.

In general, newly developed high voltage and extra high voltage circuit breakers can operate practically in any multiple-shot reclosing time span. The effect of duty cycles or some repetition operations however can be limited by some issues relevant to circuit breakers such as opening or closing resistances, gas, air or fluid pressure, or derating factor according to the expected current of fault and number of interruptions due to fault during a specified time span.

Various methods of blocking the auto-reclosing schemes exist applicable in transmission lines, basically depending on the design criteria of power system. Regarding the conditions of blocking of the reclosure, the below two items are pointed out:

- In 3-phase faults: These types of faults are not common on extra-high voltage facilities (above 345 kV). But when they occur, the 3-phase faults are certainly permanent. Most of the time, 3-phase faults occur as the result of ground straps missed afterwards the maintenance of the breaker or due to structures of downed lines. Hence, it would be preferable to block a 3-phase reclosing attempt at the onset

of a 3-phase fault. It is understood from above that 3-phase transmission lines of lower voltage levels are more frequently vulnerable to temporary three-phase faults, and thus to counter such faults, using auto-reclosure task might be effective in case the generation system stability is not negatively compromised.

- Out-of-step and power swing conditions: upon detection of out of step or power swing condition, the auto-reclosing must be blocked because the auto –reclosure simulates further a system already disturbed.



3. SINGLE PHASE AUTORECLOSING AND OPERATION

3.1 Introduction

Power transmission grids tolerate the apical fault onset rate as they are vulnerable to environmental phenomena like lightning, storms, vegetation fall, fog and salt spray on dirty insulators. Three phase shunt and three phases to ground circuits constitute the balanced faults in transmission lines, while single line-to-ground, line-to-line and double line-to-ground faults are unbalanced in nature. The protection relay system in a transmission grid is integrated for detection of the abnormal signal denoting faults and isolates the faulted part relative to other portions of the system with minimum disturbance and damage to equipment.

A widespread protective technique for the protection of high and extra high voltage grid is distance relaying principle thanks to their high speed fault clearance in comparison to over-current relays. The role of a distance relay is estimating the electrical distance to the fault and comparing the results with a given threshold and thereby determining the zone to be protected. Regarding the hardware tools, distance relays have gradually evolved and developed from electromechanical relays to static relays and even further to microprocessor based (digital) relays. Upon the onset of an electrical transmission line, the distance relays can detect the faulted line and fault type. However, depending upon the pre-fault loading, fault resistance and remote end in-feeds, the relays may be having under reach/over reach state. In such a condition, the impedance determined by the digital distance relay estimation is reduced with the increase in speed at which the estimation is being obtained. Therefore, an impedance relay adjusted according to a predetermined reach setting cannot operate at arbitrarily high velocity. For the protection of long transmission lines over the grid, often the distance protection scheme is applied. It works as the principal protection for overhead grid lines and implements back-up protection for the adjacent elements of the grid including busbars, generators, transformers, motors, and feeders, etc. Distance protection is a preferable technique in that it is more selective, faster and

less susceptible to changes in the power system conditions. Another advantage of digital distance protection is that it can be conveniently employed for a unit protection plan, if applied using a communication link.

Principally, a distance relay recognizes and calculates the impedance of the faulted part of a transmission line considering the measured voltages and currents at the relay mounting location. The fault impedance so measured will be compared to the impedance of transmission line programmed to be protected. Should the measurement of the fault line impedance show a value lower than the value set impedance of the transmission line, the system assumes and decides that there exists a fault on the transmission line across the relay and the reach point. This means that the distance protection in question in its most basic form can make a protection decision regarding the measured voltage and current at the relay installation location.

3.2 Single Phase to Ground Fault

As the transmission network is a mesh grid, the overcurrent relays are unable to provide quick and coordinated protection. Distance relays can measure the impedance obtained from the local measurements of current and voltage. The transmission line impedance is normally distributed following uniform patterns over the line length. Accordingly, a distance relay with almost reasonable accuracy can discriminate between the line internal faults and external faults through measurement of apparent impedance during the onset of a fault and thereby determining the protection “zone”. Referring the sample circuit provided in Fig. (1), there can be a total; of 11 potential (shunt) types of fault in the considered system: AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABC and ABCG. The fault current path from source to the fault location and backward to the source is called as the fault loop.

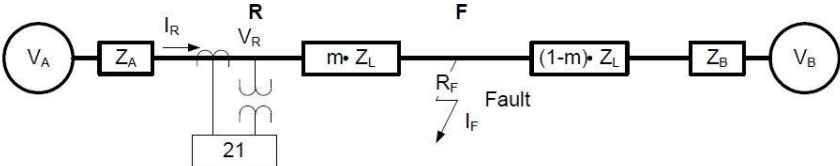


Figure 3.1: Two ended transmission line.

At the relay location (R) the voltages can be explained as functions of currents of relay (R) and voltages at the fault point (F). We can write using symmetrical components:

$$V_{1R} - I_{1R} \times m \times Z_{1L} - V_{1F} = 0 \quad (3.1a)$$

$$V_{2R} - I_{2R} \times m \times Z_{2L} - V_{2F} = 0 \quad (3.1b)$$

$$V_{0R} - I_{0R} \times m \times Z_{0L} - V_{0F} = 0 \quad (3.1c)$$

It must be noted that a fully transposed transmission line has identical positive and negative sequence impedances. Adding the above three equations gives:

$$V_{1R} + V_{2R} + V_{0R} - I_{1R} \times m \times Z_{1L} - I_{2R} \times m \times Z_{2L} - I_{0R} \times m \times Z_{0L} - V_{0L} - V_{1L} - V_{2L} = 0 \quad (3.2)$$

Supposing an AG fault and detecting that:

$$V_{0F} + V_{1F} + V_{2F} = I_F \times R_F \quad (3.3a)$$

$$V_{0R} + V_{1R} + V_{2R} = V_{AR} \quad (3.3b)$$

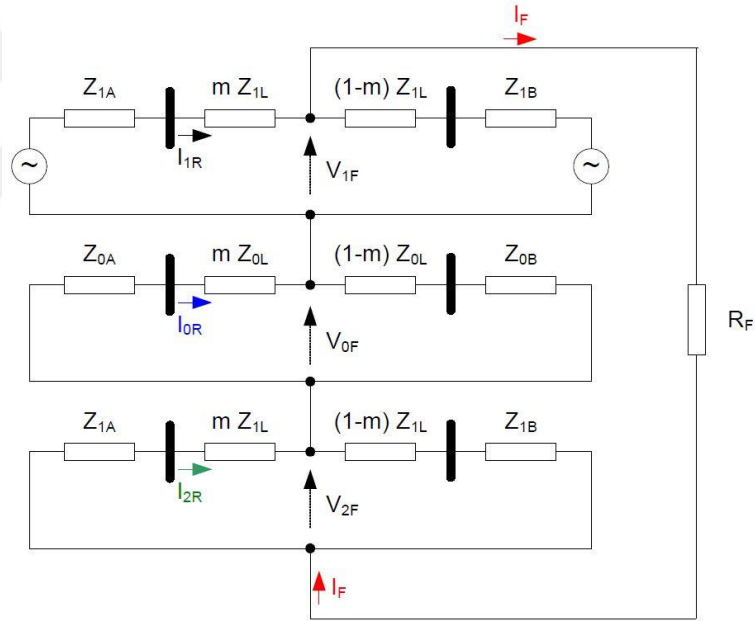


Figure 3.2 : Grid equivalent diagram of single-line-to-ground faults.

The equation (3.2) can be re-written as the following:

$$V_{AR} - m \times Z_{1L} \times \left(I_{1R} + I_{2R} + \frac{Z_{0L}}{Z_{1L}} \times I_{0R} \right) - I_F \times R_F = 0 \quad (3.4)$$

Then the zero-sequence current can be added and subtracted at the relay without the change of the equation (3.4) meaning:

$$V_{AR} - m \times Z_{1L} \times \left(I_{1R} + I_{2R} + I_{0R} - I_{0R} + \frac{Z_{0L}}{Z_{1L}} \times I_{0R} \right) - I_F \times R_F = 0 \quad (3.5)$$

Realizing that:

$$I_{1R} + I_{2R} + I_{0R} = I_{AR} \quad (3.6)$$

The equation (3.5) can be re-written as the following:

$$V_{AR} - m \times Z_{1L} \times \left(I_{AR} + I_{0R} \times \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) \right) - I_F \times R_F = 0 \quad (3.7)$$

Equation (3.7) results in the renowned zero-sequence compensation concept and zero-sequence compensating factor. With the compensated current introduced:

$$I_{AR} + I_{0R} \times \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) = I_{AR} + I_{0R} \times K_0 \quad (3.8)$$

This way the equation determining the ground distance protection:

$$V_{AR} - m \times Z_{1L} \times (I_{AR}) - I_F \times R_F = 0 \quad (3.9)$$

If the RF is zero, the equation (3.9) can be re-written as follows:

$$m \times Z_{1L} = \left(\frac{V_{AR}}{I_{AR} + I_{0R} \times K} \right) \quad (3.10)$$

Hence, under ideal conditions, the apparent impedance of a ground fault shall be equal to the positive sequence impedance existing in between the relay and the fault location, proportionate to the distance to the fault.

3.3 Protection Zones

To protect the power grid components, the power system is often divided into some protection zones. The protection zone in general is comprised of a generator, a transformer, a bus, a transmission line and a distribution line or motor.

The protection zones overlap each other in a way that each portion of the power system can be protected. Each protective zone for example has circuit breakers and relays that cover one or several power system components. The array of circuit breakers makes the isolation of protected zone possible if a fault hits one

transmission line, and in the meantime, other parts of the power grid keep working, supplying electrical power to the consumers.

In faulty or irregular power system conditions, the protection relays initially recognize the condition and issue trip signals to the relevant circuit breakers for the isolation of the fault affected zone. In order to mitigate the protective relays' failure adverse consequences, the protective back-up is provided at the nearby zones.

The function of back-up zones is isolating the faulty zone together with the zones connected to the fault affected zone, in case the primary relays were unable to perform the isolation of the original faulted zone.

The distance relay is planned out to under-reach the remote terminal. One conclusion to the definition of the underreach is that the relay will see faultless as compared to the setting. "Overreaching" is some kind of protection through which the relays at bus terminal can act dealing with the faults beyond the other remote terminal. They may undergo restrictions for tripping till an approaching signal from a remote terminal has demonstrated whether the fault is beyond the protected line portion. The distanced relays zone at far end is open, i.e. the remote point where the distanced relay's reach locates cannot be accurately determined so that accepting some uncertainty about its exact reach is inevitable, which constitutes about 5% of the setting.

The optimal state would be having all the faults inside the dotted line area instantaneous tripping.

But because of this uncertainty at the far end, in order to be sure that the end of line section is not overreached, an under reaching zone also needs to be accepted (zone 1). Usually the zone 1 is set somewhere between 85 and 90 percent of the length of line with instantaneous tripping.

Obviously the 1st zone lonely cannot protect the transmission line thoroughly; in fact, the area between the zone 1 end and the bus B might not be protected. Hence the distanced relay shall be equipped with one backup zone, which is set to consciously overreach further away than the of the transmission line remote terminal. This is called as the distance relay zone 2 and it must be set to operate at slower speed in a way that for faults occurring in the next line section, the zone 1 of the next line could operate prior zone 2 of the distanced relay at A.

Remember that relay R_{ab} zone 2 must not reach beyond relay R_{bc} zone 1, or some faults may occur simultaneously in R_{ab} and R_{bc} , second zones, leading to unwanted

tripping of both lines. The coordination by distance and time observed here, will lead to nesting of the protection zones, as shown in Figure 3.4

It's worth noting that the 2nd zone of a distanced relay will be backing up of the distanced relay of adjacent line. But this is the case only for a portion of the adjoining line, dependent to the reach point distance of the 2nd zone. For the purpose of provisioning a backup function for the whole line, generally an additional protection zone is provided for the relay at A which represents the 3rd protection zone, extending 120 to 180 percent of the contiguous line section. The 3rd zone should counterpart in terms of time and distance with the second zone of the adjacent circuit; generally, the 3rd zone's acting time is set to 1 s order. Figure 3.3 shows the three protection zones of the two-line AB-BC sections.

We should have look to the limiting causes now. Firstly, a complexity is developed due to the unequal lengths of adjacent lines. In case, a bordering line's length is smaller than 19 percent of the line under protection, its zone 2 overreaches the 1st zone of the smaller line for sure. In a similar manner, zone 3 of the 1st line might overreach the zone 2 of the other line. The setting guides of the above reach zones must be taken as approximate, so that they can meet a certain situation possible. Zone 3 was primarily considered as the remote backup of zones 1 and 2 of the neighboring line should a relay or circuit breaker prevents locally from fault clearance. But upon reach regulation, characteristic of the zone 3 must provide protection vs. faults while avoiding operation for abnormal system conditions including heavy loads or stability fluctuations.

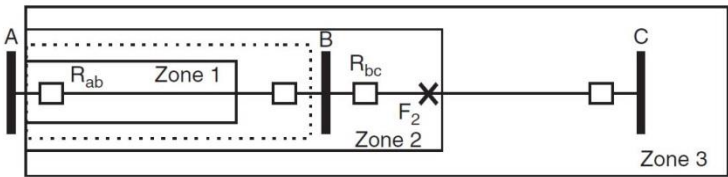


Figure 3.3 : Zones of protection.

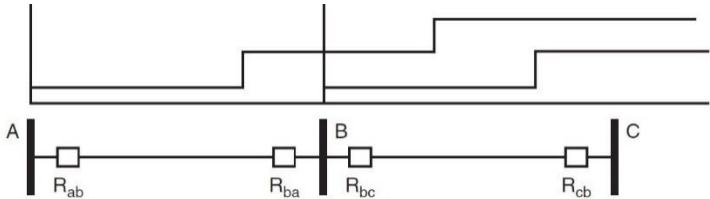


Figure 3.4 : Time-Distance diagram.

3.4 Characteristics of the Distance Relay

There are numerical relays that make measurement of the absolute fault impedance and decide if an operation is necessary in accordance with the boundaries of the impedance determined on the R/X diagram. But the conventional distance as well as analytical relays that imitate the components of historic relays is unable to assess the pure impedance. They only make a comparison between the measured voltage of fault and imitation voltage obtained from the current of fault and the zone impedance setting to decide whether the fault falls inward or farther of zone. Such impedance comparators or algorithms of distance relay impedance which can imitate the conventional comparators are categorized in accordance with their polar essence, signal inputs quantities and the technique through which the comparisons are affected.

The prevalent comparator types can correlate the analogous amplitude or phases of two input values to determine the acting characteristics which represent either solid lines or circles upon plotting on an R/X diagram. The establishment of impedance operating characteristic forms at each step of the distance relay designing evolution, and complexity is conducted by the technology available as well as the reasonably acceptable expenses.

3.4.1 Comparison of magnitude and phase

A comparator lies within the core of every protective relay. It produces a Boolean output (0 or 1) by receiving one or more analog input signals and gives.

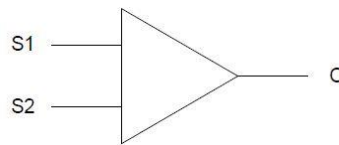


Figure 3.5 : Simple comparator.

A comparator in a distance component produces (1) as an output whenever the comparator characteristic impedance (Z_C) is “higher” than apparent impedance pertinent to a specific fault loop is. Ideally the distance relay comparator may take the following curve when it is illustrated in the impedance plane.



Figure 3.6: Ideal Distance Comparator.

For a number of reasons, the characteristics depicted in Fig. (5) cannot be employed in practical equipment. Due to the resistance characteristic of the fault, the apparent impedance having been measured at the relay cannot faithfully represent the fault location.

3.4.2 Plain impedance characteristic

This characteristic does not consider the angle of phase between among the current and voltage that are applied to it. Hence, the impedance characteristic of it when depicted on R/X graph represents a sphere, having its center at the coordinates origin and a radius identical in value to its setting in ohms. The procedure is performed for all the impedances that are lower than the regulated setting, in other words, all the points that fall inner of the sphere. Therefore, the R-X characteristics depicted in Fig. (11.7) is non-directional and will work for all types of faults in conjunction with the AL vector and also regarding the whole faults occurring trailing the busbars up to impedance AM. It is noteworthy that A is the relaying location and ARB establishes the angle by which the relay voltage leads the fault current of relative to a fault occurring on the line AB. RAC represents the corresponding leading angle relative to a fault occurring on the line AC. Vector AB is representing the relay forwarding impedance, among the relaying point A and end of the AB line. Vector AC denotes the impedance of line AC behind the relaying point. AL shows the reach of the immediate Zone 1 protection, adjusted to serve 80 to 85% of the protected line.

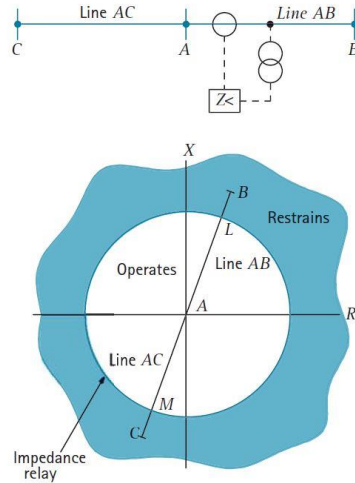


Figure 3.7: characteristic of the Impedance relay.

Using the above characteristic will put the relay at the following three major disadvantages:

- i) Being non-directional; it sees the faults in its direction and rear of the relaying point, hence, requiring a directional element to aid in correct segregation.
- ii) Non-uniformity of fault resistance inclusion.

A major discrimination quality for a distance relay is 'directional control' that makes the relay non-sensitive against faults happening farther of the protected line. Achieving this requires the adjoining of a distinct directional control component. A straight line on the R/X graph shows the impedance characteristic related to the control element. Hence the combination characteristic of the directional and impedance relays shall be the semi-circle APLQ demonstrated in in Figure 3.8.

In case a fault hits at the point F close to the point C on the parallel line CD, the directional unit RD at the point A shall restrain because of the current I_{F1} . In the meantime, the impedance unit shall be denied operating by prohibiting the output of the unit RD. If such a control is not available, the under-impedance component may operate before the opening of the circuit breaker C.

If the current is reversed via the relay from I_{F1} to I_{F2} upon opening of C, this can lead to disoperation and tripping of the sounded line in case the directional unit RD operates prior to resetting of the impedance unit.

This can be regarded as an example of the requirement for considering the appropriate coordination of several relay elements to achieve predictable performance of the relay during the evolution of fault circumstances.

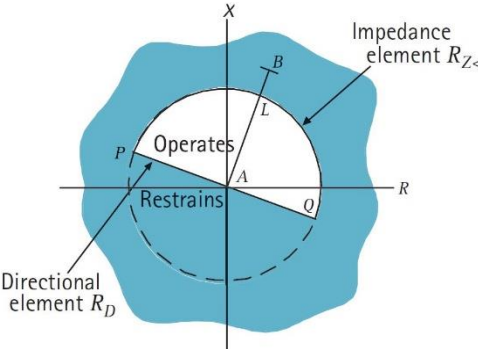


Figure 3.8: Characteristic of combined directional/impedance relay.

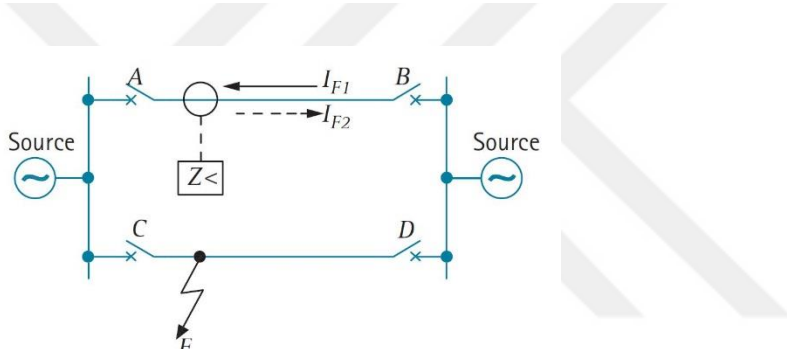


Figure 3.9: Circuit diagram for the usage of directional/impedance.

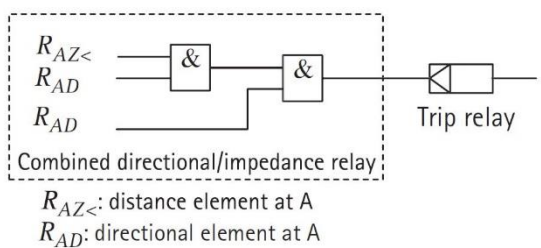


Figure 3.10 :Directional and impedance elements logic at A.

3.4.3 Self-polarized mho relay

A straight line on an admittance diagram illustrates the characteristic of a mho impedance element. It is able to combine the discriminating qualities of directional and range control, and thereby the ‘contact race’ problems that encountering by diverse reach and directional control elements is removed. By adding a polarizing

signal removing the aforesaid problems is achieved. Mho impedance elements are so favorable for economic reasons. Consequently, they have been widely utilized globally for many years and their advantages and defects are now well realized.

The impedance characteristic is regulated by adjusting Z_n , the impedance reach, along the diameter and ϕ , the angle of displacement of the diameter from the R axis. Angle ϕ is called as the Relay Characteristic Angle (RCA). The relay will operate for values of fault impedance Z_F that lie within its characteristic. It is mentioned that fault angle causes the variation of the impedance reach. The fault angle of the protected line will be dependent upon the corresponding values of R and X at the system operating frequency since comprise of resistance and inductance. During existence of an arcing fault, or happening of an additional resistance earth fault (tower footing resistance), the impedance angle is changed by an increase in the resistive component value of fault impedance. Hence under resistive fault conditions a relay angle that normally is equal to the line angle will under-reach. It is normal that the line angle be higher than the setting of the relay angle, in a way the relay could be able to detect a partial value of fault resistance without causing under-reach. But, identification of differential angle between the line angle θ and the relay characteristic angle ϕ is necessary. The resulting characteristic is illustrated in Figure 3.8 in which AB shows protected line length. With setting of the θ higher than ϕ , AB would be equivalent to:

$$AQ = \frac{AB}{(\theta - \phi)} \quad (3.11)$$

Because of the arc physical nature, its resistance is a nonlinear due to the non-linear relationship between the current and voltage of the arc. The formula of the value of arc resistance can be expressed as:

$$R_a = \frac{28710}{I^{3.4}} \quad (3.12)$$

$R_a = \text{arc resistance (ohms)}$

$L = \text{length of arc (meters)}$

$I = \text{arc current (A)}$

The arc resistance impact is negligible in long overhead lines carried by the towers with neutral and earth system. the earth fault resistance decrease the setting of the first zone and it is detected in the second zone of the Mho relay. This problem is usually

removed by the use of a relay with a cross-polarized mho or a polygonal characteristic.

As for the power system resistance-earthed, it must be noted that this does not require to be considered in respect of the relay settings other than the effect that declined fault current may produce on the value of arc resistance observed. The earthling resistance is present in the source behind the relay and can only modify the source angle and source to line impedance ratio for earth faults. It is therefore taken into account only when evaluating the relay performance in terms of system impedance ratio.



3.4.4 Quadrilateral characteristic

Adjustable forward reach and resistive reach settings provides the Quadrilateral characteristic which illustrates in Figure 3.11. however, resistive inclusion of this characteristic is superior than any mho-type characteristic in short lines. To avoid issuing excessive error signals in the zone reach accuracy, it is customary to impose a maximum resistive reach in terms of the zone impedance reach. Quadrilateral elements with plain reactance reach lines might arise reach error problems pertinent to the resistive earth faults where the angle of total fault current is different from the angle of the current measured by the relay. This is true where the local and remote source voltage vectors are phase shifted in relation to each other due to pre-fault power flow. This can be addressed by selecting an alternative to the utilization of a phase current for polarization of the reactance reach line. Polygonal impedance characteristics are extremely flexible in terms of fault impedance coverage in relation to both phase and earth faults. Accordingly, most digital and numerical distance relays now offer this form of characteristic. Another important factor is that the additional expenses of implementing this characteristic through discrete component electromechanical or early static relay technology do not arise.

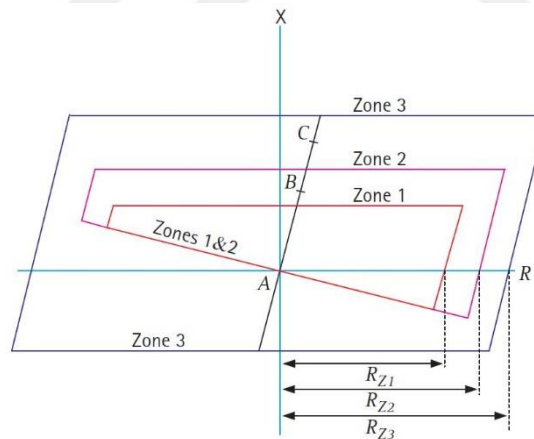


Figure 3.11: Quadrilateral characteristic.



4. MODELING AND ANALYSIS OF THE SINGLE-PHASE RECLOSING

4.1 General Outline

In this chapter, firstly the modeling of the 735 KV power transmission line is described and then the characteristic of the single phase autoreclosing in the modeled system during different study cases and fault locations is analyzed. The 735 KV power transmission line system is modeled in DIgSILENT software PowerFactory and the value of the parameters re in per unit at 60 Hz frequency and 2100 MVA base. The results are used for appropriate behavior analysis of the system.

4.2 Test Network

In Figure 4.1 Single-line diagram of the network under study is shown. In this study the generator voltage is set in 1 p.u and the External Grid model is used for the other side of the network connected to Bus 4. The voltage, the angle and the frequency of the external grid connected busbar is controlled automatically by external grid. The lumped π overhead type transmission line is used and its length is 600 km divided into two subsections.

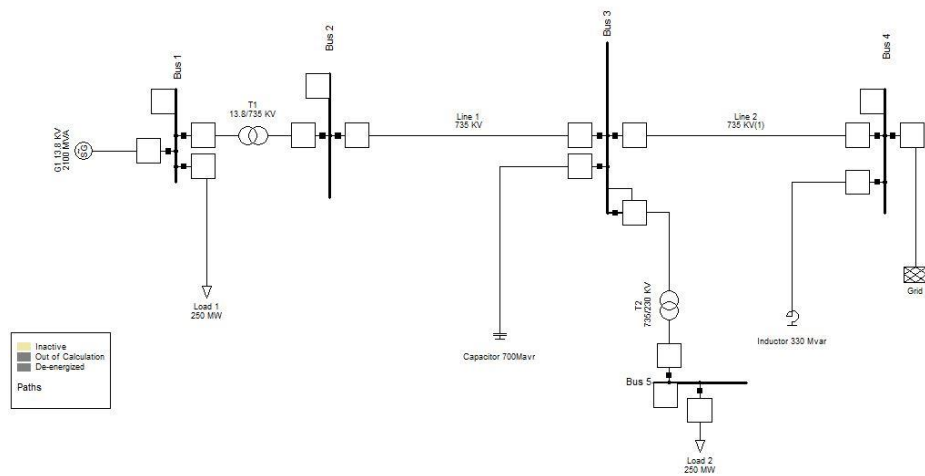


Figure 4.1: The configuration of Transmission Line system.

4.3 Basic Data and Characteristic

4.3.1 Generators

The 2100 MVA 13.8KV 60Hz Y connected round rotor generator by 0.8 PF is used in this system and the connected bus of the generator is chosen as PV bus.

Table 4.1 list the parameters related to the two-axis model of the synchronous machine used for the system.

Table 4.1: Generator parameters in 735KV transmission line system.

Unit No	V (P.U)	Ra (P.U)	X'd (P.U)	X'q (P.U)	Xd (P.U)	Xq (P.U)	T'do (sec)	T'qo (sec)	Xl (P.U)
1	1	0.006	0.21	0.34	2.01	1.89	1.08	0	0.22

4.3.2 Governors

Governors were designed to control the turbine speed and power by adjusting the input water flow entering the turbine. In old power plants, the mechanical and electromechanical governors were often used while in modern power plants, the electrical governors are used. The reasons to use governors in the power system are as follows:

- Active power adjusting
- Adjusting the changes of turbine valves to keep the turbine rotation speed and generator rotor in synchronous speed rate under any conditions.

When P_{ref} changes in the power systems, the governors change the steam valve to change the output mechanical power (P_m). Regardless of the loss, if the output mechanical power is bigger than the output electrical power (P_e), the generator rotation speed will increase and the governors will feel this speed change. Thus, they will turn the steam valve off to reduce the output power and if the output mechanical power is smaller than the output electrical power, the generator rotation speed will reduce and the governors will be forced to turn the steam valve on. Then, in the general mode, the generator rotation speed has a direct relationship to the product frequency of the generator.

In this simulation, the governor of gov-IEEE G1 type was used for generator. All parameters related to the governors are based on IEEE standard.

4.3.3 Automatic voltage regulator (AVR)

AVR systems are used in the power system to adjust the voltage. AVRs usually have a slow response and due to the high values of rheostat, the switching resistances and moving connections. So for changing the status of moving parts need enough time.

Based on the Figure 4.3, the AVRs adjust the Exciter output power to control the terminal voltage (V_t). When the reference voltage changes, the AVR output voltage (V_R) changes exciter output voltage (E_{fd}) resulting in terminal voltage change. In order to control the terminal voltage changes, the voltage transformers or rectifiers are used. If terminal voltage reduces, the AVR increases its output voltage. Consequently, E_{fd} and V_t increase. In this simulation, the AVR of avr-IEEE1 type was used.

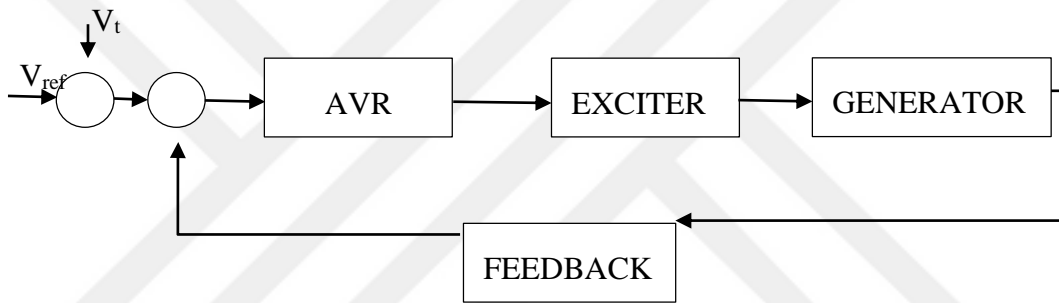


Figure 4.2 : Block diagram of power generation unit.

4.3.4 Lines/Transformers

Table 4.2 provides the network line data used for the system. All values are expressed in the same MVA base.

Table 4.2: Line data for 735 KV transmission line system.

From bus	To bus	Line data		
		R	X	B
2	3	0,01273	0,35199	0
3	4	0,01273	0,35199	0

Table 4.3: Transformer data for 735 KV transmission line system.

No	HV	LV	Transformers data				Connection
			$R_{(HV)}$	$X_{(HV)}$	$R_{(LV)}$	$X_{(LV)}$	
1	735	13.8	0,90	0,92	0,1	0,079 9	YNd0
2	735	230	0,002	0,15	0,998	0,85	YNd0

4.3.5 Load characteristics

Table 4.4 lists the load parameters of the test system. All the loads are also delta connected in this system in order to reduce the harmonic during normal conditions.

Table 4.4: Load data for 735 KV transmission line system.

Load	P(MW)
1	250 MW
2	250 MW

4.3.6 Shunt Reactors and Capacitors

Since the voltage of the transmission line systems ending bus due to the shunt capacitance effect depends on type of transmission line, length of line and line voltage. (Ferranti effect). The Shunt reactors are designed for connection to the ends of high voltage transmission lines or to high-voltage cables by absorbing reactive power. For the purpose of controlling the line voltage.

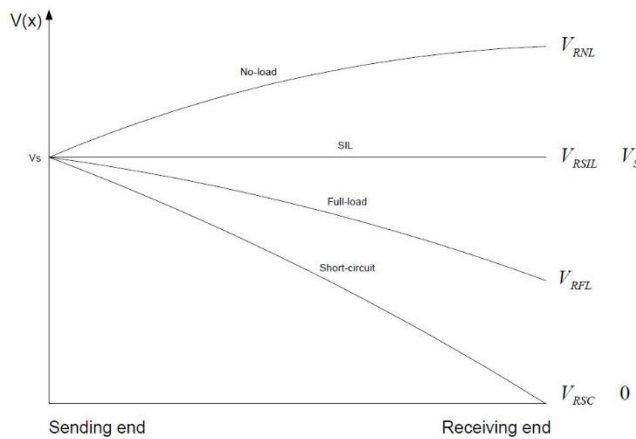


Figure 4.3: Voltage profiles of an uncompensated line.

Table 4.5: Reactor and Capacitor data for 735 KV transmission line system.

Bus No	Q(Mvar)
1	700 Mvar (C)
2	330 Mvar (L)

4.4 Load Flow Results

A load flow was carried out using Power factory 15.1 software. The obtained results are illustrated in the Table 4.6. It is worth to note that all values of voltages and active and reactive powers are indicated in per unit in the same MVA base.

Table 4.6: Load flow results of 735 KV transmission line system.

		DigSILENT PowerFactory 15.1.7		Project:735KV Transmission Date: 4/25/2019				
Load Flow Calculation				Busbars/Terminals				
AC Load Flow, unbalanced, 3-phase (ABC) Automatic Tap Adjust of Transformers Consider Reactive Power Limits			Yes Yes	Automatic Model Adaptation for Convergence Max. Acceptable Load Flow Error for Nodes Model Equations				
				No 1,00 kVA 0,10 %				
Grid: Grid		System Stage: Grid		Study Case: 735 KV				
				Annex: / 1 //				
rated Voltage [kV]	Bus-voltage [kV]	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [kA]	Loading [%]	Additional Data	
[p.u.]	[deg]							
Bus 2 735,00	0,99 420,53 0,99 420,55 0,99 420,39	28,91 -91,10 148,91						
Cub_1 /Lne	Line 1	A 465,32 B 465,56 C 465,33	39,50 39,50 40,53	1,00 1,00 1,00	1,11 1,11 1,11	11,14 11,14 11,14	Pv: 4600,96 kW Pv: 4590,74 kW Pv: 5021,17 kW	cLod: -0,00 Mvar cLod: -0,00 Mvar cLod: -0,00 Mvar
Cub_1 /Tr2	T1	A -466,56 B -466,80 C -466,57	-39,50 -39,50 -40,53	-1,00 -1,00 -1,00	1,11 1,11 1,11	67,65 67,65 67,65	Tap: 0,00	Min: -2 Max: 2
Bus 3 735,00	0,99 420,80 0,99 420,76 0,99 421,10	12,79 -107,17 132,82						
Cub_1 /Lod	General Load	A 0,48 B 0,40 C 0,42	109,98 109,97 110,06	0,00 0,00 0,00	0,26 0,26 0,26		P10: 0,00 MW P10: 0,00 MW P10: 0,00 MW	Q10: 0,00 Mvar Q10: 0,00 Mvar Q10: 0,00 Mvar
Cub_1 /Shnt	Capacitor 700	A 0,38 B 0,38 C 0,38	-229,45 -229,40 -229,77	0,00 0,00 0,00	0,55 0,55 0,55			
Cub_1 /Lne	Line 1	A -460,72 B -460,97 C -460,30	91,66 91,29 90,51	-0,98 -0,98 -0,98	1,11 1,11 1,11	11,14 11,14 11,14	Pv: 4600,96 kW Pv: 4590,74 kW Pv: 5021,17 kW	cLod: -0,00 Mvar cLod: -0,00 Mvar cLod: -0,00 Mvar
Cub_1 /Lne	Line 2	A 375,15 B 375,91 C 376,01	14,44 14,51 15,29	1,00 1,00 1,00	0,89 0,89 0,89	8,94 8,94 8,94	Pv: 3026,35 kW Pv: 3050,92 kW Pv: 3065,15 kW	cLod: -0,00 Mvar cLod: -0,00 Mvar cLod: -0,00 Mvar
Cub_1 /Tr2	T2	A 83,47 B 83,04 C 83,50	13,38 13,64 13,91	0,99 0,99 0,99	0,20 0,20 0,20	63,98 63,98 63,98	Tap: 0,00	Min: 0 Max: 0

Table 4.6 (continued): Load flow results of 735 KV transmission line system.

Grid: Grid		System Stage: Grid		Study Case: Study Case			Annex:		/ 2	
rated Voltage [kV]	Bus-voltage [p.u.] [kV]	deg	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [kA]	Loading [%]	Additional Data		
Bus 4 735,00	1,00 424,34 1,00 424,30 1,00 424,42	-0,01 -119,99 120,00								
Cub_1 /Shnt	Inductor 330	A B C	0,00 0,00 -0,00	109,99 109,97 110,03	0,00 0,00 -0,00	0,26 0,26 0,26				
Cub_1 /Xnet	Grid	A B C	-372,12 -372,86 -372,94	179,62 179,86 179,08	-0,90 -0,90 -0,90	0,97 0,98 0,97		Sk":10000,00 MVA		
Cub_1 /Lne	Line 2	A B C	-372,12 -372,86 -372,94	69,63 69,89 69,05	-0,98 -0,98 -0,98	0,89 0,89 0,89	8,94 8,94 8,94	Pv: 3026,35 kW Pv: 3050,92 kW Pv: 3065,15 kW	cLod: -0,00 Mvar cLod: -0,00 Mvar cLod: -0,00 Mvar	L: 300,00 km
Bus 1	13,80	1,00 7,97 1,00 7,97 1,00 7,97	33,16 -86,85 153,15							
Cub_1 /Sym	G1 13.8 KV	A B C	499,71 500,40 499,90	78,28 78,23 78,85	0,99 0,99 0,99	63,48 63,57 63,53	72,30 72,30 72,30	Typ: PV		
Cub_3 /Lod	Load 1	A B C	33,34 33,33 33,33	0,00 -0,00 0,00	1,00 1,00 1,00	4,18 4,18 4,18		P10: 33,33 MW P10: 33,33 MW P10: 33,33 MW	Q10: 0,00 Mvar Q10: 0,00 Mvar Q10: 0,00 Mvar	
Cub_2 /Tr2	T1	A B C	466,37 467,06 466,57	78,27 78,24 78,85	0,99 0,99 0,99	59,35 59,44 59,40	67,65 67,65 67,65	Tap: 0,00	Min: -2	Max: 2
Bus 5	230,00	0,99 131,48 1,00 132,61 0,99 130,97	11,99 -107,38 132,75							
Cub_1 /Lod	Load 2	A B C	83,20 83,92 82,88	-0,67 0,24 0,43	1,00 1,00 1,00	0,63 0,63 0,63		P10: 0,00 MW P10: 0,00 MW P10: 0,00 MW	Q10: 0,00 Mvar Q10: 0,00 Mvar Q10: 0,00 Mvar	
Cub_2 /Tr2	T2	A B C	-83,20 -83,92 -82,88	0,67 -0,24 -0,43	-1,00 -1,00 -1,00	0,63 0,63 0,63	63,98 63,98 63,98	Tap: 0,00	Min: 0	Max: 0

					DigSILENT	Project:
					PowerFactory	
					15.1.7	Date: 4/25/2019

Load Flow Calculation	Complete System Report: Voltage Profiles, Grid Interchange	
AC Load Flow, unbalanced, 3-phase (ABC)	Yes	Automatic Model Adaptation for Convergence No
Automatic Tap Adjust of Transformers	Yes	Max. Acceptable Load Flow Error for Nodes 1,00 kVA
Consider Reactive Power Limits	Yes	Model Equations 0,10 %

Grid: Grid	System Stage: Grid		Study Case: Study Case		Annex:		/ 1	
rtd.V [kV]	Bus - voltage [p.u.] [kV]	deg	-10	-5	Voltage - Deviation [%]		+5	+10
BUS-1								
Bus 2	735,00	0,991	728,45	28,91				
BUS-2								
Bus 3	735,00	0,992	728,60	12,79				
BUS-3								
Bus 4	735,00	1,000	734,89	-0,01				
Bus 1	13,80	1,000	13,80	33,16				
Bus 5	230,00	0,990	227,98	11,99				

Table 4.6 (continued): Load flow results of 735 KV transmission line system.

Grid: Grid		System Stage: Grid				Study Case: Study Case		Annex:		/ 2
Volt. Level	Generation [MW]/ [Mvar]	Motor Load [MW]/ [Mvar]	Load [MW]/ [Mvar]	Compensation [MW]/ [Mvar]	External Infeed [MW]/ [Mvar]	Interchange to	Power Interchange [MW]/ [Mvar]	Total Losses [MW]/ [Mvar]	Load Losses [MW]/ [Mvar]	NoLoad Losses [MW]/ [Mvar]
13,80	1500,00 235,36	0,00 0,00	100,00 0,00	0,00 0,00	0,00 0,00			0,00 0,00	0,00 0,00	0,00 0,00
						735,00 kV	1400,00 235,36	0,08 115,82	0,05 105,34	0,03 10,48
230,00	0,00 0,00	0,00 0,00	250,00 0,00	0,00 0,00	0,00 0,00			0,00 0,00	0,00 0,00	0,00 0,00
						735,00 kV	-250,00 -0,00	0,01 40,93	0,00 1,60	0,01 39,34
735,00	0,00 0,00	0,00 0,00	1,30 330,00	1,13 -688,62	-1117,93 538,56			29,56 645,79	29,56 645,79	0,00 0,00
						13,80 kV	-1399,92 -119,54	0,08 115,82	0,05 105,34	0,03 10,48
						230,00 kV	250,01 40,93	0,01 40,93	0,00 1,60	0,01 39,34
Total:	1500,00 235,36	0,00 0,00	351,30 330,00	1,13 -688,62	-1117,93 538,56		0,00 0,00	29,65 802,55	29,61 752,73	0,04 49,82

Table 4.7: Load flow results in 735 kV transmission system.

Bus	Voltage (P.U.)	Angle(deg)
1	1	33.16
2	0.991	28.91
3	0.992	12.79
4	1	-0.01
5	0.990	11.36

Tables 4.6 and 4.7 represents the load flow analysis of 735KV transmission system, which consists of 1 generator, 2 loads, 2 lines and 2 Transformers. The nominal frequency of the transmission system is 60 Hz and the mains voltage level are 735 kV (nominal voltage).

4.5 EMT (Electromagnetic Transient) Simulation During Normal Condition

In this part an EMT simulation kernel is used in the purpose of calculating time domain transient voltages and currents of the lines and buses during normal operation.

The results are shown in figure 4.4 and Figure 4.5. voltages are shown as phase voltage an in their peak values and RMS values are obtained by:

$$V_{rms} = \frac{V_m}{\sqrt{2}} \times \sqrt{3} \quad (4.1)$$

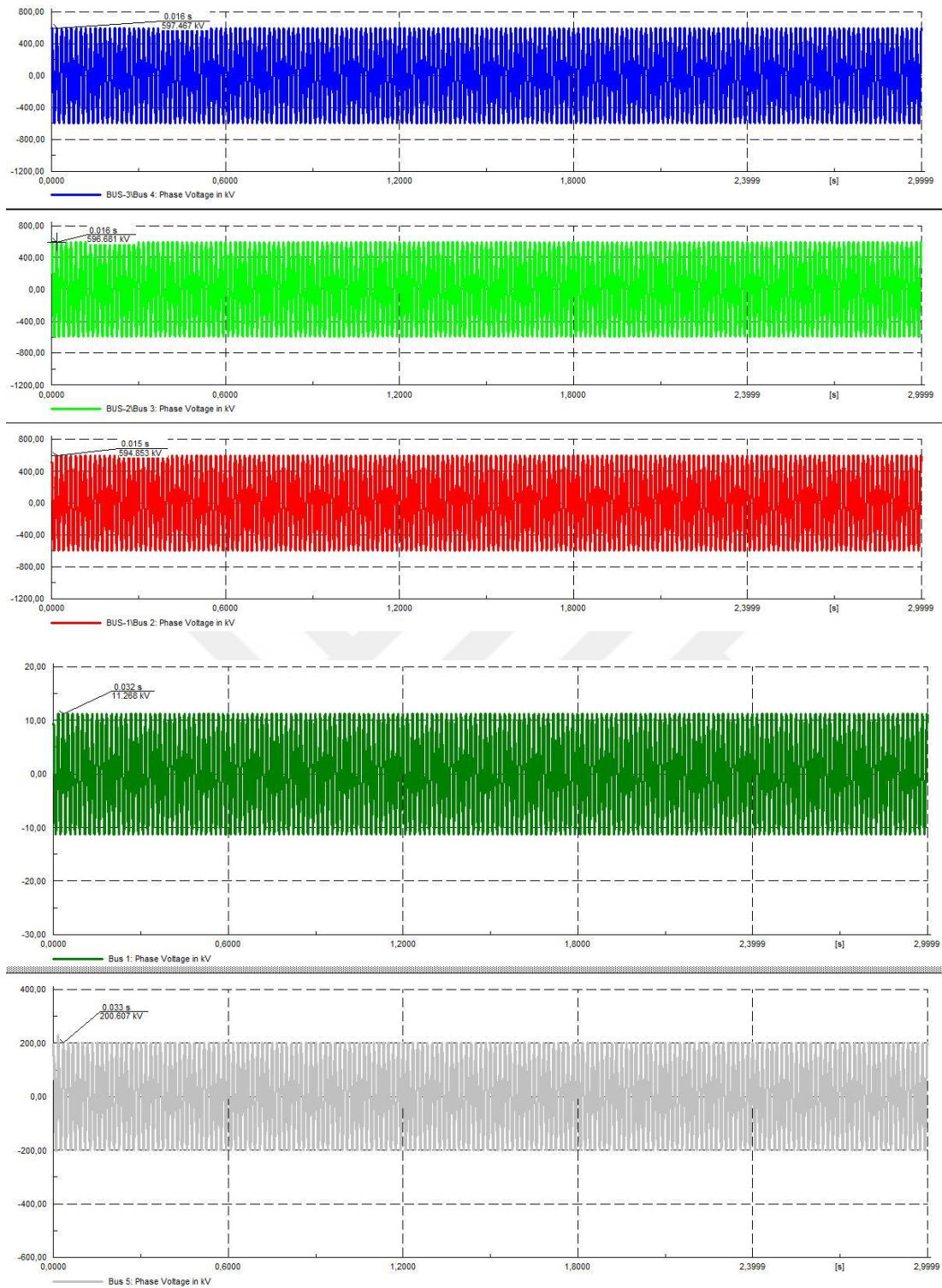


Figure 4.4: Phase voltages at buses.

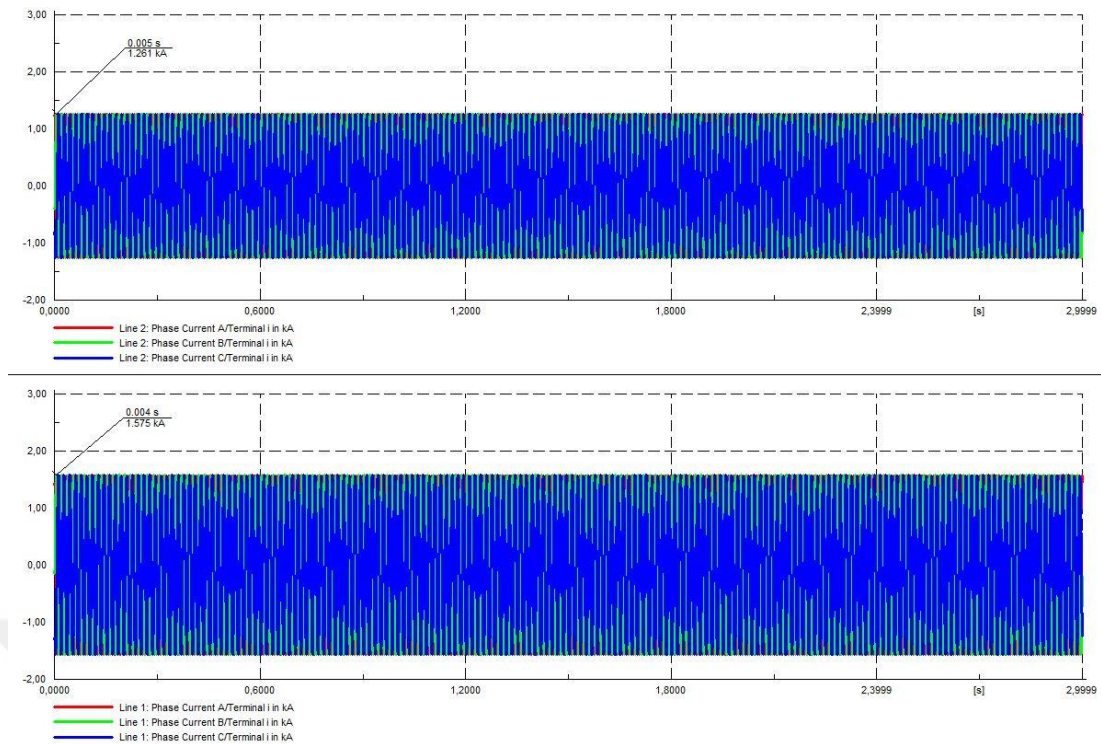


Figure 4.5: Phase currents at lines 1 and 2.

4.6 Transmission line protection

The distance relay SIEMENS 7SA522 is used in this study and is implemented at the two ends of the transmission lines 1 and 2 to detect the all the faults happened in transmission system. Fast and selective fault clearance on transmission and cables and overhead lines is provided by this relay. Some of the features of this relay is:

- High-speed tripping time
- Detection of Self-setting power swing d for frequencies up to 7 Hz
- Adaptive auto-reclosing (ADT)

Supporting various protocols for connecting to control system

- IEC 61850 Ethernet
- IEC 60870-5-103 protocol
- PROFIBUS-FMS/-DP
- DNP 3.0
- 2 serial protection data interfaces for tele (pilot) protection

– Time synchronization via

In distance protection impedance is measured using CTs and PT and determine the fault impedance at the place where the relay is installed by measuring the short circuit voltage and current.

In this study three zone protection and 1 reversal protection with backup instantaneous protection is employed to provide lines 1 and 2 and also busbars protection during unintentional various faults.

by using load flow calculation, the currents and voltages are obtained and CT and CVT settings calculated.

Table 4.7: CT and VT settings in 735 kV transmission system

Line	I(A)	CT(A)	CVT(V)
1	1114	1200/1	735000/100
2	892	1000/1	735000/100

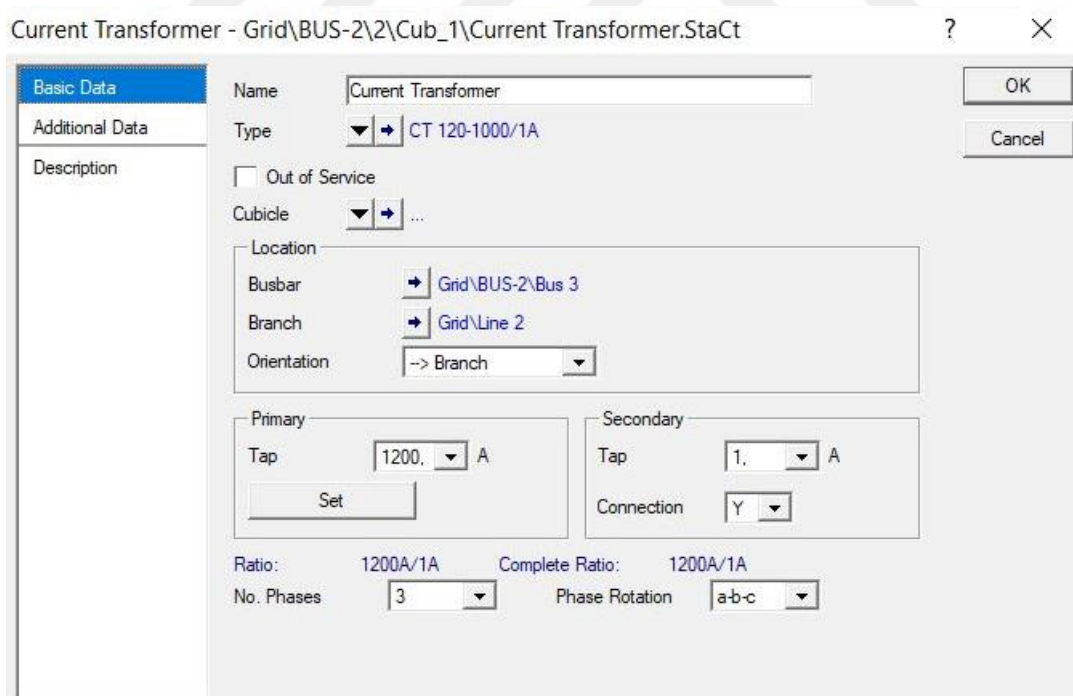


Figure 4.6: CTs setting.

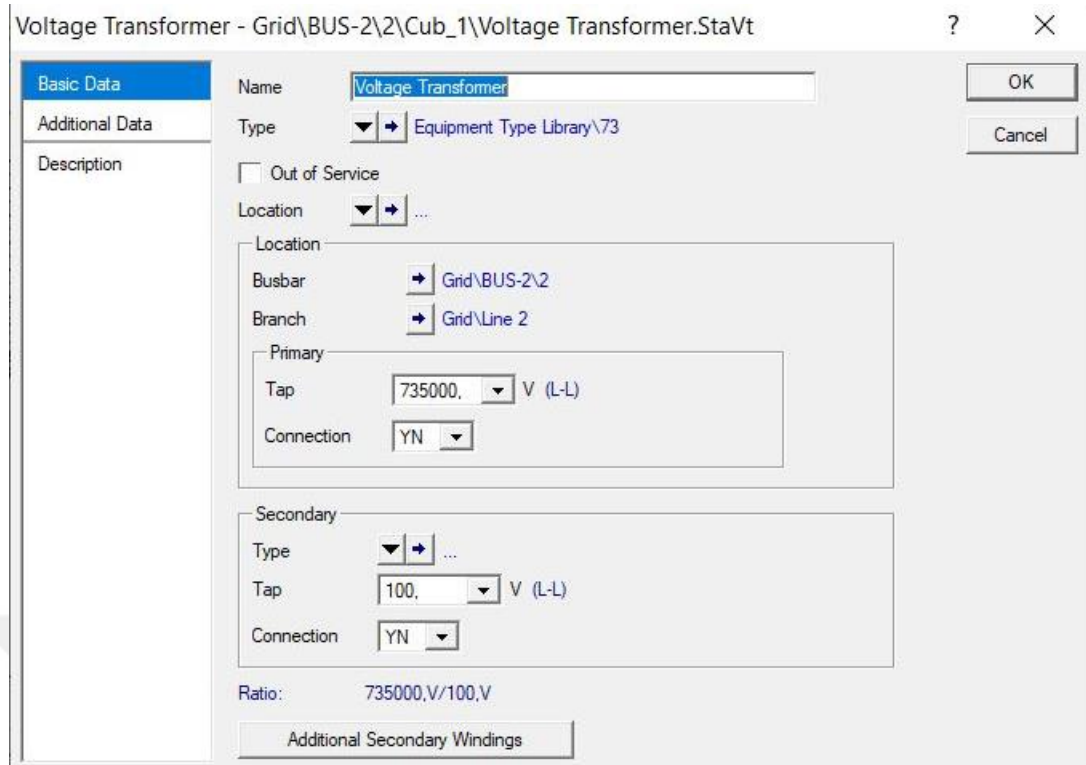


Figure 4.7: CVTs Setting.

it is impractical to set the protection to 100% of the line length due to the imprecisions in distance measurement, caused by transformation and measurement, and line impedance inaccuracies errors. For setting the under-reaching zone (1st zone) a security boundary (10 % -15 %) from the remote end of the line must be considered in order to guarantee protection selectivity. The rest of the line are covered by an over-reaching zone (2nd zone) which, should have a time delay of 250-300 ms by considering protection of the adjacent line to avoid overlapping. This time delay incorporates the tripping time of the circuit-breaker, delay of the distance measuring elements along with the security restrain.

The first zone of protection is chosen to the 80% of the line 1 for R12.

$$Z_{L1.sec} = \frac{N_{CT}}{N_{CVT}} \times Z_{L1.Pri} \quad (4.2)$$

$$Zone\ 1 = 0.8 \times Z_{L1.sec}$$

$$Zone\ 2 = 1.2 \times Z_{L1.sec}$$

$$Zone\ 3 = Z_{L1.sec} + 0.5 Z_{L2.sec}$$

4.6.1 Zero-sequence compensation factor (K0)

In single line to ground faults, proper operation of the distance relay is not guaranteed by the positive sequence impedance of the remote end and relay, since the impedance calculated is not equal to the positive-sequence impedance due to the impact of zero-sequence current. However, the zero-sequence compensation factor (K0) is defined to compensate the zero-sequence current and correct operation of the grounding element is provided.

K0 factor is mainly expressed as:

$$K_0 = (Z_0 - Z_1) / KZ_1 \quad (4.3)$$

where

Z1: The impedance of the positive-sequence from relay to the fault location.

Z0: zero-sequence line impedance from relay to the fault location.

K: can be equal to 1 or 3, depending on the relay design.

K0 value is unique which is depended on the line type and values for Z1 and Z0.

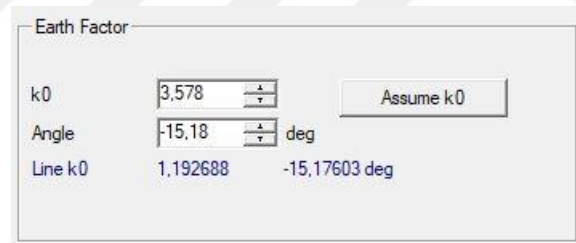


Figure 4.8: Earth compensation factor of the transmission system.

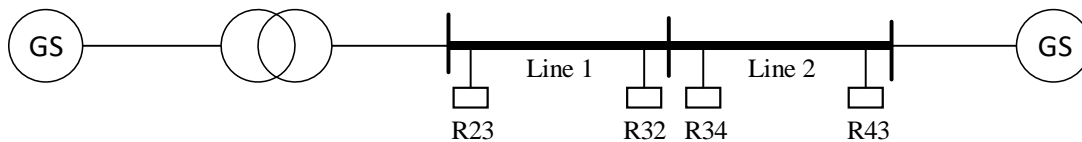


Figure 4.9: Single Line diagram of the transmission system.

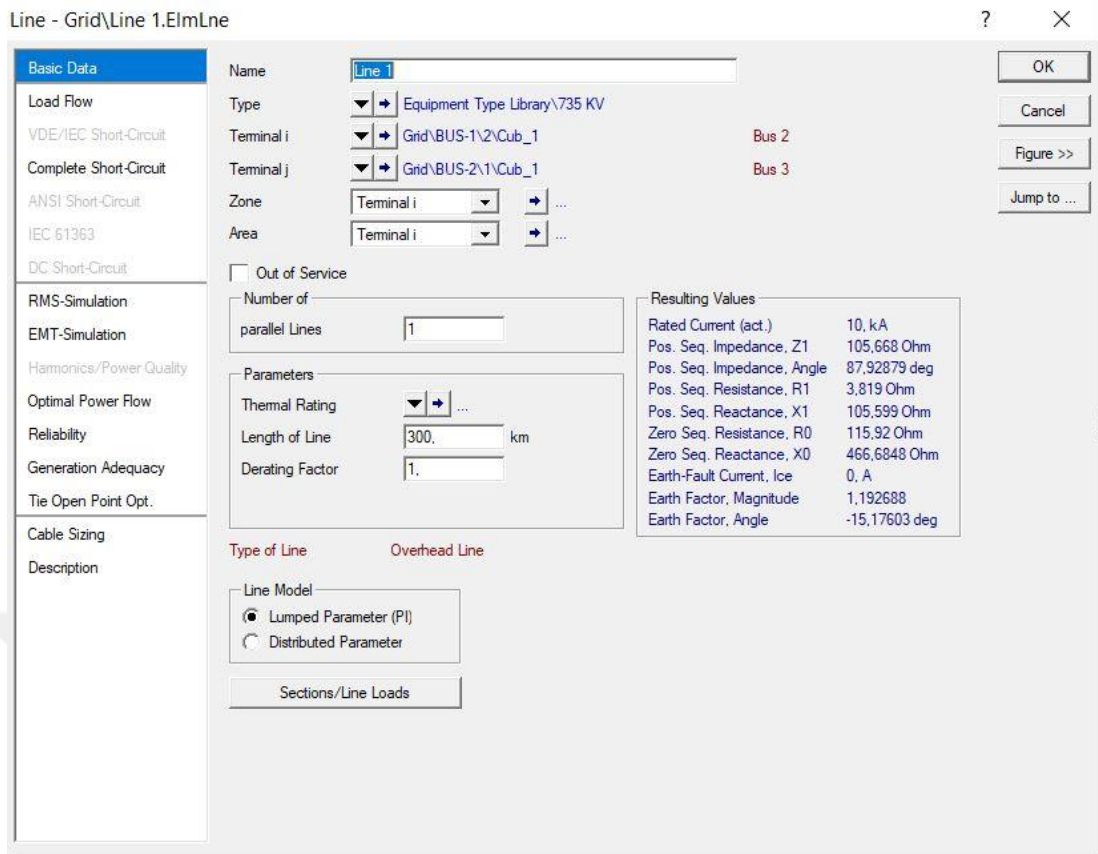


Figure 4.10: Line Parameters and impedance.

The first zone is acts instantaneously and send a trip signal to the related CB to open with time setting of $t=0$ s. The relay will instantaneously send trip signal to open the circuit breaker If a fault happens within main protection relay. The second zone time delay is 400 ms since it acts as a backup protection for the main protection of the adjacent line. A time delay of 800 ms is supposed for the third zone of protection.

Characteristic of R-X Plots for R23, R32 which are located at the two ends of the transmission line 1 and R34, R43 for the transmission line 2 are illustrated in figure 4.10 and figure 4.11.

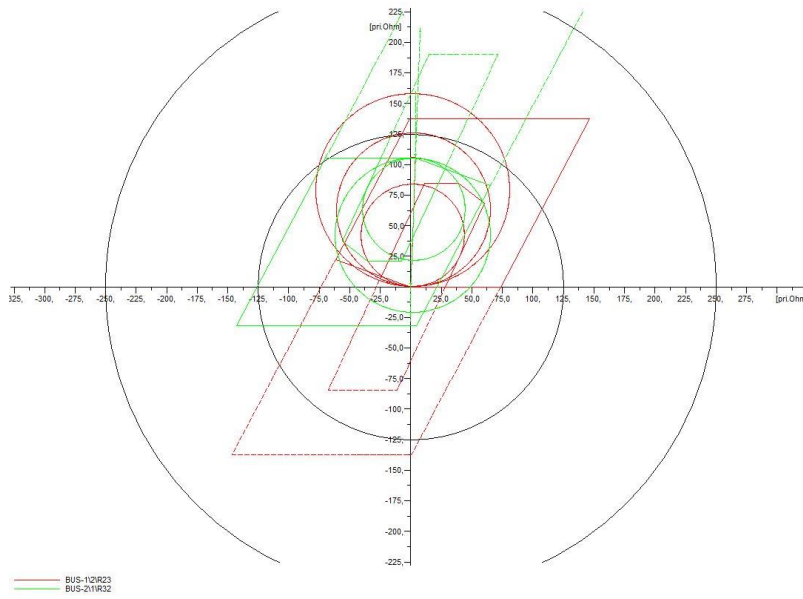


Figure 4.11: The R-X plot for the R23 and R32 relays.

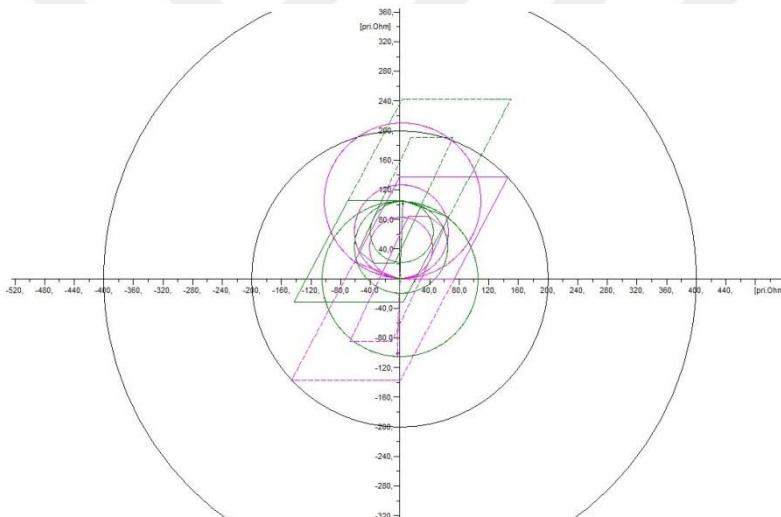


Figure 4.12 : The R-X plot for the R34 and R43 relays.

The Time-Distance diagram of the relays also is mapped out in figure 4.12. The Time-Distance diagram indicates relays tripping times as a function of the short-circuit location.

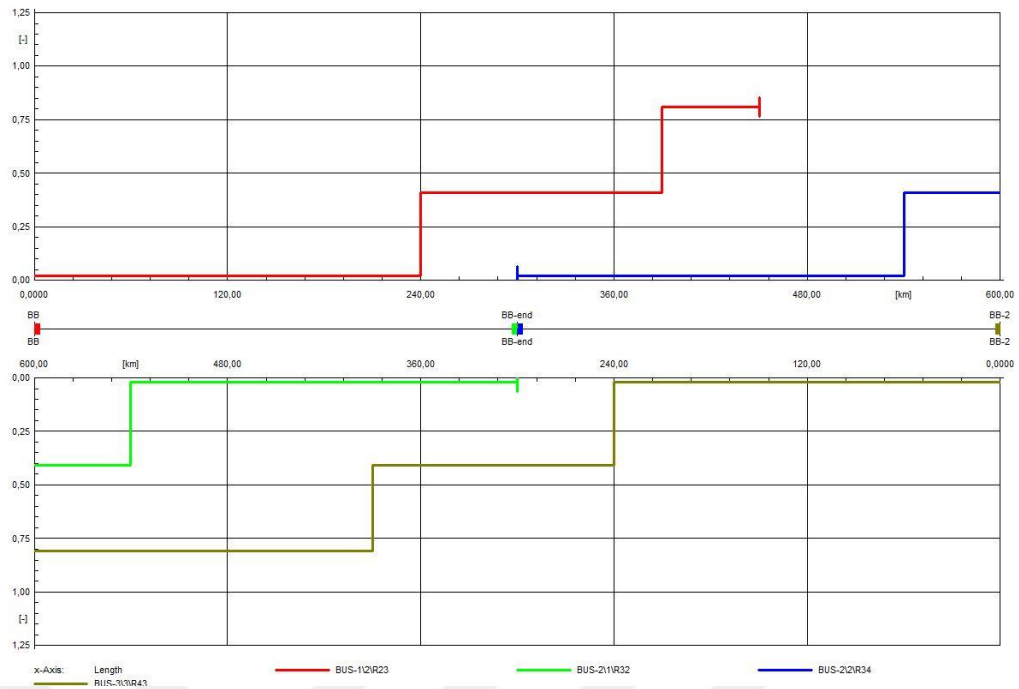


Figure 4.13: The Distance - Time diagram of the relays.

4.7 Short-Circuit Analyses

In this part, 4 different single line to ground faults in different locations of the transmission line is studied and the results obtained from short –circuit analyses and EMT transient simulation are shown as below. The short circuit analysis is based on the complete method and the break time for all types of faults is 100 ms.

- *Study Case 1:* in this study case a single phase to ground fault with solid fault impedance is simulated at 15% percent of the line 1 and due to the R-X plot it is detected in $t = 20$ ms in the first zone of the R23 and in the second zone of the R32 in $t = 410$ ms. It means that the relays are located correctly and clear the fault at 20 ms.

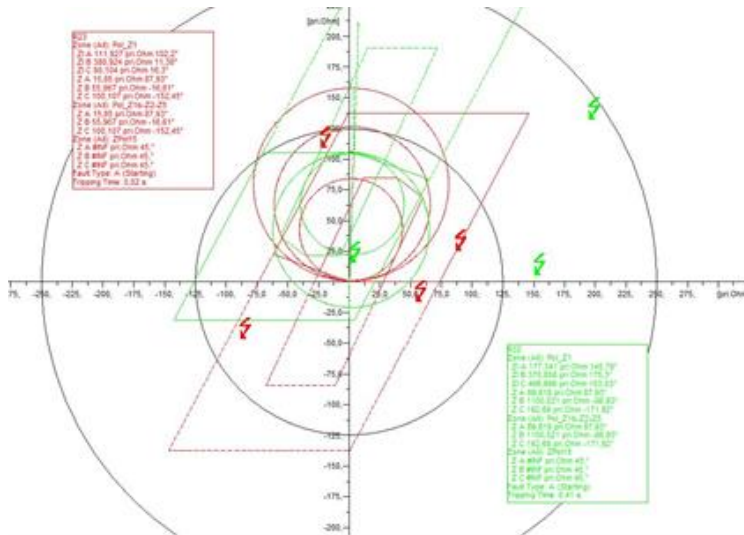


Figure 4.14: The R-X plot of R23 and R32 during single phase to ground short-circuit at 15% of line 1 without autoreclosing.

Table 4.8 : Short circuit voltages and currents at phases.

Phase	Voltage		Initial SC current		Peak SC current (KA)
	KV	Degree	KA	Degree	
Phase A	0	0	5,61	-51,54	15.16
Phase B	401,92	-100,09	0	0	0
Phase C	491,84	146,88	0	0	0

Study Case 2: The first study case is repeated at 50% percent of the line 1 and due to the R-X plot it is detected in $t = 20$ ms in the 1st zone of the R23 and in the 1st zone of the R32 in $t = 20$ ms. It means that the relays are located correctly and clear the fault at 20 ms.

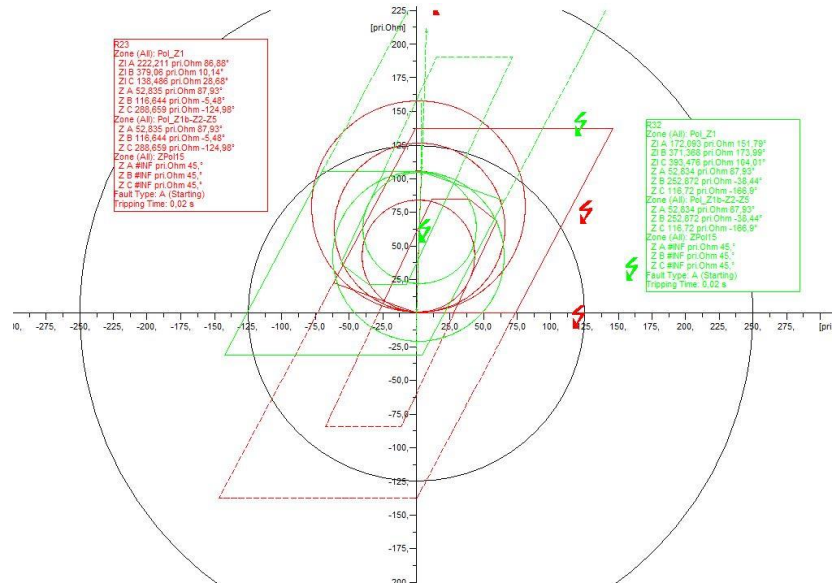


Figure 4.15 : The R-X plot of R23 and R32 during single phase to ground short-circuit at 50% of line 1 without autoreclosing.

Table 4.9: Short circuit voltages and currents at phases.

Phase	Voltage		Initial SC current		Peak SC current (KA)
	KV	Degree	KA	Degree	
Phase A	0	0	4,05	-59,37	10.87
Phase B	439,33	-109,31	0	0	0
Phase C	487,49	147,35	0	0	0

Study Case 3: Like the aforementioned cases the single phase to ground fault simulated at 90% of the line 1 and due to the R-X plot it is detected in $t = 410$ ms in the 1st zone of the R23 and in the 1st zone of the R32 in $t = 20$ ms.

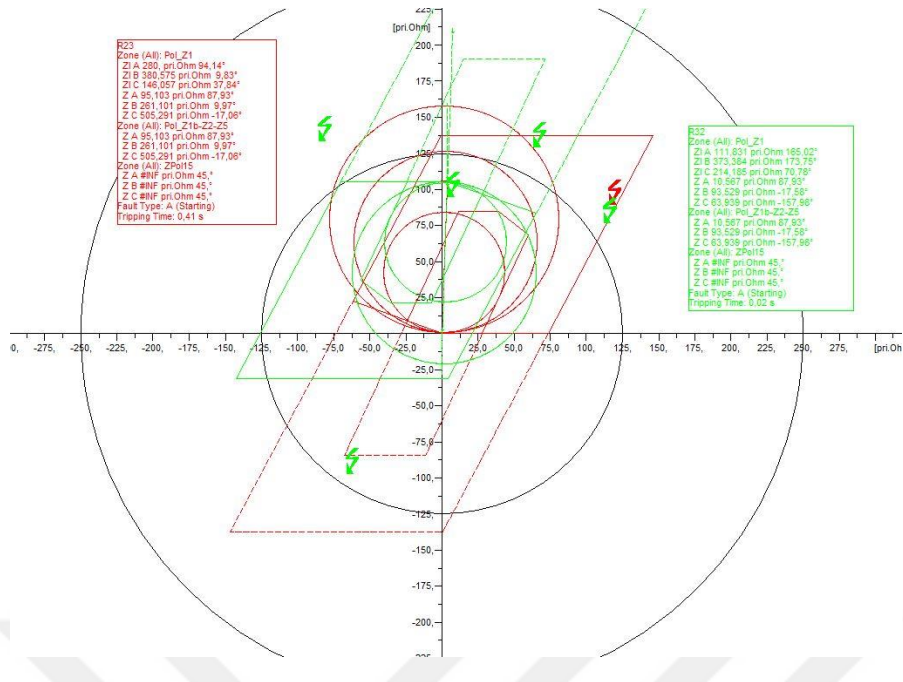


Figure 4.16: The R-X plot of R23 and R32 during single phase to ground short-circuit at 90 % of line 1 without autoreclosing.

Table 4.10: Short circuit voltages and currents at phases.

Phase	Voltage		Initial SC current		Peak SC current (KA)
	KV	Degree	KA	Degree	
Phase A	0	0	4,79	-68.97	12.74
Phase B	404.57	-104,36	0	0	0
Phase C	420.60	132.50	0	0	0

Study Case 4: in this case, the single phase to ground fault is considered at the bus 3 and R23 and R43 relay will operate to open the related circuit breakers and clear the fault. The fault is located in the second zone of the relays and both of them will operate at t=410 ms.

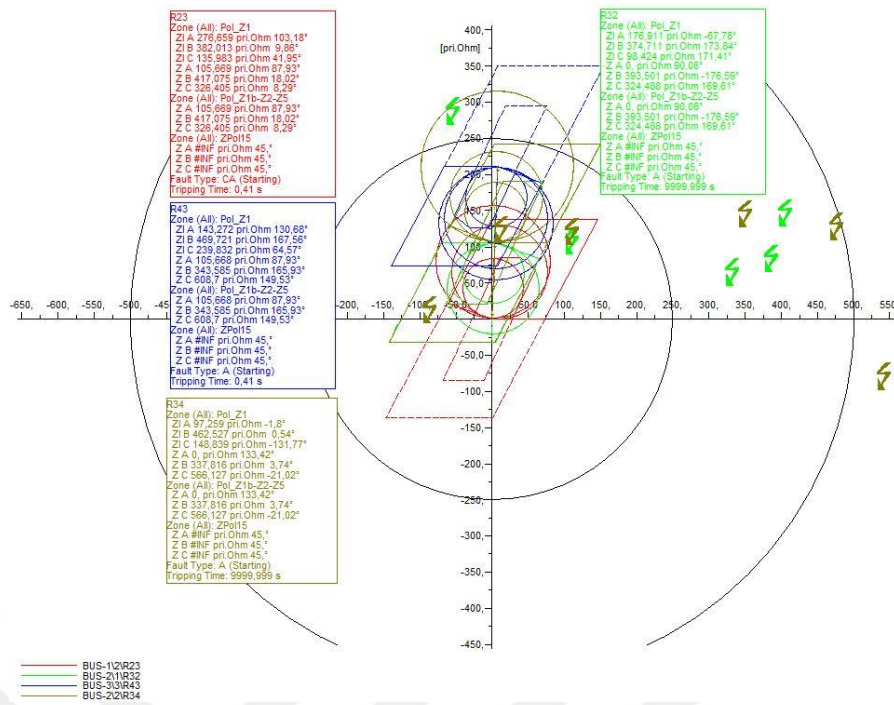


Figure 4.17: The R-X plot of R23 and R32 during single phase to ground short-circuit at Busbar 3.

Table 4.11: Short circuit voltages and currents at phases.

Phase	Voltage		Initial SC current		Peak SC current (KA)
	KV	Degree	KA	Degree	
Phase A	0	0	5.55	-72.11	14.72
Phase B	391.58	-96.54	0	0	0
Phase C	381.85	132.04	0	0	0

4.8 Auto-reclosing Simulation and Analysis

In this part, the autoreclosing function of the SIEMENS 7SA522 is used to analyze the behavior of the single-phase auto reclosing in EHV systems like 735 KV transmission systems. Different scenarios are assessed in this part and different fault locations and considerations for fault clearing time are examined. After the operation of the protective relay and circuit breakers opening, deionization time is required to reclose the circuit breakers called Dead time. Dead time is defined as the interruption between the circuit breakers opening and reclosing of the circuit breakers to resume the transmission line power.

$$t = 10.5 + \frac{KV}{34.5} \quad (4.4)$$

For 735 kV lines, the dead time is about 0.45 sec or 32 cycles. But this is for the three-phase enclosure where the simultaneous tripping of the three phase is needed. For the single-phase reclosing is approximately about twice as long as the three phase reclosure and about 1 second or 66 cycles, but it depends on the length and circuit configuration of the transmission line. The simulation step size is 0.05 ms or 20 KHz.

- *Scenario 1:* First a single phase to ground fault is occurred in 30% of the line at time $t = 0.5$ sec and the protection system is deactivated.

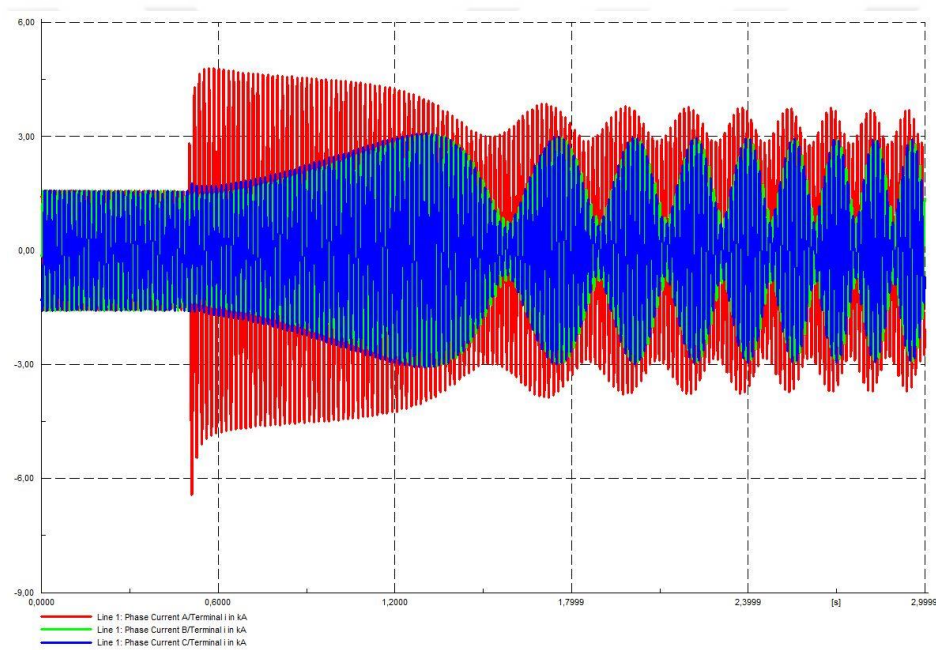


Figure 4.18: Phase currents during single phase to ground fault at 30% of the line 1 without autoreclosing.

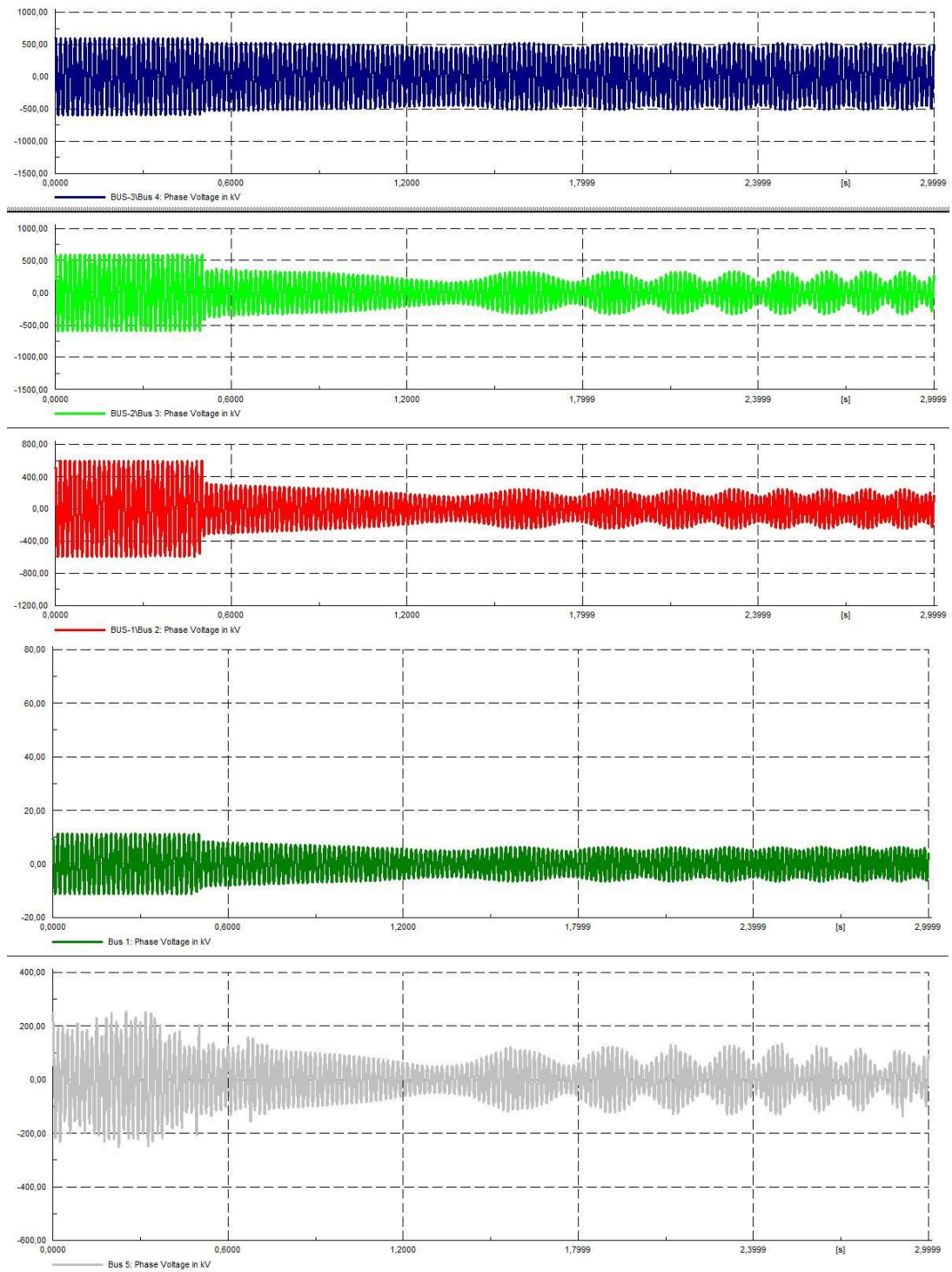


Figure 4.19: Bus voltages during single phase to ground fault at 30% of the line1.

Table 4.12: Bus voltages in single phase to ground fault at 30% of the line 1.

Bus No	Rated Voltage (KV)	Voltage (KV)
1	13.8	11.35
2	735	543.92
3	735	668.51
4	735	875.46
5	230	209.39

By activating protection relays it has seen that the relays R23 and R32 send tripping signals to the circuit breakers for opening the faulty phase at $t=523$ ms and 23 ms after occurring the fault and then by increasing currents in two other sound phases, relays trip and circuit breakers will open at $t= 1.032$ s to protect the rest of the system from overheating and overcurrent problems.

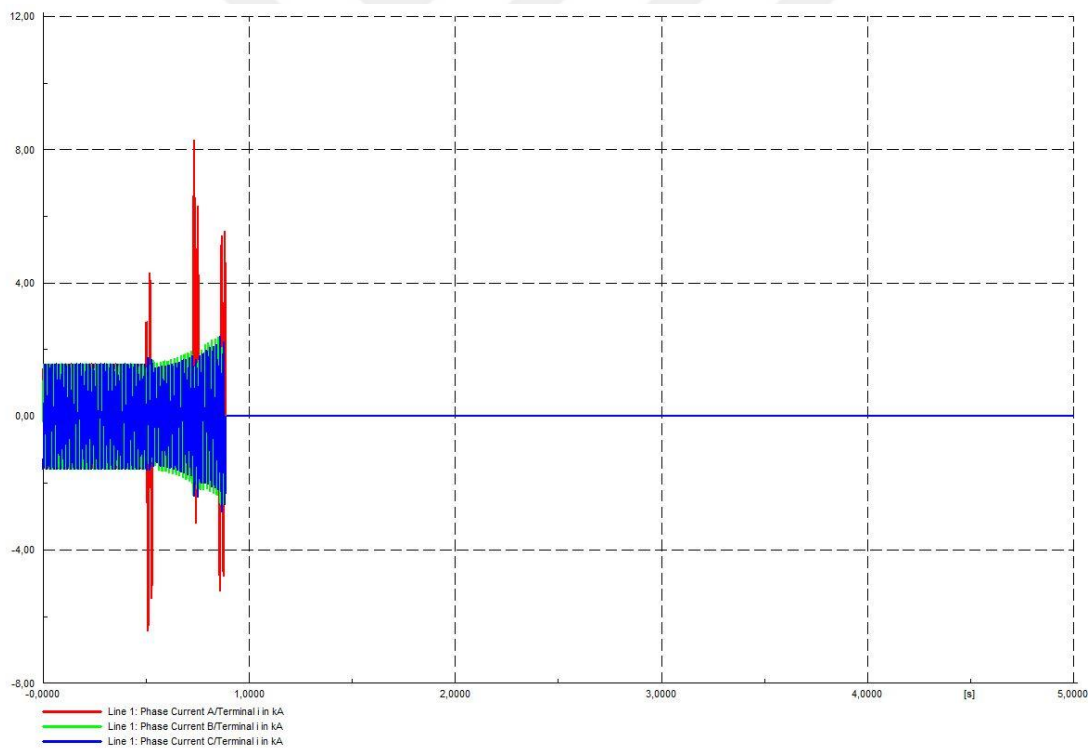


Figure 4.20: Phase currents during single phase to ground fault at 30% of the line1 with protection system.

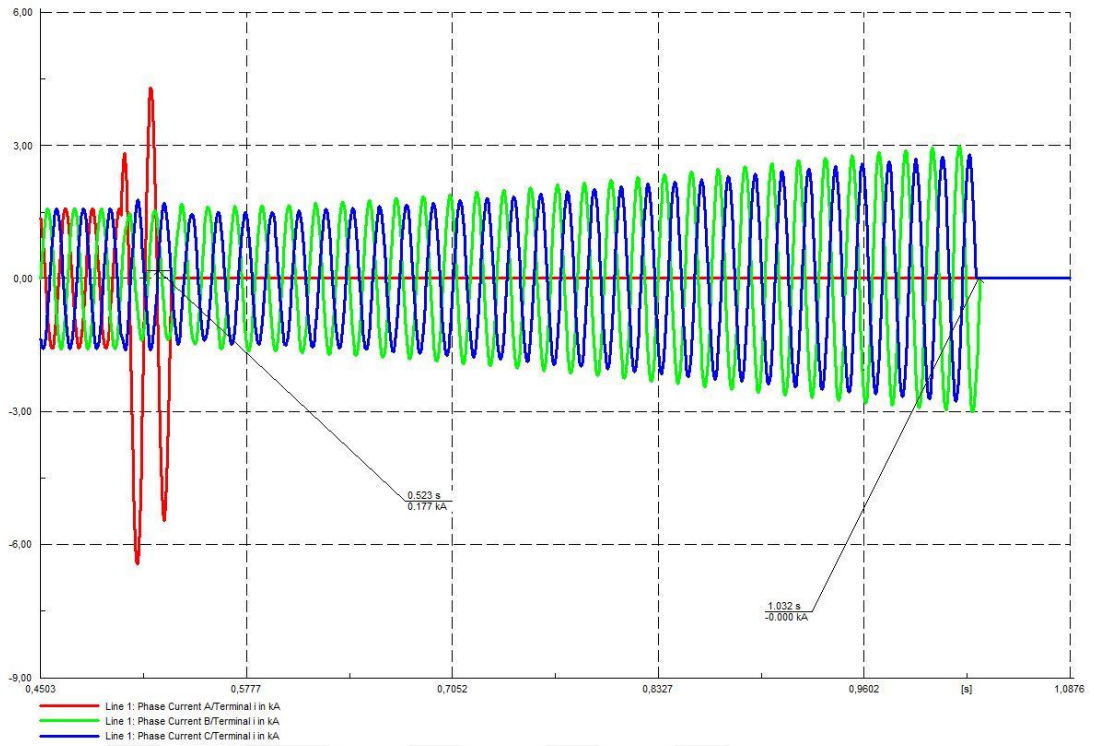


Figure 4.21: Phase currents during single phase to ground fault at 30% of the line1 with protection system.

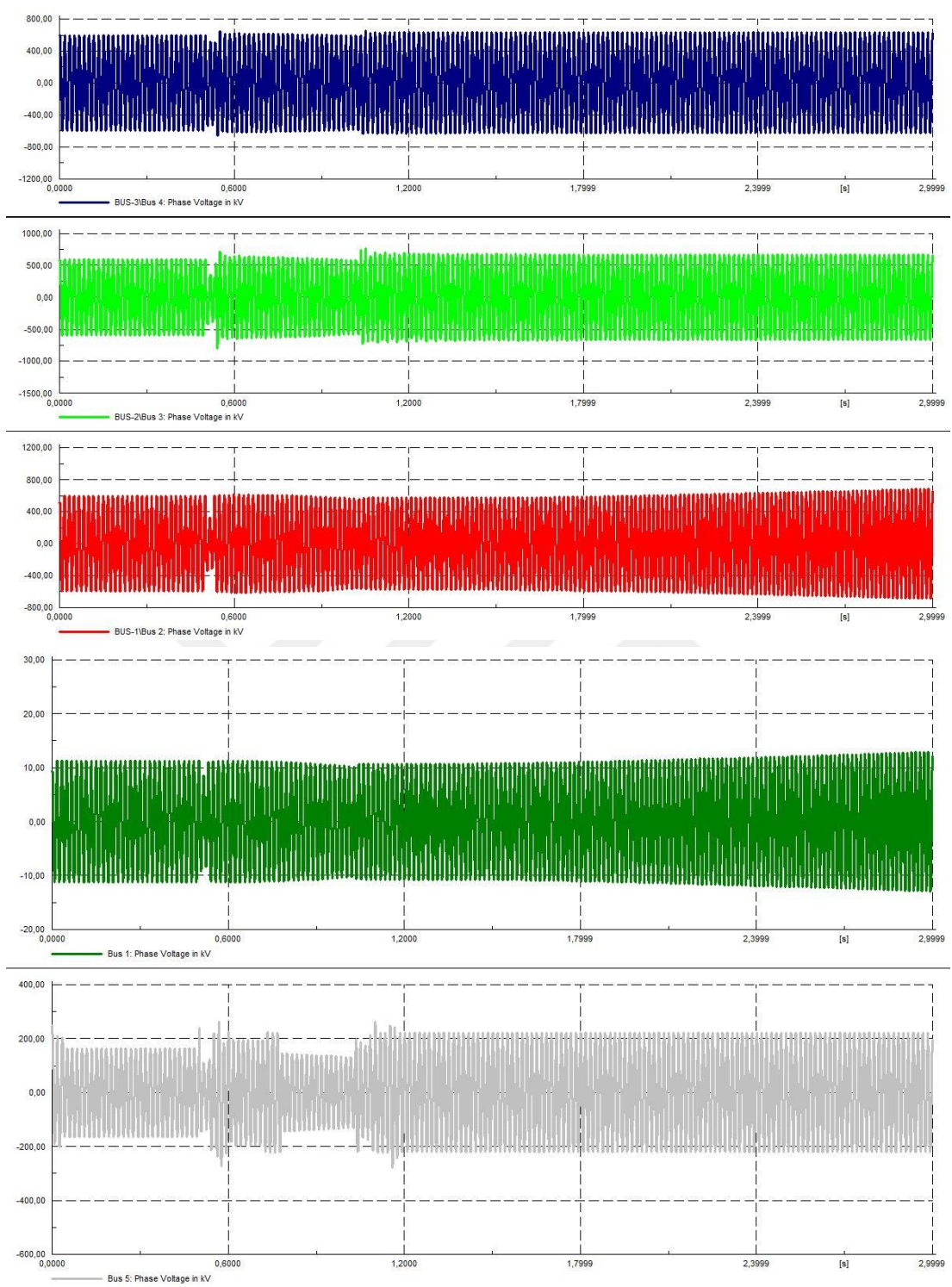


Figure 4.22: Bus voltages during single phase to ground fault at 30% of the line l with protection system .

Table 4.13: Bus voltages after CB's opening due to single phase to ground fault at 30% of the line 1.

Bus No	Rated Voltage (KV)	Voltage (KV)
1	13.8	21.99
2	735	1117.19
3	735	1117.02
4	735	1032.25
5	230	350.11

Due to the overvoltage protection which should be considered in EHV transmission systems, relay trips the circuit breakers of the two other sound phases for about 579 ms after occurring the fault, the first shot is considered 200 ms after fault occurring.

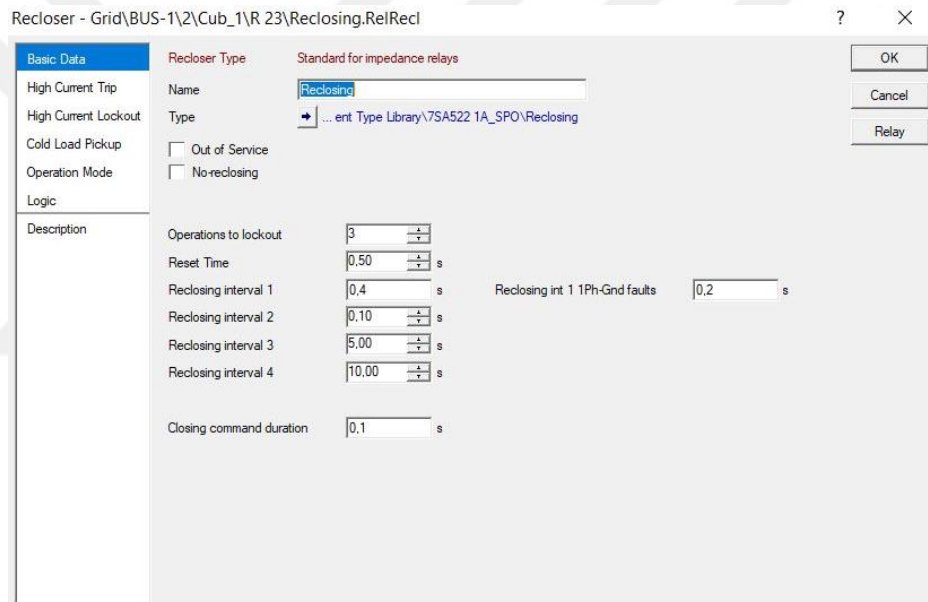


Figure 4.23 :Autorecloser settings for 735 KV Transmission system.

We consider that the fault is cleared after opening of the CB's and before 1st reclosing at 100 ms after CB's opening. So it is seen that the reclosure is successful and after about 10 seconds, the system will resume to its normal condition and operation. The figure 4.19 and 4.20 illustrate the successful reclosing of the autorecloser.

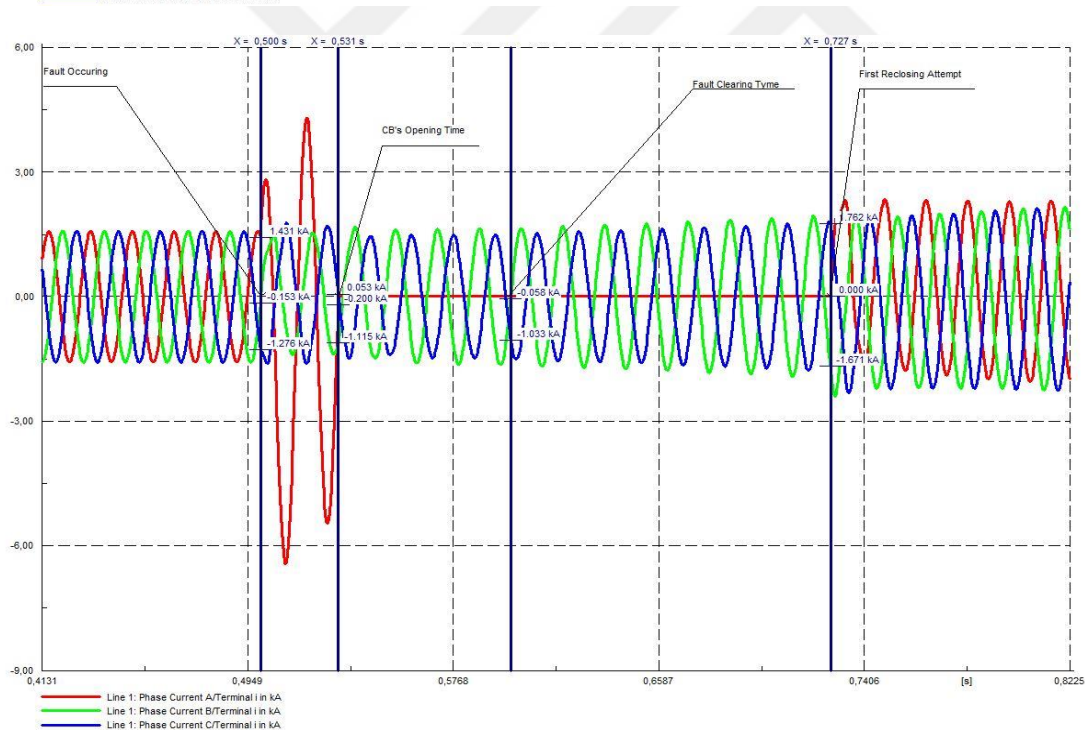
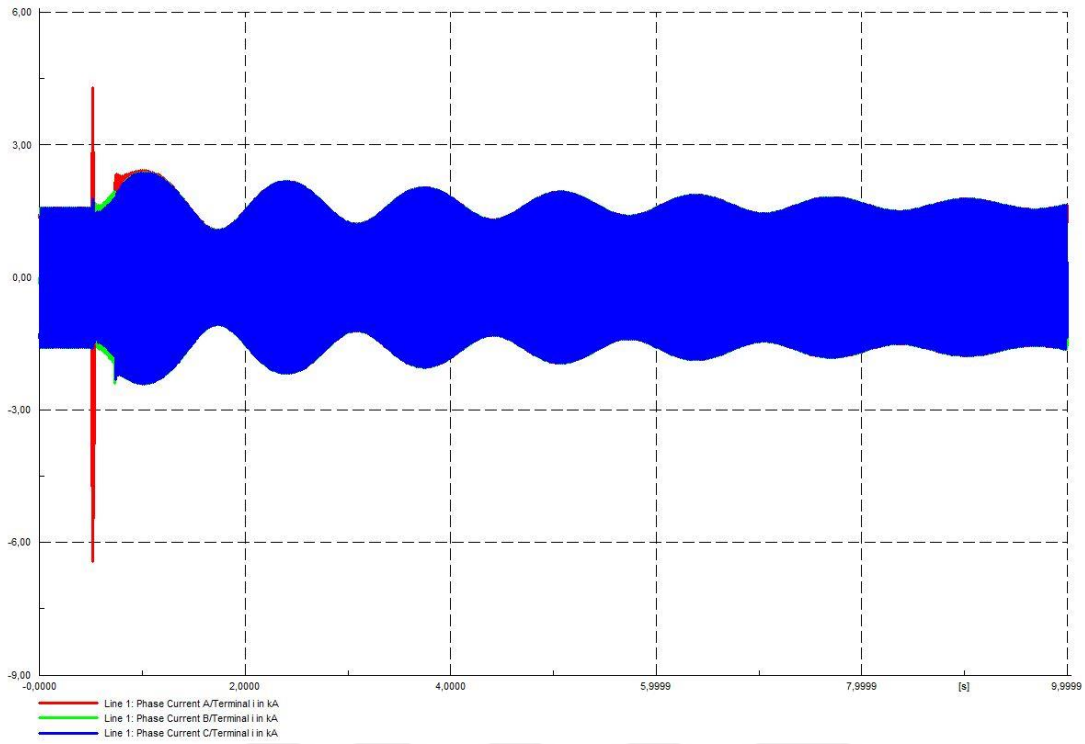


Figure 4.24: Phase currents after fault clearing and 1st reclosing.

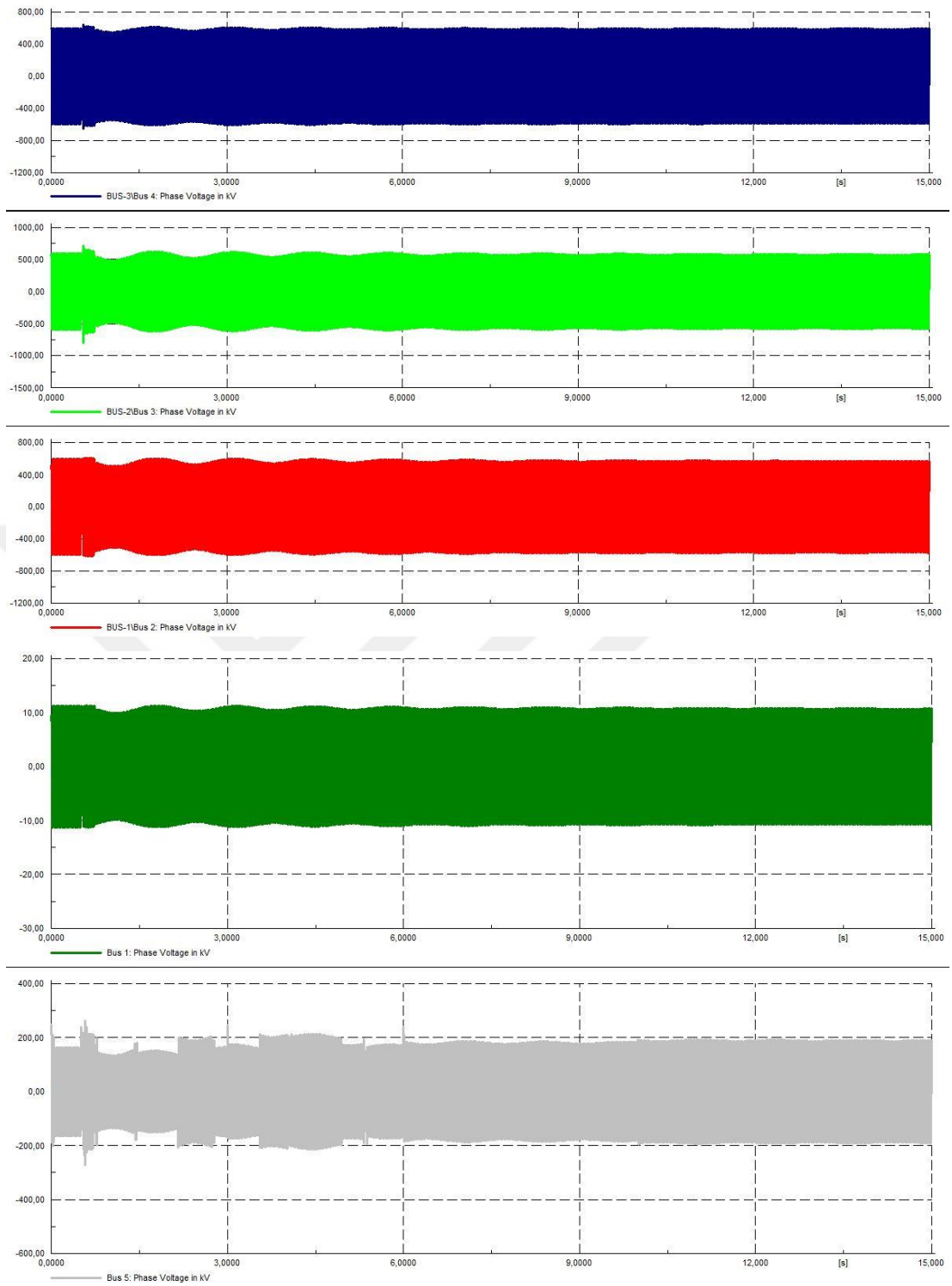


Figure 4.25: Bus voltages after clearing the fault and 1st reclosing.

Table 4.14: Bus voltages after clearing the fault and 1st reclosing.

Fault (ms)	CB's opening (ms)	Fault clearing (ms)	1 st reclosing (ms)	Reset time (ms)
500	532	700	727	500

Scenario 2: The first scenario is repeated in this case for the fault occurring at 50% of the line 1. The fault is occurred in 500 ms and CB of the faulty phase is opened at $t= 534$ ms. The second phase is opened at $t=734$ ms and the third phase is opened after the third attempt of reclosing at $t= 891$ ms. The voltages of the busses and currents of the line 1 phases and the protection system operation in the absence of the clearing fault are plotted in figure 4.21 and 4.22.

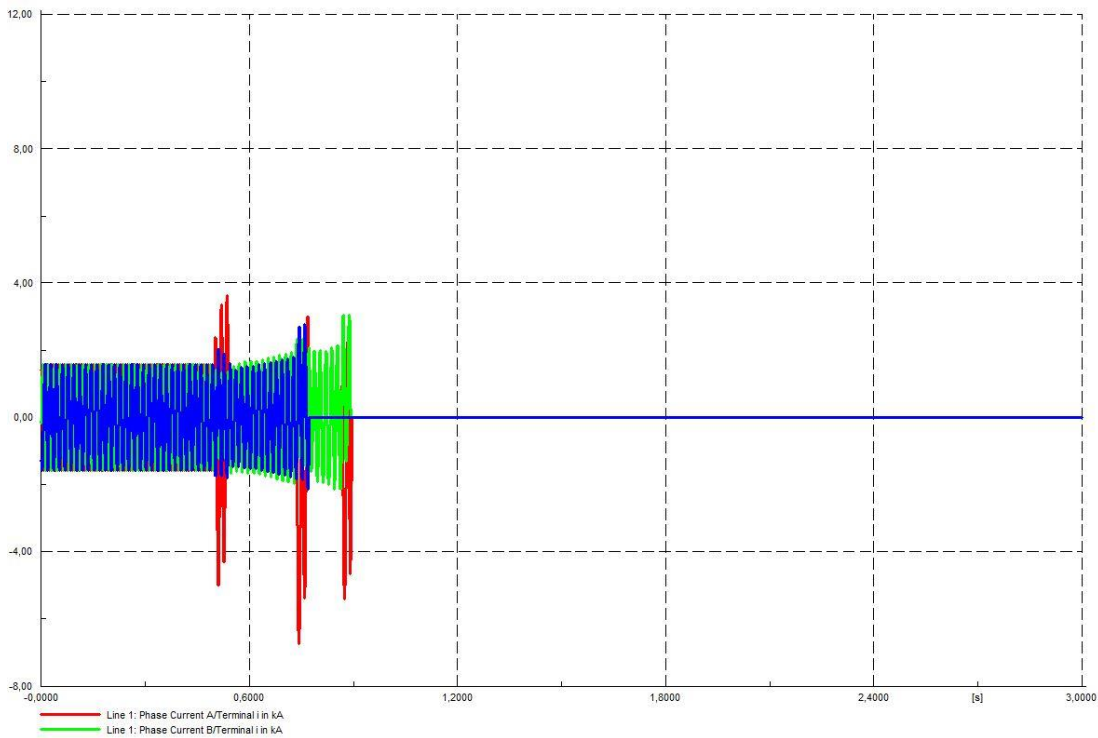


Figure 4.26: Phase currents during single phase to ground fault at 50% of the line1 with protection system.

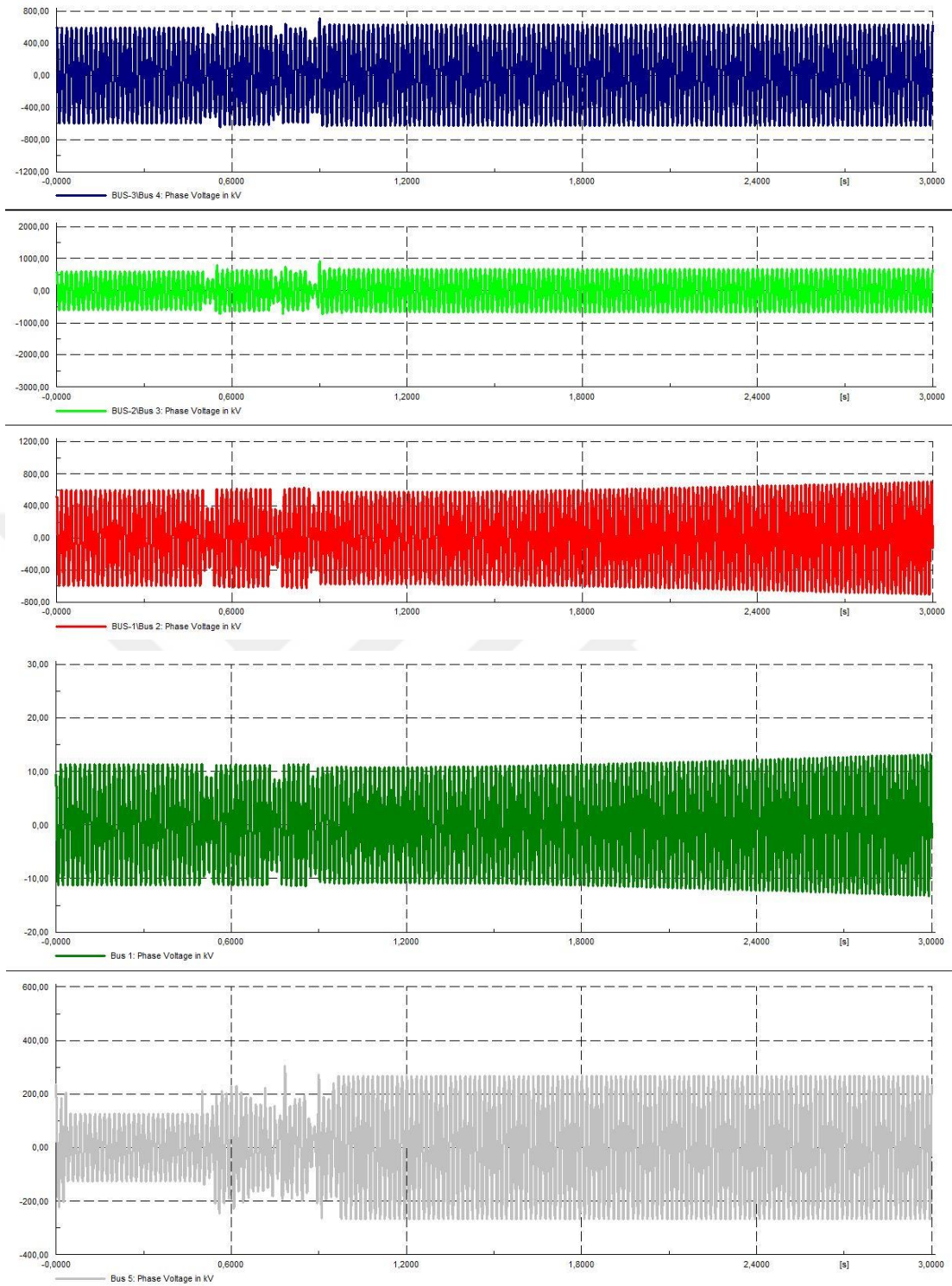


Figure 4.27: Bus voltages during single phase to ground fault at 50% of the line1 with protection system .

Table 4.15: Reclosing and fault settings.

Bus No	Rated Voltage (KV)	Voltage (KV)
1	13.8	27.55
2	735	1467.46
3	735	1119.75
4	735	1035.32
5	230	350.94

The simulation time for the purpose of showing the stability of the system is considered about 15 seconds. The fault clearing time is considered 200 ms after single phase to ground fault happening and the second attempts are as same as the table 4.14. At the fault location the both of the relays protecting the line 1 is tripped at $t=520$ ms.

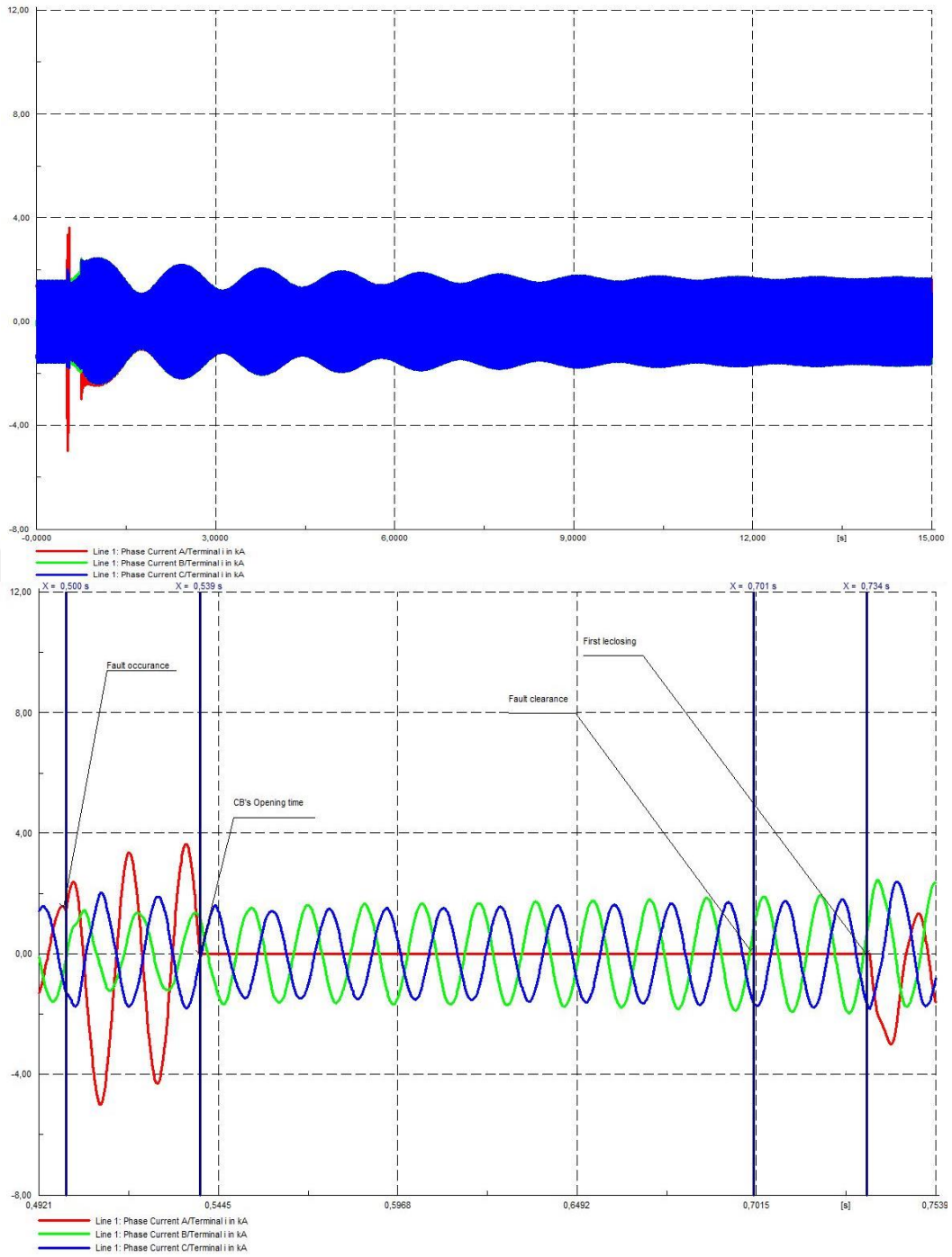


Figure 4.28: Phase currents after fault clearing and 1st reclosing.

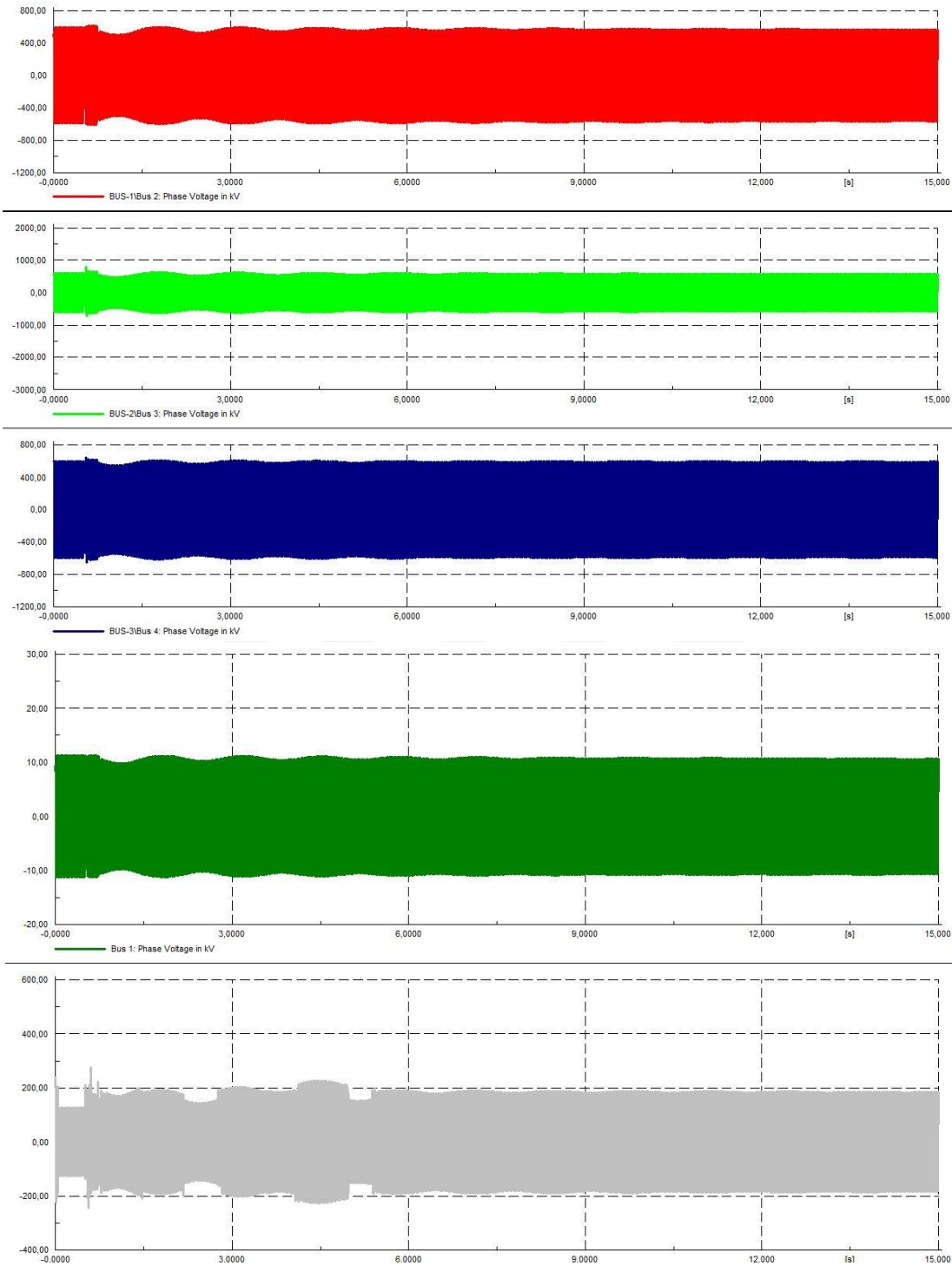


Figure 4.29: Bus voltages after clearing the fault and 1st reclosing.

Table 4.16: Reclosing and fault settings.

Fault (ms)	CB's opening (ms)	Fault clearing (ms)	1 st reclosing (ms)	Reset time (ms)
500	539	700	734	500

Scenario 3: The first scenario is repeated in this case for the fault occurring at 85% of the line 1. The fault is occurred in 500 ms and the fault is in the second protection zone of the R23 and its related circuit breaker will open at $t=1.1$ s because the 400 ms delay in the second zone, but the backup relay, R32, will open immediately at $t=531$ ms and the autorecloser will operate after opening the circuit breaker related to the R23. Due to the current increasing in other phases, the R32 will trip and open the sounded phases before R23 open the related circuit breaker and the reclosing is unsuccessful.

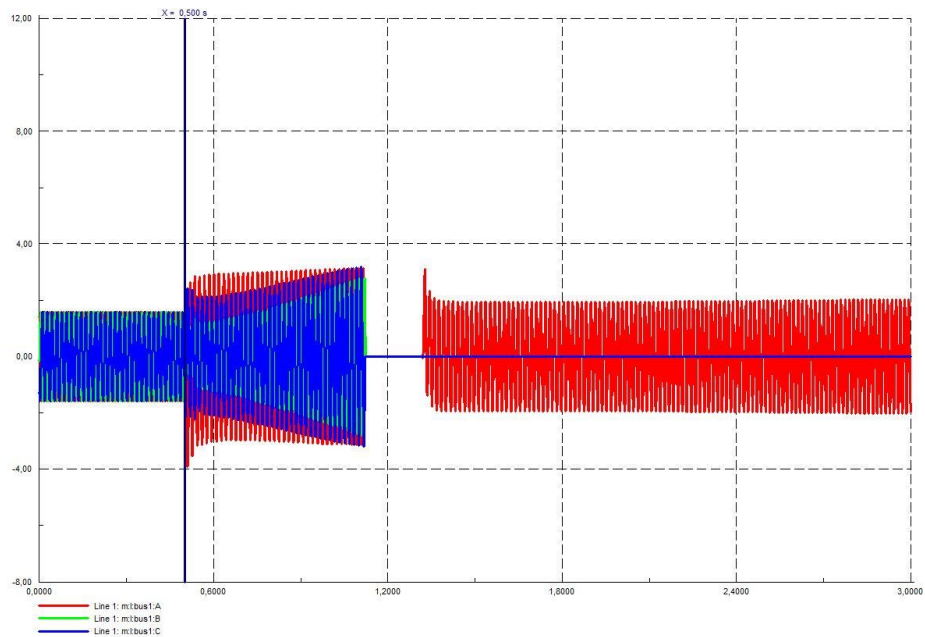


Figure 4.30: Phase currents during single phase to ground fault at 85% of the line 1 with protection system.

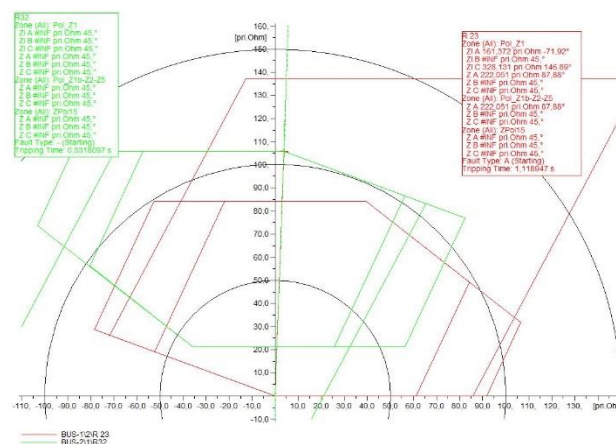


Figure 4.31: R-X plot of R23 and R32.

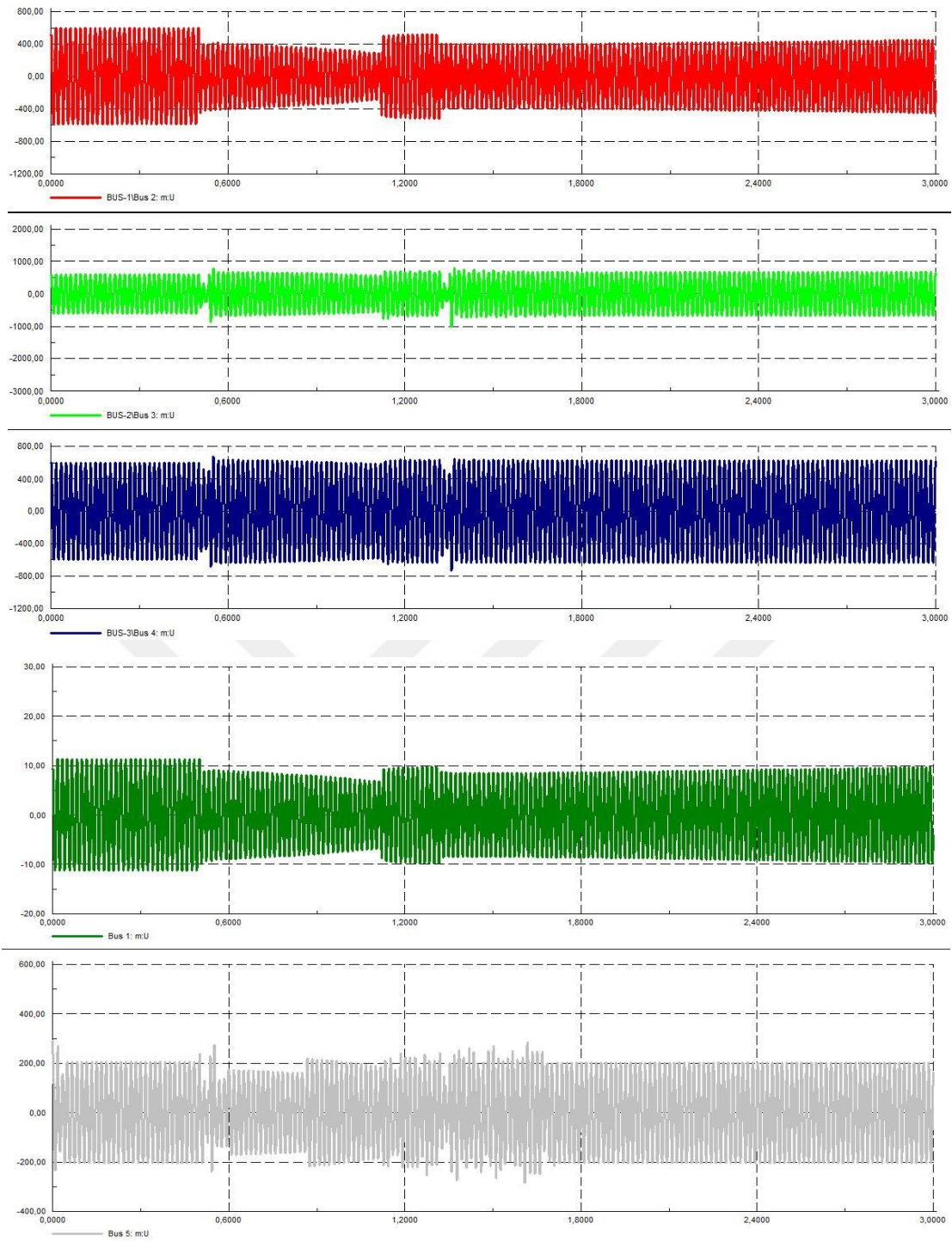


Figure 4.32: Bus voltages after clearing the fault and 1st reclosing.

The problem will be solved by using pilot protection using power line carrier (PLC) to open the circuit breakers simultaneously by sending trip signal from R32 to R23 and both of the breakers at the two end of the line will open at $t = 531$ ms and the reclosing will successfully restore the electric power in the transmission line.

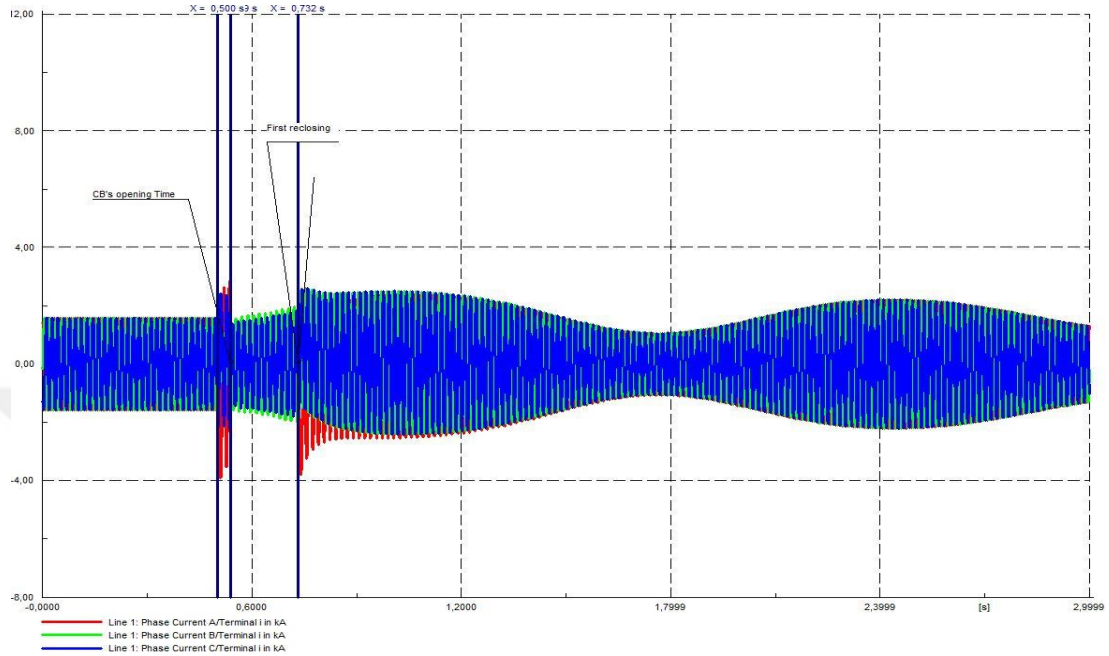


Figure 4.33: Phase currents after fault clearing and 1st reclosing.

Table 4.17: Bus voltages after autoreclosing due to single phase to ground fault at 85% of the line 1.

Bus No	Rated Voltage (KV)	Voltage (KV)
1	13.8	11.42
2	735	659
3	735	840.22
4	735	937.94
5	230	264.09

It can be derived from the different scenarios tested in this study, the high speed single phase auto reclosing can resume the power to the transmission line after about 15-25 sec depended on the location of the fault in transmission line and distance pilot protection accompanied by the overvoltage protection has the correct responds and the protection in EHV transmission systems is a suitable protection method.



5. CONCLUSION AND DISCUSSIONS

Single-phase auto-reclosing can be used in the most of the networks specially EHV transmission networks of 400 KV and above where the power transfer and stability of the system is major issues in transmission systems. The stability of the power system can be developed by single phase tripping which opens only the faulty phase, synchronization is preserved through the sounded phases. At normal conditions the power system is in balanced condition; that is, the generation and consumption rates are in equilibrium state. During the fault, the system should be able to clear the fault immediately to let the power back to the system and control the system frequency and voltage and make it stable. In this thesis different scenarios and study cases is simulated and examined in the 735 KV transmission system using Power Factory 15.1 software. The distance pilot protection with Mho and Quadrilateral characteristics is employed in this study in accordance with overvoltage protection and auxiliary overcurrent protection. The pilot protection will trip both circuit breakers of the line, simultaneously for all fault cases to provide enough time for deionization of the arc path.

According to results of the fourth chapter, high speed single phase auto reclosing is needed in EHV systems to back the system to the normal conditions and maintain the synchronism and serving the load continuously. The delayed operation of the circuit breakers in opening of the faulty phase cause current increasing and voltage decreasing in the healthy phases and the protection system will trip the other phases and cause an unsuccessful single phase reclosing. The time for the stability of the system after reclosing is rely on the location of the fault and it can be reduced by adding some voltage regulators to the system.

The disadvantages of the single phase autoreclosing is preserving of the fault arc resulting in a secondary arc due to the existence of innate capacitance between the sounded phases of the transmission line and the faulty phase which contribute to an unsuccessful reclose. The solution is to let the secondary arc extinguishes itself by delaying the auto reclosing which is unsatisfactory from a system adherence

perspective. Using of shunt reactors on high-voltage (EHV) transmission line in face of the high voltage production by shunt capacitors on an unloaded or a open ended line are also useful. Another drawback is the producing of the negative sequence by an unbalanced system. Reclosing the open phase or tripping the sounded phases will remove the negative sequence which effects generators on the system.

For further works, it is assumed to eliminate negative sequence by adding a grounding capacitor at the end of the line. During normal operation the grounding capacitor is disable and is introduced only when one phase remains open before reclosure. It also used some arc models to modeling the secondary arc to evaluate the secondary arc extinction time and measuring recovery voltage.



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