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REDUCTION OF SWITCHING OVERVOLTAGES BY MEANS OF CONTROLLED SWITCHING

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REDUCTION OF SWITCHING OVERVOLTAGES BY MEANS OF CONTROLLED SWITCHING

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science

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ABSTRACT

REDUCTION OF SWITCHING OVERVOLTAGES
BY MEANS OF CONTROLLED SWITCHING

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This thesis analyzes the controlled switching methods applied to modern SF6 type circuit breakers for the purpose of reducing switching overvoltages. Main emphasis is placed on controlled switching methods applied at extra high voltage level, since the cost of failures caused by switching overvoltages is highest in this voltage level.

After a brief introduction about circuit breakers in general, switching overvoltages and controlled switching methods are analysed. Also a case study about controlled switching of an unloaded overhead line is provided, and success of controlled switching method is evaluated.

Keywords: Controlled Switching, Switching Overvoltage, EMTP, Circuit Breaker

ÖZ

ANAHTARLAMA AŞIRI GERİLİMLERİNİN
KONTROLLÜ ANAHTARLAMA İLE AZALTILMASI

Güneri, Melih
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Bu tez çalışmasında, anahtarlama aşırı gerilimlerinin düşürülmesi amacıyla modern SF6 tipi kesicilerde uygulanan kontrollü anahtarlama metodları incelenmiştir. Özellikle anahtarlama aşırı gerilimlerinin yarattığı hasarın en yüsek olduğu çok yüksek gerilim seviyesinde kullanılan kontrollü anahtarlama metodları incelenmiştir

Kesicilerin genel özelliklerine dair genel bir girişten sonra, anahtarlama aşırı gerilimleri ve kontrollü anahtarlama metodları incelenmiştir. Ayrıca yüksüz enerji nakil hatlarında yapılan anahtarlamalara dair bir örnek çalışma sunulmuş ve kontrollü anahtarlama metodlarının başarısı değerlendirilmiştir.

Anahtar Kelimeler: Kontrollü Anahtarlama, Anahtarlama Aşırı Gerilimleri,
EMTP, Devre Kesiciler

To My Family

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LIST OF ABBREVIATIONS

SF6 : Sulphurehexafluorid

EHV: Extra high voltage

RRDS: Rate of rise of dielectric strength

RDDS: Rate of decrease of dielectric strength

CB: Circuit breaker

TRV: Transient recovery voltage

FPTC: First pole to clear

EMTP: Electro Magnetic Transients Program

ATP: Alternative Transients Program

OHL: Overhead line

S/S: Substation

CHAPTER 1

INTRODUCTION

1.1 – General introduction

Electrical energy with its wide area of use, is one of the indispensable parts of our lifes. Supply of electrical energy is vital for nearly all our daily activities, ranging from using personal computers to feeding infrastructure items like telecommunications, lighting and heating. Such a crucial supply should meet some standard requirements regarding quality and availability.

Quality of electrical energy supply is difficult to define and assess. But mainly, it can be defined in terms of its consistency with nominal values such as voltage and frequency. Also, it may include definitions about level of disturbances, like harmonics, voltage dips and surges. On the other hand, availability of electrical energy supply is rather easy to define; it should be ready on demand. That is, any user may reach the supply at any time needed.

Todays large scale power systems are very complex networks, formed by huge generating stations and transmission-distribution systems to supply generated energy to the end users. In order to sustain quality and availability of electrical energy supply in such complex networks, control and protection systems should be designed to cope with any expected adverse conditions, like failures, overload conditions and dielectric stresses. Any disturbance in a power system should be immediately detected and the source of disturbance should be isolated from the system, which is obtained by fast switching operations

Switching operations are carried not only for isolating faults, but also for connecting or disconnecting parts of the network in order to achieve several goals such as isolating parts of a system for maintenance or balancing production and consumption. Any switching operation means a change in the state of the system. Since physically it is not possible to switch between two states perfectly, there will inevitably be a transient response within the system during this change, which may be in the form of overcurrents or overvoltages.

Transient overvoltages generated in a power system after a switching operation are referred as switching overvoltages. Switching overvoltages may sometimes be of important severity and possible cause for faults and degredation of equipment lifetimes. Power system equipments are designed to withstand expected overvoltages, but the cost of these equipments increase as the overvoltage level of the system increases. Hence any reduction in overvoltage level a power system means a considerable saving in cost of investment and operation.

Several solution methods have been proposed and applied to reduce switching overvoltages, namely, pre-insertion resistors, pre-insertion inductances, permanent inductances, surge arrestors and controlled switching. Among these, controlled switching of circuit breakers has become an increasingly useful method for reducing switching overvoltages for a range of specific load cases.

1.2 – Controlled switching

As defined by the Working Group 13.07 of CIGRÉ, "controlled switching is the term which is commonly used to describe the use of an electronic control equipment to facilitate operation of the contacts of a switching device at a pre-determined point in relation to an electrical reference signal"[1] [2]. There are also some other terminologies used for this technique such as "synchronized switching” or “point-on-wave switching”. Within this thesis the term “controlled switching” will be used to point out the related technique.

In controlled switching technique, there are mainly two critical stages. Firstly, an optimum operation point on the reference voltage or current wave should be determined such that the resulting transient overvoltage after operation is minimum. This task needs considerable attention, since the optimum operation point differs according to the type of the load to be switched. Secondly, the instant to apply the related operation command to the circuit breaker should be determined such that the circuit breaker operates at the pre-determined point. In order to accomplish this task, operation times of the circuit breaker should be known. Even though circuit breaker operation times can be measured on a case to case basis, environmental and operational parameters substantially effect operation times. Hence any controlled switching application should take these variations into account.

As a result, it can be said that operational details of controlled switching applications depends mainly on two factors; the type of the load to be switched and the operational characteristics of the particular circuit breaker to be used. In order to designate a proper controlled switching application, a profound understanding of switching overvoltages phenomena and circuit breaker operation is vital.

Controlled switching is not a recent subject, it has been investigated for more than 35 years. But its application areas are not wide yet, partly because of the fact that the technological maturity of these applications has been reached just within the last decade by the enormous developments in electronics technology. Result of a survey conducted by the Working Group A3.07 of CIGRÉ about controlled switching applications installed between 1984 and 2001 are given in Table 1.1 [3] Considering the increasing use of controlled switching technique, especially in well defined load cases, it can be said that the results given in Table 1.1 may not be reflecting the present situation. Nevertheless it can be used to estimate the overall installation trends and satisfaction with different load cases.

Table 1.1 – Controlled switching aplications installed between 1984-2001

Application	Percentage of total conventional controlled switching applications (1984 – 2001) (total number:2500)
Shunt capacitor energising and/or de-energising	64 %
Shunt reactor energising and/or de-energising	17 %
Transformer energising only or energising supported by controlled de-energising	17 %
Line energising and auto-reclosing (uncompensated /shunt reactor compensated)	2 %
Combined controlled opening and closing of 3 pole operated mechanically staggered circuit breaker's	7 %

An important point to note in Table 1.1 is the dominance of installed number of applications for shunt capacitor switching. In shunt capacitor switching controlled switching technique is used to reduce transient overcurrents at closing operations and reduce transient overvoltages at opening operation. Shunt capacitors are generally used at distribution voltage level for the purpose of power factor compensation. However at transmission voltage level, power factor compensation is not applied and shunt capacitors are used for voltage regulation purposes in very long overhead lines at very high voltage levels (>750 kV). Hence controlled switching of shunt capacitors is very rarely applied in transmission level, which is the primary focus of this thesis as it will be described in the following subchapter.

In shunt reactor switching case, controlled switching is used to reduce transient overcurrents at closing operations, whereas at opening operation it is used for reducing transient overvoltages. Controlled switching technique is quite mature and popular application in shunt reactor switching. Within the scope of this thesis opening operations will be emphasized, since overvoltages generated at closing operations are moderate. Yet, application of controlled switching for closing operations will also be mentioned, in order to define application areas of controlled switching technique.

Controlled switching of power transformers is an evoluting application, and it is used to reduce inrush currents in transformer energisation. Technical maturity of controlled switching in this case has not been reached yet, as it will be mentioned in related chapter, but even with the present state of the art acceptable results can be achieved with controlled switching.

Use of controlled switching for reducing overvoltages encountered in overhead line switching is also an evoluting application. In this load case controlled switching is used at closing, and especially re-closing, operations. Controlled switching technique promises considerable advantages in this case, such as use of much compact overhead line towers and reduction in tower insulators. Moreover increasing voltage level of an existing line is also possible by controlled switching technique. In this thesis study controlled switching technique applied for unloaded overhead line switching will mainly be emphasized, considering the possible cost reducing outcomes.

Traditional measures for reducing switching overvoltages, such as pre-insertion resistors are costly and they generally decrease the reliability of circuit breakers in long term. Increasing use of controlled switching eliminates this costly applications, and this saving in investment and operational costs make controlled switching an attractive technique. Today controlled switching is accepted to be a must in some applications such as shunt reactor and capacitor switching, but some application areas such as transformer switching and controlled fault interruption are still under evolution. It is generally accepted that controlled switching will be a standard application provided with circuit breakers in the near or mean term future.

1.3 – Scope and purpose of this thesis

The purpose of this thesis is to investigate the use of a technique, namely the controlled switching technique, for limiting transient overvoltages generated after switching operations in an extra high voltage (EHV) power system.

The term EHV is used for the voltage levels above 345 kV [4]. The main reason for limiting the scope of this thesis study to EHV level is that, damages caused by overvoltages in this voltage level are much more costly in comparison to the lower voltage levels. It should be noted that the cost of damages mentioned above is not determined just by the failure of a power system equipment itself, but by the loss of supply and reduction in the system reliability.

Applicational possibility and details of controlled switching is directly related with the circuit breaker technology. Within this thesis main emphasis will be placed on applications for circuit breakers which use SF_6 gas as an interrupting medium. This emphasis is determined because of the fact that the vast majority of circuit breakers produced today and within the past decade are of SF_6 type. It is noteworthy that discussions provided in the following chapters may well be applicable to other types of circuit breakers using oil or pressurized gas as an interrupting medium, but it should be remembered that the specific functionality and performance of a high voltage circuit breaker is highly dependent on the type of interrupting medium.

In the following discussions, theoretical background, application areas and future possibilities of controlled switching technique will be investigated. Also a simulation study about unloaded overhead line switching will be provided and results of this simulation will be investigated to assess the success of controlled switching.

CHAPTER 2

CIRCUIT BREAKER FUNDEMANTALS

2.1 – Introduction

Circuit breakers are defined by the Institude of Electrical and Electronics Engineers (IEEE) as " a mechanichal device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time and breaking currents under specified abnormal circuit conditions such as those of short circuit" [5]

Circuit breakers are mechanical devices used in an electrical system to connect and disconnect parts of a network. They are designed to withstand the most severe stresses experienced by any equipment on a power system and to protect other equipment from overstresses, particularly under fault conditions.

Controlled switching principles and application details depend highly on the behaviour of the circuit breaker to be used. Consequently a profound understanding of how circuit breakers operate and how their behaviour is influenced by various aspects, is fundamentally important for the development of an appropriate control scheme. Within the context of this thesis study, it is important to provide a description about the fundamentals of modern SF_6 type high voltage circuit breakers.

Detailed analysis of high voltage circuit breakers, even if only restricted to those using SF_6 gas as an interrupting medium, constitutes a major research area which involves combining a diverse range of disciplines ranging from arc physics to high voltage engineering and power system analysis to mechanical engineering. Main intention in the following discussion is to identify those aspects of high voltage SF_6 circuit breakers, which have direct effect on the development of a controlled switching application.

A circuit breaker must perform four primary functions:

1. Carry rated current at rated voltage and power frequency when in closed position
2. Interrupt rated currents at rated voltage and power frequency on command
3. Maintain rated dielectric (power frequency and impulse) withstand levels when in open position
4. Change its position from open to close and vice versa in a very short time

The most demanding function among these is the item 2, since the circuit breaker must satisfactorily operate in a wide range of possible switching conditions, ranging from small load currents which might be either highly inductive or highly capacitive to rated asymmetrical fault current. The dielectric, thermal and even mechanical stresses placed on the circuit breaker under these different switching conditions vary widely from case to case and a circuit breaker is expected to operate even at most adverse conditions. In order to meet this onerous demands placed, circuit breakers are designed and tested according to a very extensive range of rated switching duties with associated performance requirements [6][7].

Another demanding request from the circuit breakers is to change its position in a very short time frame. This onerous demand is fulfilled by the strong operating mechanisms of high voltage circuit breakers which provide an energy in the range of 1 kJ to 20 kJ depending on individual characteristics of the circuit breaker concerned.

2.2 – General description of circuit breakers

Circuit breakers are mainly classified according to the interrupting medium they use for current interruption. There are mainly three types of interrupting mediums used at EHV level, namely, air blast, oil and SF_6 gas. As mentioned before, most of the circuit breakers produced today and over past decades are of SF_6 type, and even though there are other types of circuit breakers presently in service, it is clear that those will also be replaced by SF_6 type in the near future.

Circuit breakers utilizing SF_6 gas has been subjected to evolution for more than 40 years. Early designs were based on two pressure interrupters where electric arc was cooled by compressed SF_6 gas from a separate reservoir [8][9]. Modern HV SF_6 interrupters are single pressure interrupters, where the SF_6 gas is compressed by the pistons connected to operating mechanism. Modern SF_6 interrupters are generally classified into two groups, those are puffer and self-blast type.

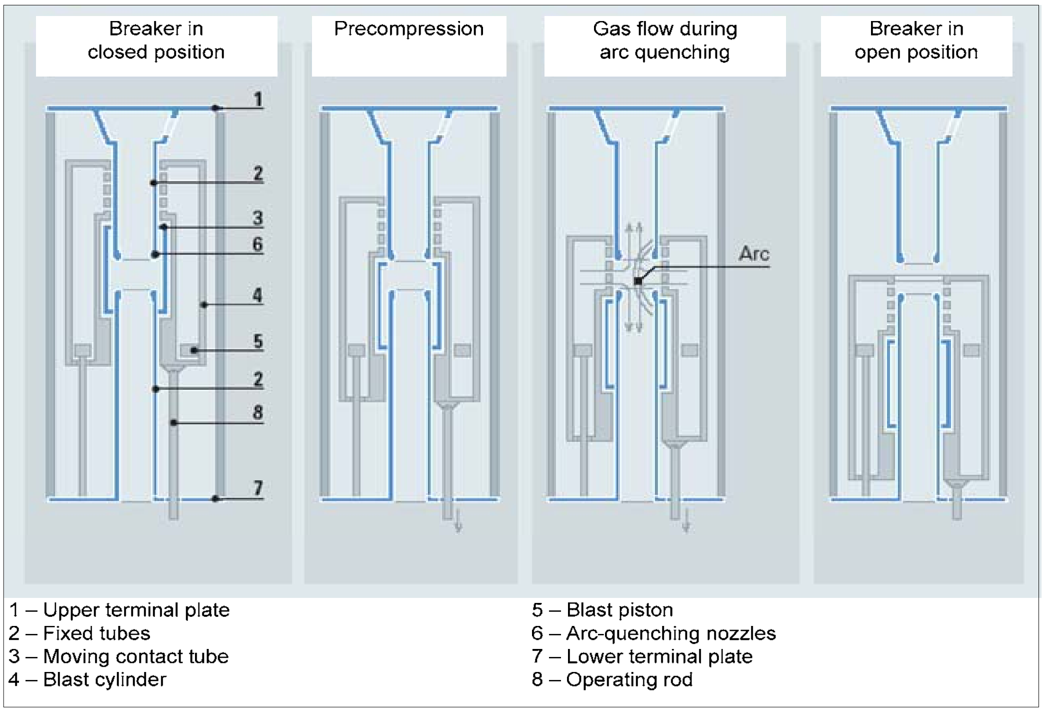


Figure 2.1 – Basic scheme of HV circuit breaker interrupter

In puffer type interrupters, the mechanical energy provided by the operating mechanism is used to compress the gas, whereas in self blast type the gas is compressed also by the heat energy drawn from the electric arc. Figure 2.1 gives an illustrative example of modern puffer type circuit breakers [10].

Operation of the circuit breaker given in Figure 2.1 is described as follows [10]; "The conducting path is made up of the terminal plates (1 and 7), the fixed tubes (2) and the spring-loaded contact fingers arranged in a ring in the moving contact tube (3). The fixed tubes (2) are connected by the contact tube (3) when the breaker is closed. The contact tube (3) is rigidly coupled to the blast cylinder (4), the two together with a fixed annular piston (5) in between forming the moving part of the break chamber. The moving part is driven by an operating rod (8) to the effect that the SF6 pressure between the piston (5) and the blast cylinder (4) increases. When the contacts separate, the moving contact tube (3), which acts as a shutoff valve, releases the SF6. An arc is drawn between one nozzle (6) and the contact tube (3). It is driven in a matter of milliseconds between the nozzles (6) by the gas jet and its own electrodynamic forces and is safely extinguished. The blast cylinder (4) encloses the arcquenching arrangement like a pressure chamber. The compressed SF6 flows radially into the break by the shortest route and is discharged axially through the nozzles (6). After arc extinction, the contact tube (3) moves into the open position."

Circuit breakers are also classified according to their operating mechanisms. Poles of a circuit breaker may be operated individually by an independent mechanism per each pole or they may be operated together by a common mechanism. The first type of circuit breaker mentioned is generally referred as single pole operated, while the latter one is referred as three pole operated. In some cases an intentional mechanical delay is introduced between poles of the three pole operated circuit breakers. This type of operation is generally referred as staggered pole operation.

Controlled switching technique can not be applied to three pole operated circuit breakers, since the operating instant of each pole can not be controlled individually. Staggered pole operated circuit breakers can be used for controlled switching, but the flexibility required for some of the application cases may not be fulfilled sufficiently because of the constant delay between circuit breaker poles. Single pole operated circuit breaker is the most appropriate type for the controlled switching applications. In the following chapters describing controlled switching applications, circuit breaker to be used will be assumed to be of single pole operated type.

Another classification criteria for circuit breakers is the type of operation mechanism. Mechanical energy of a circuit breaker may be provided by pneumatic, hydraulic or spring based operating mechanisms. Among these types spring driven operating mechanisms have gained a general acceptance in last decade because of its higher reliability in comparison with other types [11]. It should be noted that the recent developments in circuit breaker technology has introduced a new operating mechanism type using digitally controlled servomotor drives which provide more consistent operating times in comparison to the other mechanism types..

Circuit breakers are further classified according to their structural design in mainly two groups, namely live tank and dead tank. Main difference between these two types is that, in dead tank type circuit breakers, vessel(s) surrounding and containing interrupter(s) is at ground potential, whereas in live tank type it is at a potential above ground [5]. It should be noted that for controlled switching applications, there is no difference between these two types.

2.3 – Current interruption and initiation processes

Current interruption and initiation processes are not only mechanical, but also electrical events. A clear discrimination between electrical and mechanical events in these processes is necessary for development of controlled switching principles.

Before providing descriptions about current interruption and initiation, it is important to give some basic definitions of the terms used in conjunction with circuit breaker operations. The following terms will be used throughout this thesis in accordance with the definitions provided by the International Electrotechnical Commission [6]

Opening time: The time which passes between the electical command being issued to the circuit breaker and the galvanic contact seperation in all breaker poles

Break time: The time between the command being issued and the extinction of arcing (current flow end) in all breaker poles

Arcing time: The time in which the arc burns at the circuit breaker pole concerned during switch off

Closing time: The time which passes between the electical command being issued to the circuit breaker and the galvanic touch in all breaker poles

Make time: The time between the command being issued and the occurance of arcing (current flow start) in the first braker pole

Pre-arcing time: The time in which the arc burns at the circuit breaker pole concerned during closing

2.3.1 – Current interruption process

Current interruption is acquired by seperation of circuit breaker contacts by the driving mechanism. When the contacts of a circuit breaker seperates, the magnetic energy stored in the system forces current to flow. Just before the contacts of the circuit breaker seperate, the current flows through a very narrow surface, and the high current density in this case melts the contact material, which leads a gas discharge in the surrounding medium. After this discharge, a plasma channel is generated between the circuit breaker contacts. This channel is referred as electric arc, and it is the only known element, except from power semiconductors, to change from conducting to nonconducting state in a very short period of time [9] If this arc plasma can be cooled sufficiently at the instant where the current magnitude is zero, then the current can be successfully interrupted.

There are several theories which describe the overall process of current interruption (i.e. Cassie theory, Mayr theory). But it should be noted that a detailed examination of these theories is beyond the scope of this thesis, since the arc physics involved in current interruption is very complex and constitutes a major research area in itself.

In the current interruption process, there are mainly two stresses applied to a circuit breaker, namely thermal and dielectic stresses. For successful interruption a circuit breaker must fulfill following requirements:

1 – It should sufficiently cool the arc plasma at current zero to achieve thermal interruption

2 – It should maintain a minimum rate of rise of dielectric strength (RRDS) exceeding the rate of rise of the recovery voltage (RRRV) across its contacts to achieve dielectric interruption

The thermal stress is primarily governed by the magnitude of the arcing current and thermal interruption failure is generally observed when interrupting high magnitudes of current. During the interruption process an arc plasma channel is generated between circuit breaker contacts, as mentioned before, and this arc plasma typically reaches to temperatures in the order of 7,000 to 25,000 K during the process [9]. At such high temperatures SF_6 brakes down to form a highly energized, ionized plasma between the circuit breaker contacts. When the current is interrupted, there remains a still hot gas between circuit breaker contacts. As the voltage between circuit breaker contacts increases because of the source and load side voltage difference, charged particles in this hot gas start to drift creating a post arc current. This current together with the voltage across circuit breaker contacts results in an energy input to the still hot channel and this energy input may reconstitude the plasma channel which leads to a thermal breakdown. In order to avoid thermal breakdown after current interruption, the circuit breaker must succesfully cool the arc channel.

The dielectric stress is generally referred as the recovery voltage, which is the voltage that appears accross circuit breaker contacts after current interruption. The recovery voltage can be considered in two successive time intervals. In the first interval, the recovery voltage is formed by the transient responses from both sides of the circuit breaker. In the second interval, the recovery voltage is formed by the power frequency voltages from both sides of the circuit breaker. The dielectric stress, which may cause a failure in current interruption is the first one, which is referred as transient recovery voltage (TRV). In other words, "transient recovery voltage is the difference in the power system response voltages on the source side and on the load side of the circuit breaker [12]."

In order to withstand these dielectric stresses following the current interruption, the circuit breaker needs to establish a sufficient physical gap between its opened contacts before a current zero occurs. In an opening operation, circuit breaker's voltage withstand capability increases as the contacts apart. The rate at which the withstand capability increases is referred to as Rate of Rise of Dielectric Strength (RRDS) and is directly influenced by the speed of the contacts. Most modern circuit breakers can be assumed to have a constant opening speed according to their design and ratings. Hence the contact gap can generally be considered to be increasing linearly with time during the opening process.

In cases, where the dielectric withstand level becomes lower than the transient recovery voltage across circuit breaker contacts at any instant during the current interruption process, a voltage breakdown between circuit breaker contacts occur. These voltage breakdowns are divided into two categories [13]:

1 – Reignitions: Voltage breakdown within the first 1/4 cycle after interruption.

2 – Restrikes: Voltage breakdown within 1/4 cycle or more after interruption.

The nature and shape of transient recovery voltage is dependent on the circuit to be interrupted. Simplified recovery voltages in the example circuit of Figure 2.2 , for resistive, capacitive and inductive load cases are given in Figure 2.3 , Figure 2.4 and Figure 2.5 respectively.

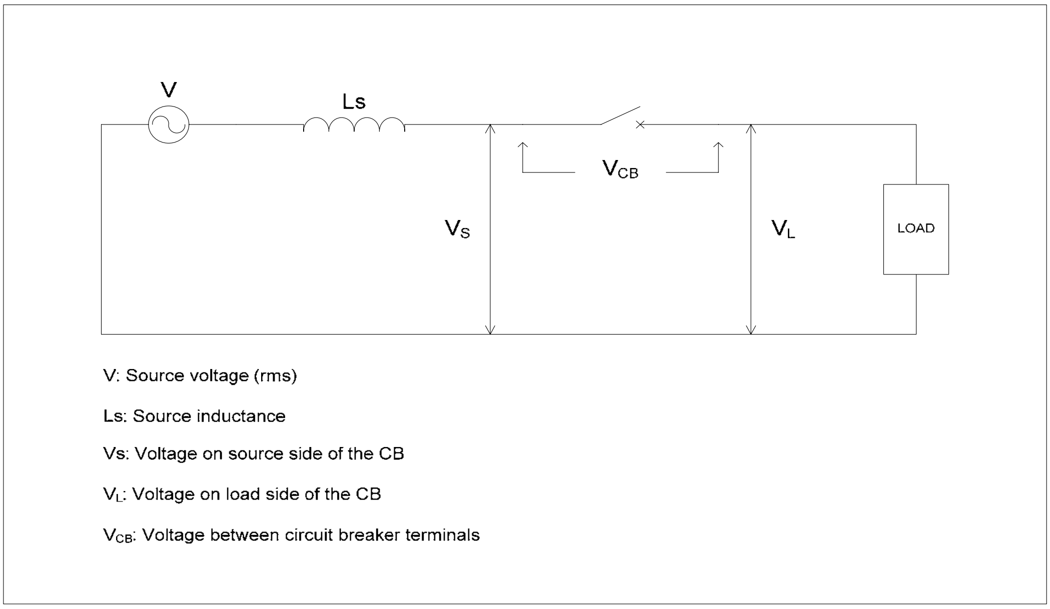


Figure 2.2 – Example circuit for recovery voltage on a circuit breaker

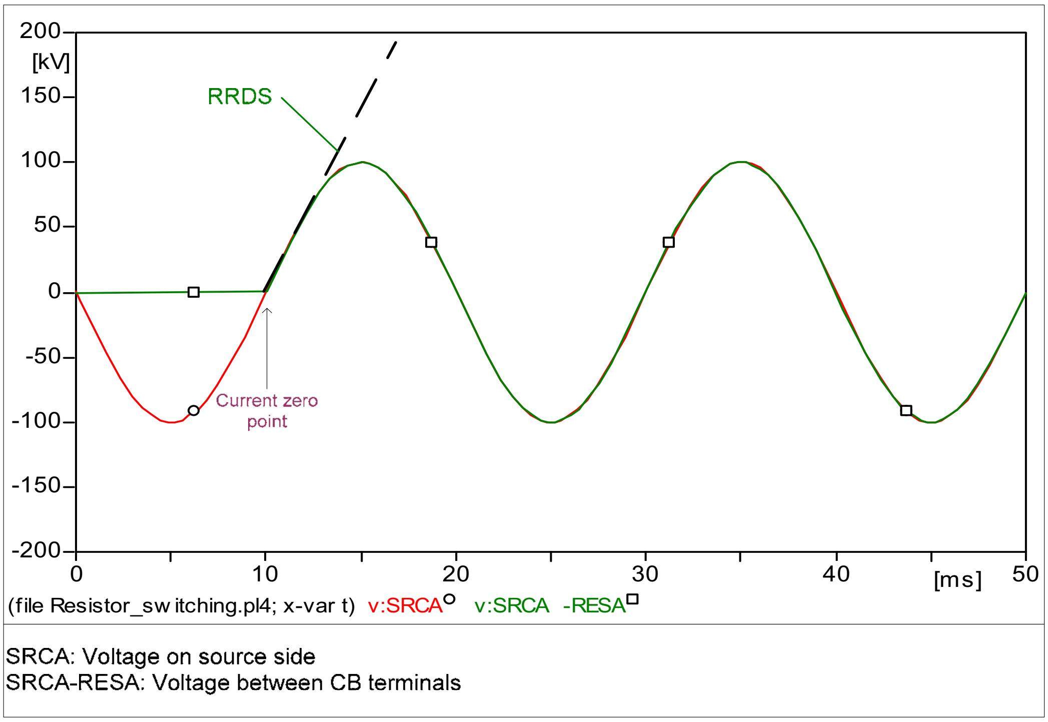


Figure 2.3 – Recovery voltage for resistive load case

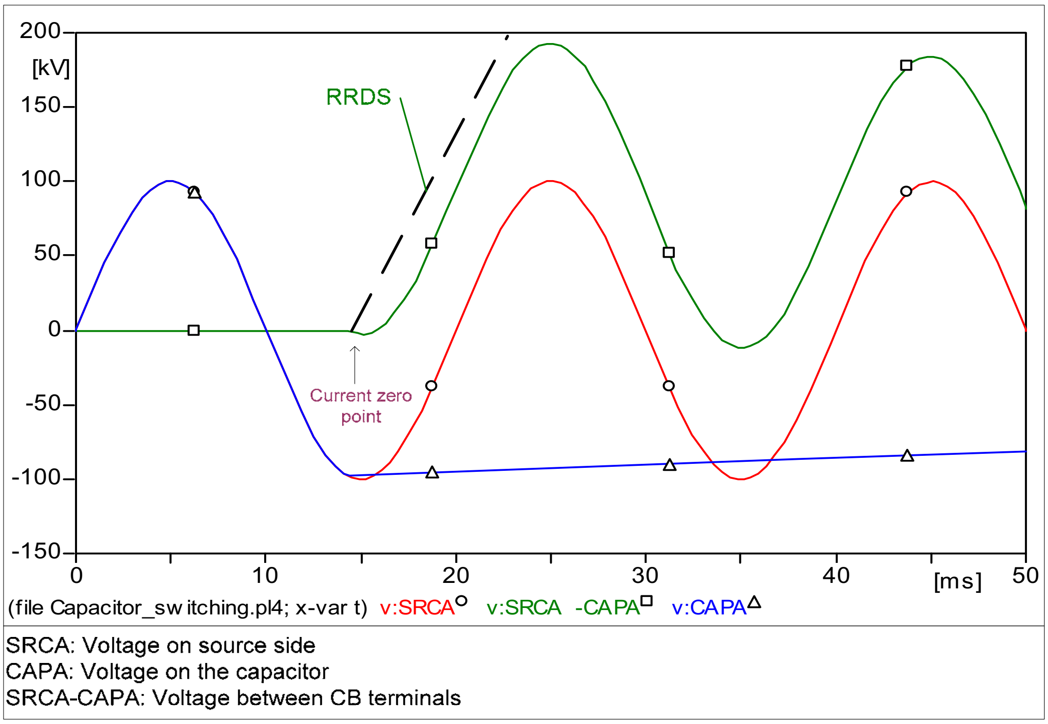


Figure 2.4 – Recovery voltage for capacitive load case

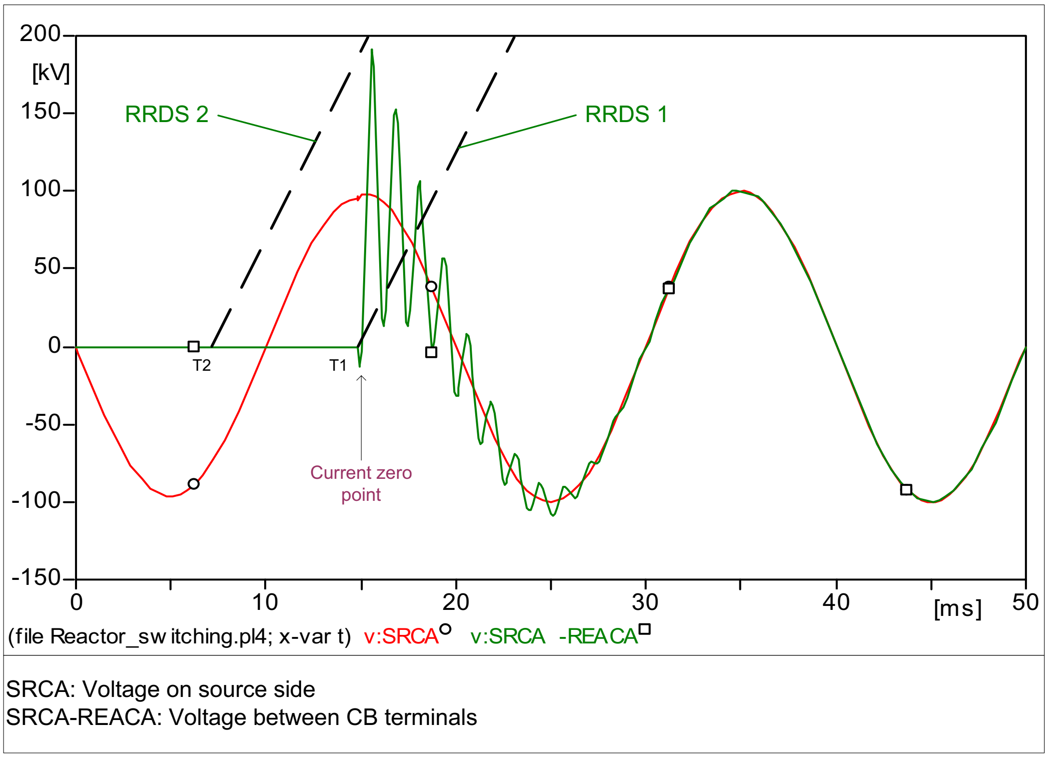


Figure 2.5 – Recovery voltage for inductive load case

Dielectric strength requirements from a circuit breaker for succesfull current interruption differs for various load cases. Details of how such recovery voltages occur in different load cases will be provided in the next chapters.

Circuit breakers are designed to withstand these transient recovery voltages. Circuit breaker's RRDS capabilities are normally designed according to the capacitive switching case with near zero arcing time. There are several reasons for this design criteria:

1 – The majority of circuit breakers are installed on overhead line (or cable) circuits, where no load switching is generally frequent. This no load conditions are generally capactive in nature.

2 – In inductive current interruption case, Rate of Rise of Recovery Voltage (RRRV) is generally very fast, such that it is almost impractical to design a

circuit breaker with an adequate RRDS capability for switching with near zero arcing time.

3 – In capactive switching case, current to be interrupted is generally much smaller than the circuit breaker's rated short circuit current (especially under no-load line or cable conditions), which means that current interruption with very short arcing times is highly possible since the circuit breaker is not inhibited by thermal interruption constraints in this case. Interruption with small arcing times means that the circuit breaker has to establish its recovery voltage withstand capability from a very small contact gap.

The worst case for capacitive current interruption occurs where contacts of the circuit breaker seperates immediately prior to a current zero. In this case the circuit breaker's RRDS capability should be such that it can withstand the capacitive TRV waveshape (1-cosine) without leading to a re-strike. Such an RRDS characteristic is illustrated in Figures 2.3, 2.4 and 2.5.

Taking this RRDS characteristic derived from the capactive switching case and applying it to the resistive and inductive cases, it is possible to observe the reignition / restrike performance of the circuit breaker in resistive and inductive load cases. For the resistive interruption case the evolution of the recovery voltage is not faster than for the capacitive interruption case. Hence the withstand capability derived from the capacitive case is adequate for interrupting current in resistive case.

Evolution of recovery voltage for inductive load case is much faster than for the capacitive case. If the contacts of the circuit breaker seperates immediately before the current zero (T1), then current interruption would possibly fail because of dielectric breakdown as shown in Figure 2.5 with RDDS 1. In order to withstand the inductive recovery voltage, the circuit breaker must develop a minimum contact gap prior to the current zero. If the contacts of the circuit breaker separate sufficiently before the current zero (T2), then the circuit breaker builds up a adequate contact gap prior to the current zero. Hence the dielectric withstand of the circuit breaker becomes sufficiently high to withstand the large and fast developed recovery voltage as shown in Figure 2.5 with RDDS 1.

2.3.2 – Current initiation process

When the contacts of a circuit breaker approach each other, dielectric withstand level between contacts gradually decreases. The rate at which this withstand level is generally referred as Rate of Decrease of Dielectric Strength (RDDS). RDDS characteristics of circuit breakers depend on the several factors such as contact speed and interrupting medium. Nevertheless, RDDS characteristics of modern circuit breakers can generally be approximated by a linear function of time as shown in Figure 2.6

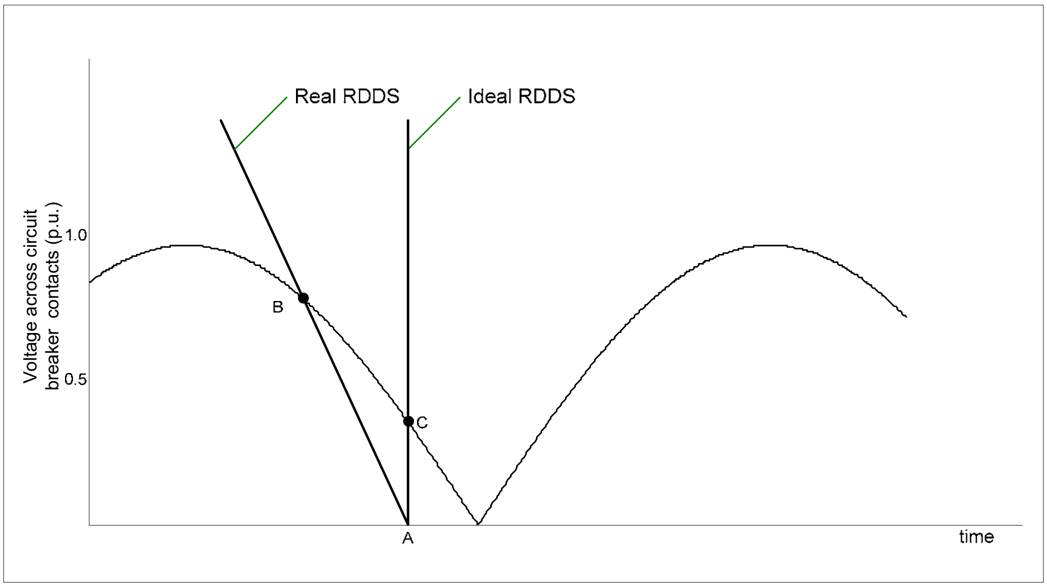


Figure 2.6 – RDDS characteristics of circuit breakers

In Figure 2.6 ideal and real RDDS characteristics are provided. In ideal RDDS, contact speed of the circuit breaker is infinite, whereas in real case it has a finite value. As the contacts of the circuit breaker approach each other, voltage between circuit breaker contacts becomes higher than the dielectric withstand level. At this point a voltage breakdown occurs and current flow starts. This flow of current before actual contact touch is referred as pre-stike, and the instant when the circuit breaker pre-strikes is referred as making instant. Making instants for real and ideal RDDS characteristics are shown in Figure 2.6 with points B and C, respectively. Then the circuit breaker completes its closing operation at point A where the contacts touch each other.

The slope, S_0, of the RDDS is defined as [1];

$$S_0 = k_0 U\omega \tag{2.1}$$

where,

k_0 is the normalized value of the RDDS

U is the peak value of the system phase to earth voltage

ω is the angular frequency of power system voltage

For an ideal circuit breaker k_0 and consequently S_0 is infinite, whereas for real circuit breakers S_0 lies in a range between 35 kV/ms to 100 kV/ms [1].

2.4 – Variations in operating times of circuit breakers

For controlled switching applications, operating time consistency of the circuit breaker to be used is very important, since operation command to the circuit breaker is applied depending on the assumed operating times. Success of a controlled switching application is directly influenced by the difference between assumed and actual operation times. In order to have a succesfull controlled switching application, it is of great importance to estimate and consider the possible variations in circuit breaker operating times.

Variations in circuit breakers operating times can be split into two groups, mechanical and dielectric variations.

Mechanical variation is a result of variations in several factors such as control voltage, ambient temparature, accumulated number of operations, ageing effects and intervals between successive operations (idle time). Results of a survey conducted by TF13.00.1 of CIGRÉ about these variations is given in Table 2.2

Table 2.2 – Variations in circuit breaker operating times (based on the data provided in Table II of [14] *)*

Circuit breaker type	SF_6 circuit breakers					
Mechanism type	Pneumatic		Hydraulic		Spring	
Operation type	Open	Close	Open	Close	Open	Close
Control temperature -40 C to +40 C	±1.0 ms	±1.5 ms	30 µs/C	70 µs/C	30 µs/C	70 µs/C
Control voltage -15% to +10%	±1.0 ms	±1.5 ms	±0.5 ms	±1.5 ms	±0.5 ms	±0.5 ms
Stored energy available -5% to +5%	N/A	N/A	±0.5 ms	-3 ms to +2.5 ms	±0.5 ms	-3 ms to +2.5 ms
Accumulated number of operations	±1.5 ms	±1.0 ms	±1.0 ms	±2.5 ms	±1.0 ms	±1.0 ms
Infrequent operation (over 10 year life)	N/A	N/A	N/A	±10 ms	N/A	±10 ms

Data provided in Table 2.2 shows that the highest variation of operating times is experienced in infrequent operation times (i.e. long idle times). But it is also noted in the related report that obtaining reliable data in this respect is extremely difficult, mainly due to the time and cost required to conduct accurate measurements. Also, another study provided by WG13.07 of CIGRÉ [16] shows that the effect of idle time is moderate, especially in circuit breakers with spring type operating mechanisms, as shown in Figure 2.7

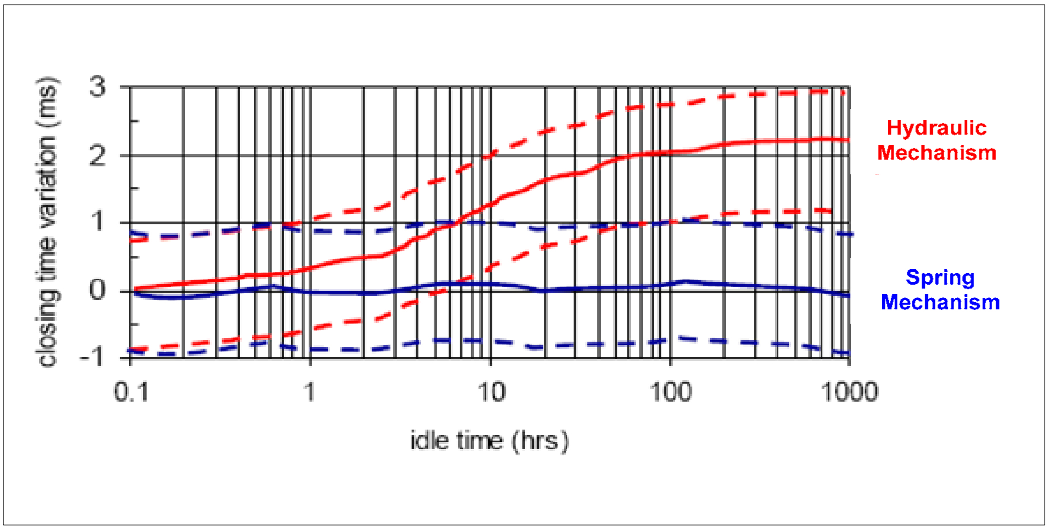


Figure 2.7 – Effect of idle time on closing time variation

Variations in RRDS and RDDS characteristics of a circuit breaker are referred as dielectric variations. These variations depend on several factors such as, contact speed, field distribution within the contact gap and SF6 gas purity. An example of dielectric variation in RDDS characteristics of a circuit breaker is shown in Figure 2.8

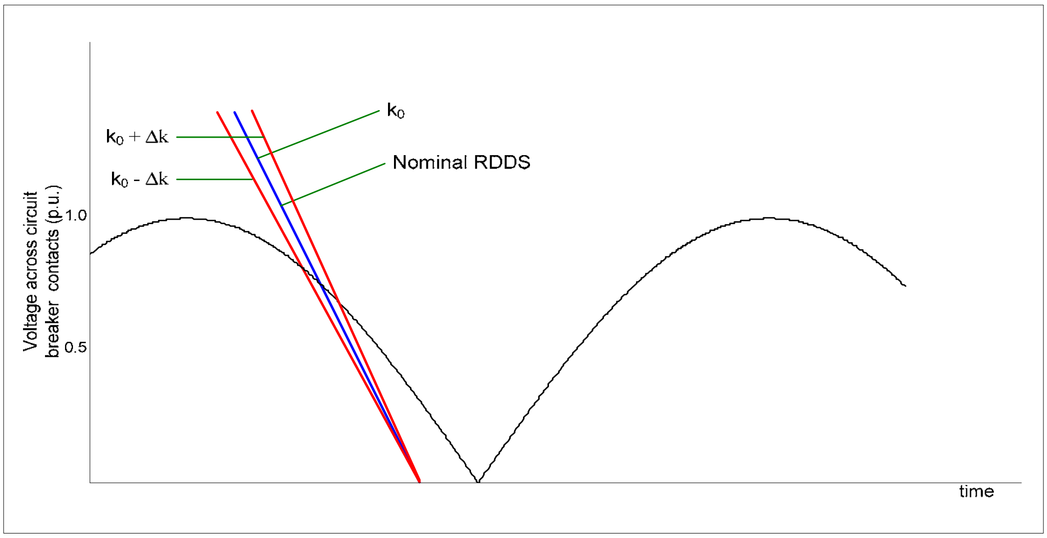


Figure 2.8 – Dielectric variations in RDDS characteristic

2.5 – Closing resistors

Closing resistor is a traditional measure applied for reducing switching overvoltages, especially on long EHV overhead lines. This resistor is switched on before the main contacts of the circuit breaker, and after the current is initiated it is bypassed by the main circuit contacts of the circuit breaker. Typical values of closing resistor are around 400 Ω, corresponding to the typical surge impedance values of long overhead lines.

When the circuit breaker makes, the voltage between circuit breaker contacts immediately before making is distributed to the source and the load sides of the circuit breaker equally, since surge impedances are equal in both sides. In this way the travelling wave imposed on the overhead line is reduced. The time the resistance is switched on is normally in the range of 5-15ms. Closing resistances are normally opened before the arcing contacts of the circuit breaker, hence they are not effective in current interruption process. Operation sequence of a closing resistor is given in Figure 2.9

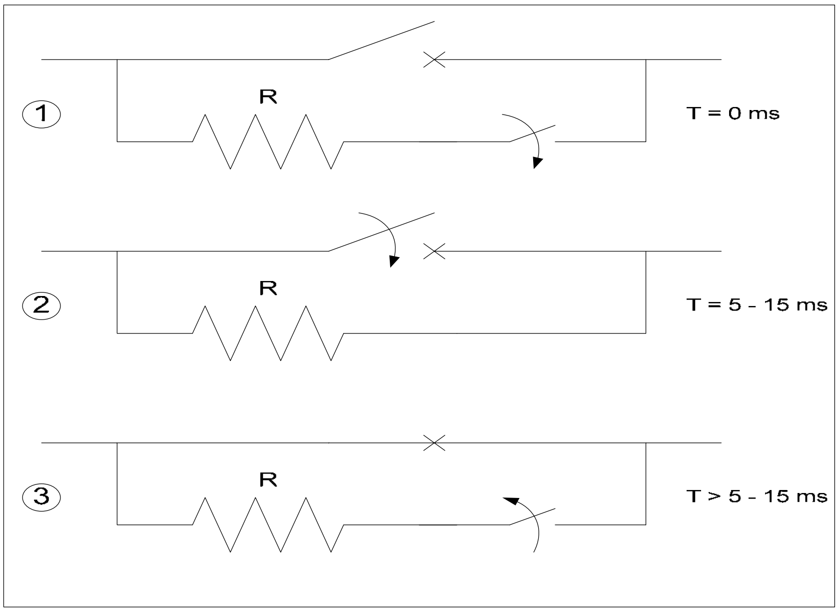


Figure 2.9 – Operation sequence of closing resistor

CHAPTER 3

SWITCHING OVERVOLTAGES

3.1 – Introduction

A switching operation means a change in the state of a power system, that is, parts of the system are connected or disconnected to form a different structure than the one existed before the operation. Such a change will result in a response from the system to readjust itself to the new state. Responses encountered within a power system in the form of overvoltages and/or overcurrents after a switching operation are called switching transients.

A switching operation leading to a transient response may be a current interruption after a fault, or a regular switching operation like reactor, capacitor, transformer or line switching. Since the switching transients are produced not only after fault interruption, but also as a result of routine operations in the system, they can not be totally avoided.

Switching overvoltages may be of important severity and in fact they are virtually the most common cause of dielectric failures in power system equipment. Formation of such unavoidable overvoltages in the system implies that the insulation level of power equipment must be designed to withstand such circumstances. On the contrary, it is clear that an increase in insulation level of a power system would mean a considerable cost, and it is not economically feasible to design the system in order to withstand all possible overvoltages expected. Consequently there should be a compromise solution provided for this problem such that, the overvoltages are limited to a minimum degree possible and the insulation level is designed to this minimum achieveable level.

It should be noted that, switching operations are not the uniqe cause of overvoltages in a power system. Lightning strikes are a source of overvoltages as well. However, insulation level of power system equipments at EHV level are determined mainly according to the switching overvoltages because of their dominant severity. Hence succesfull and reliable limitation of switching overvoltages means a considerable saving in investment for insulation of power system equipment.

Controlled switching is one of the methods used to minimize the effects of switching overvoltages. In order to determine the principles of controlled switching applications for various cases, a comprehensive understanding of mechanisms behind each case of switching overvoltages is of great importance.

In the following subchapters, switching overvoltages related to overhead line, cable and shunt reactor switching will be discussed, since these are the most common types of overvoltages encountered in an EHV network.

3.2 – Overhead line switching

Overhead lines present capacitive behaviour especially when unloaded, and switching operations in such cases are regarded as capacitive current switching. In the following discussion, main emphasis will be placed on overhead line switching overvoltages, but the descriptions given will be applicable to cables and capacitor bank switching as well.

3.2.1 – Circuit breaker opening

Transients generated when opening a circuit breaker with capacitive load may be described using the simplified single phase equivalent circuit given in Figure 3.1.

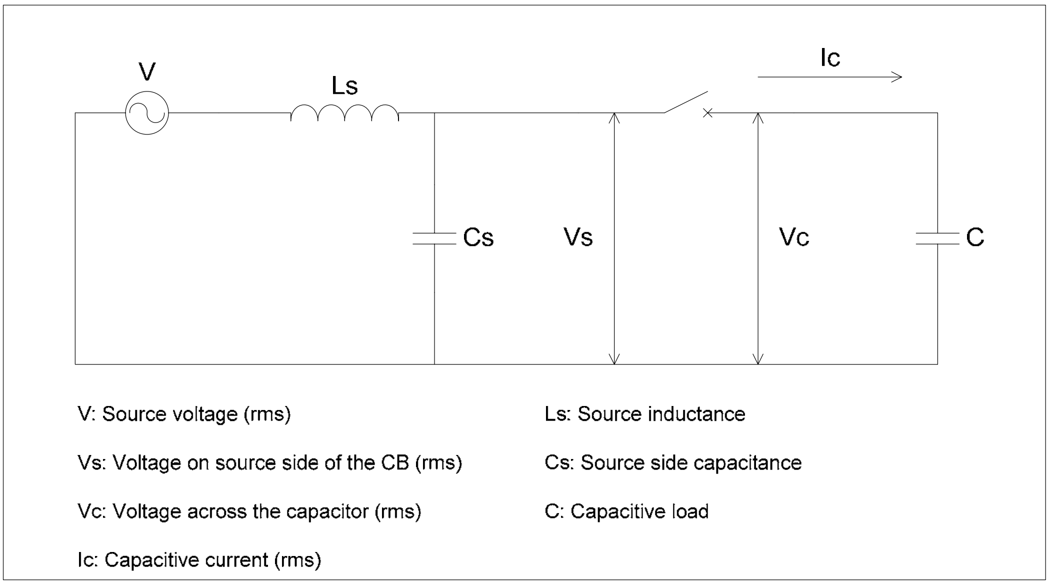


Figure 3.1 – Single phase equivalent circuit of capacitive current switching

Magnitudes of capacitive currents are small (i.e. a few amperes for unloaded cables and overhead lines) in comparison with the high short circuit currents for which the circuit breakers are designed. So, interrupting such small currents is not a heavy task, even with very short arcing times.

In capacitive loads, current Ic leads voltage Vc with 90˚ . At the point of current interruption (i.e. current zero) voltage accross capacitor terminals is the peak value of the voltage on source side of the circuit breaker. After contact seperation, some charge is trapped on the capacitor, and the voltage of the capacitor decays with time.

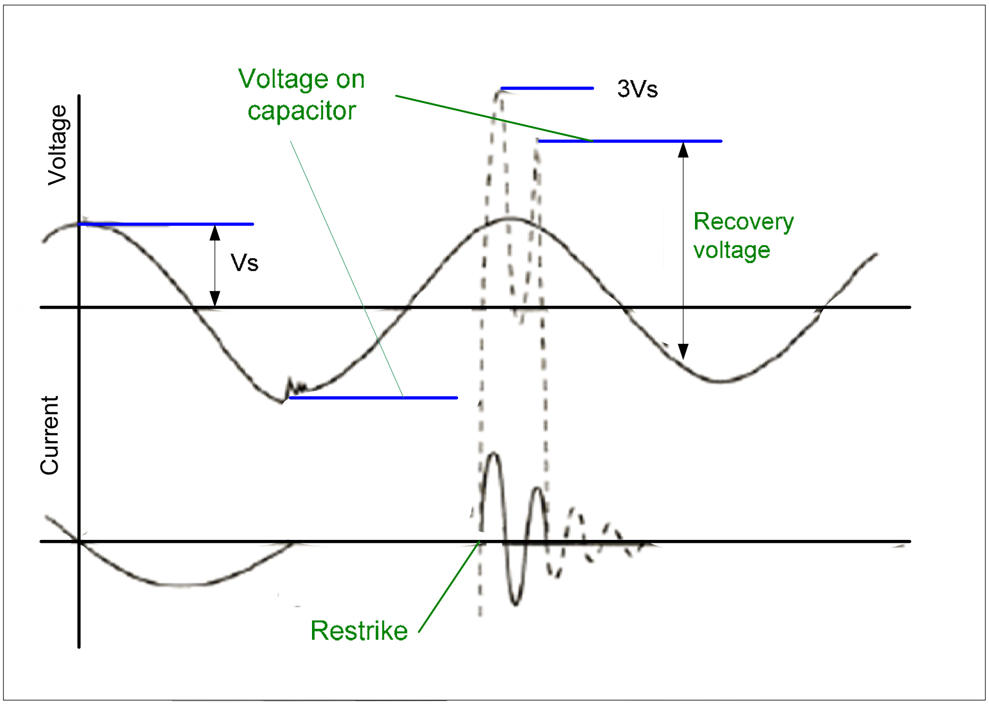


Figure 3.2 – Current and voltage relation at capacitive current interruption

If the opening command to the CB is placed at or very near to current zero point, the current is interrupted in a very short arcing time. As the contacts of the CB seperate further, TRV accross CB increases, since the voltage on the supply side changes. After a half cycle TRV reaches a value of 2 p.u. as shown in Figure 3.2.

When TRV reaches its maximum value, contacts of CB may not be apart enough to withstand TRV, and a dielectric breakdown (i.e. restrike) may be encountered. In such a case capacitor discharges itself through the arc channel with the circuits natural frequency, which is;

$$f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{\omega_0}{2\pi}$$

Assuming that the source voltage remains constant at its peak value during restrike;

$$V_s - V_c = L\frac{dI}{dt} \tag{3.1}$$

and,

$$V_c = V_c(0) + \frac{1}{C}\int I dt \tag{3.2}$$

combining Eqs. 3.1 and 3.2;

$$L\frac{dI}{dt} + \frac{1}{C}\int I\, dt = V_s - V_c(0) \tag{3.3}$$

Where $V_c(0)$ is the voltage on capacitor terminals before restrike.

Transforming this equation to Laplace domain yields;

$$Lsi(s) - LI(0) + \frac{i(s)}{sC} = \frac{V_s - V_c(0)}{L} \tag{3.4}$$

Since $I(0)$=0, then;

$$\left(s^2 + \omega_0{}^2\right) i(s) = \frac{V_s - V_c(0)}{L} \tag{3.5}$$

$$i(s) = \frac{V_s - V_c(0)}{L\left(s^2 + \omega_0{}^2\right)} \tag{3.6}$$

Transforming back to time domain;

$$I(t) = \frac{V_S - V_C(0)}{\sqrt{L/C}}\sin(\omega_0 t) \tag{3.7}$$

Voltage on the capacitor is;

$$V_c = V_c(0) + \frac{1}{C}\int I\, dt \tag{3.8}$$

From Eqs. 3.7 and 3.8, it can be rewritten that;

$$V_c = V_c(0) + \frac{1}{C}\int_0^t \frac{V_s - V_c(0)}{\sqrt{L/C}}\sin(\omega_0 t)\, dt \tag{3.9}$$

At the instant of restrike $V_c(0) = -V$ and $V_s = +V$, hence;

$$V_c = -V + \frac{2V}{\sqrt{LC}}\int_0^t \sin\omega_0 t\, dt \tag{3.10}$$

$$V_c = -V + 2V\left(1 - \cos\omega_0 t\right)$$

As it can be seen from Eq. 3.10 the voltage on CB terminals may reach to a maximum value of 3 p.u. as shown in Figure 2.2. If the high frequency restrike current is interrupted at first zero crossing, then the TRV accross CB reaches to a value of around 4 p.u, when the source voltage reverses its polarity after a half cycle. Even if the contacts of the CB moves further in the mean time, the TRV may still be high enough to cause another restrike. When the resrikes repeat further, very high magnitudes of TRV may be reached, which would result in a flashover on the outside of the interrupter.

Worst case described above is seldomly encountered, since generally first resrike occurs before the peak of TRV and the restrike current is not interrupted at its first current zero but at second or even later current zeros. Thus the trapped charge on the capacitor is usually significantly lower than the value given for the worst case [17].

Sequence of events for capacitive current interruption was studied using a simplified single phase circuit in the discussions given above. But in the real case for unloaded overhead line or cable switching, all three phases would be involved. Moreover, capacitances between phases should also be included in the discussion for overhead lines and some simplifications may also be revised.

In the real case of interrupting three phase capacitive currents, resulting effects of overvoltages are moderate. These differences in switching overvoltages between simplified single phase circuit and real case three phase circuit are governed by following effects [17] ;

- source side voltage jump
- line side initial voltage rise by the Ferranti effect
- power frequency voltage increase at the remote end of the line
- power frequency intercoupling from second and third phase to clear

When the circuit breaker is closed, instantaneous voltage on source side of the circuit breaker terminal is higher than the source voltage by $\Delta V = V_s - V$. This effect is known as Ferranti effect, and is caused by the capacitor acting as a source of reactive power [9]. After current interruption, voltage V_s adjust to V by a transient voltage wave called the initial jump [17]. This initial voltage jump results in a steep change in source side voltage and this steep change may lead to a thermal breakdown and a consecutive reigniton in the interrupting chamber. A reignition occuring soon after current interruption prolongs the arcing time and provides larger gap between circuit breaker terminals when the current is interrupted at next current zero, thus decreases the risk of a restike.

As mentioned above, unloaded overhead lines can be represented as capacitances. When the overhead line is short (<200 km), this capacitance can be represented as a lumped element. But if the overhead line is longer, capacitance should be considered as distributed. Due to the distributed nature of the inductance and the capacitance of the line, the peak value of the power frequency voltage at the remote (or receiving) end is higher than that at the circuit breaker (sending) end of the line [13]. After current interruption line side voltage oscillates in a manner similar to the initial jump on source side. Travelling waves generated in such a case returns from the remote end of the line, leading to a higher overvoltage and increases the risk of a restrike.

Up to this point, overhead lines and cables were represented as phase to ground capacitances. But in reality there are considerable capacitances between phases as shown in Figure 3.3.

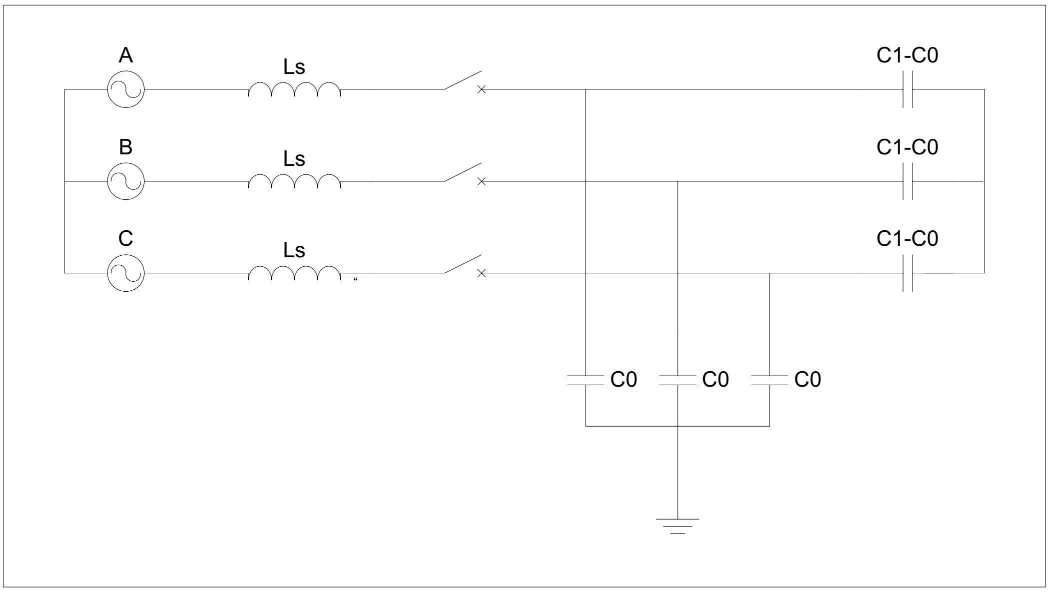


Figure 3.3 – Unloaded overhead line three phase representation

C0 is the capacitance to ground, where C1 is the total capacitance between phases and ground. Peak value of the recovery voltage in the first pole-to-clear (FPTC) as a function of capacitance ratio C1 / C0 is given in Figure 3.4. (redrawn from fig 9 in [13]). Overhead lines typically have a C1/C0 ratio of 2.0, and this value corresponds to a peak value of about 2.4 p.u. in the first pole-to-open. It can also be seen from Figure 3.4 that, when the phase-phase capacitances neglected, that is C1 equals to C0, peak value of th first phase-to-clear is 2.0, as discussed previously. However it should be noted that, cables in EHV network always have individual earth screens per phase, so there is no capacitance between phases.

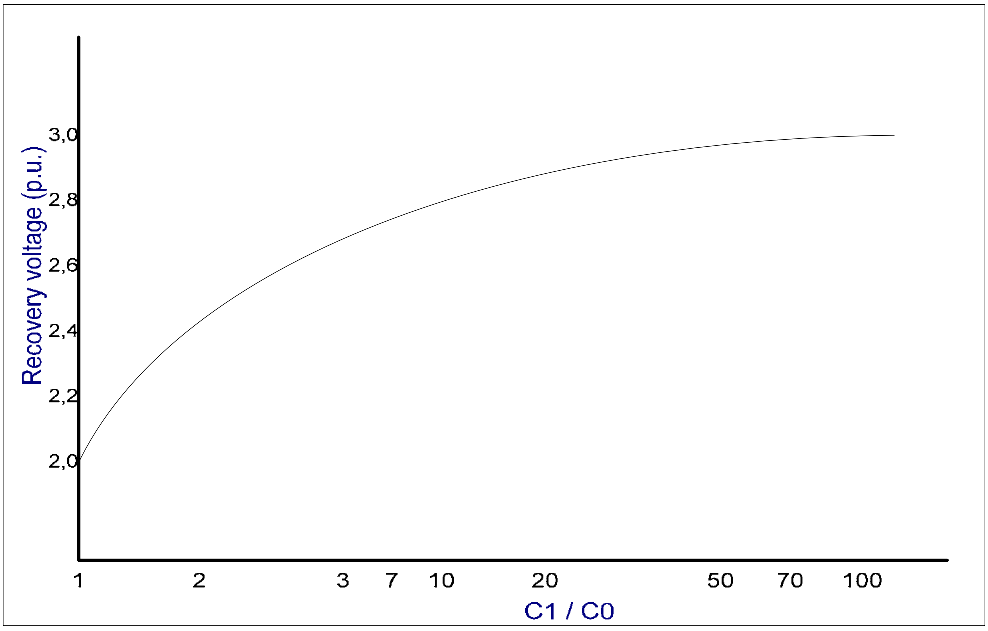


Figure 3.4 – Recovery voltage peak in the FPTC as a function of C1/C0

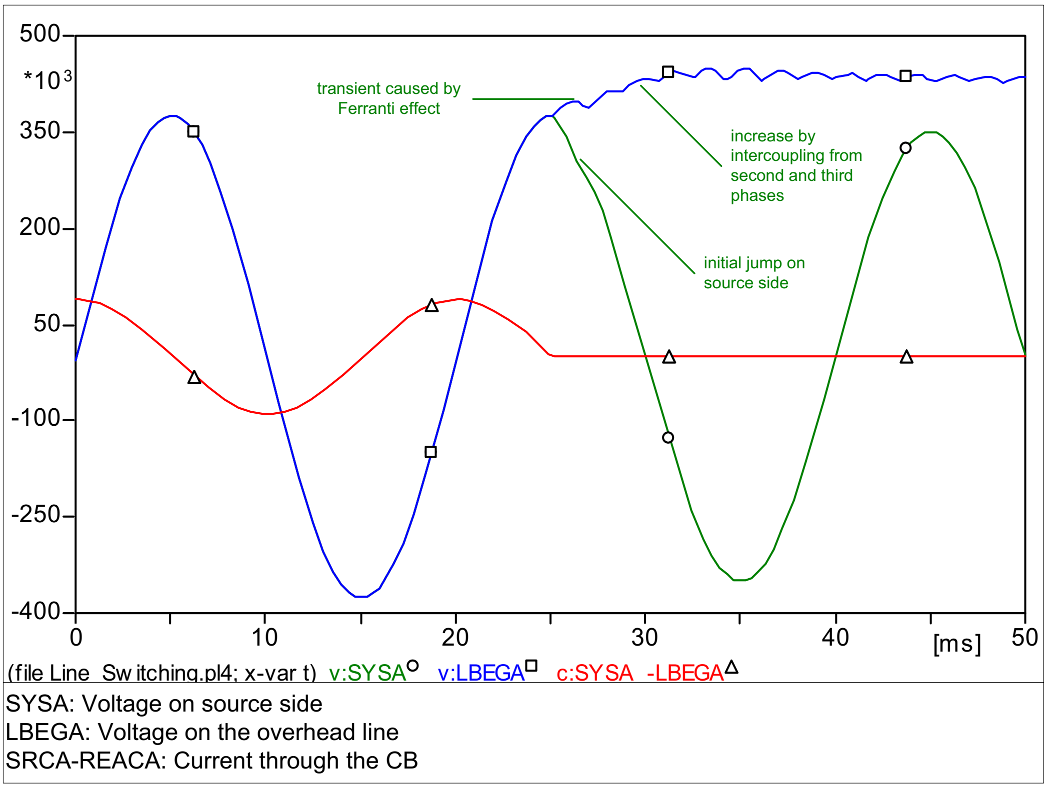


Figure 3.5 – Voltage and current waveforms after overhead line deenergising

Another difference in switching overvoltages between simplified single phase circuit and real case three phase circuit of an overhead line is that, in three phase circuits, capacitive coupling between still energized phases and the first clearing phase after current interruption superimposes a coupled voltage, which can be seen in Figure 3.5.

Ratio of coupled voltage to nominal power system frequency voltage depends on the overhead line design, but it is generally in a range around 0.2 p.u. In cases where a double line is concerned and the second line is energized, this value may reach a value about 0.4 p.u. [17], and this effect increases the risk of a restrike.

In some cases, overhead lines are compensated by a shunt reactor for voltage regulation, especially when the length of the line is long. In such cases voltage trapped on the line after current interruption does not remain constant, but oscillates between line capacitance and shunt reactor, and frequency of this oscillation is the natural frequency of the line side circuit, that is;

$$f_l = \frac{1}{2\pi\sqrt{LC}} = f_s\sqrt{\frac{X_{C,\,line}}{X_{L,\,reactor}}} = f_s\sqrt{k_l} \qquad (3.11)$$

where,

f_l is the resonance frequency of the compensated line (Hz)

L is the inductance of the reactor (H)

C is the total capacitance of the line (F)

f_s is the system frequency (Hz)

k_l is the compensation factor

Compensation factor for practical applications is generally lower than 1, which results in smaller resonance frequency than power system nominal frequency, and reduced recovery voltage at circuit breaker terminals, as it can be seen from Figure 3.6.

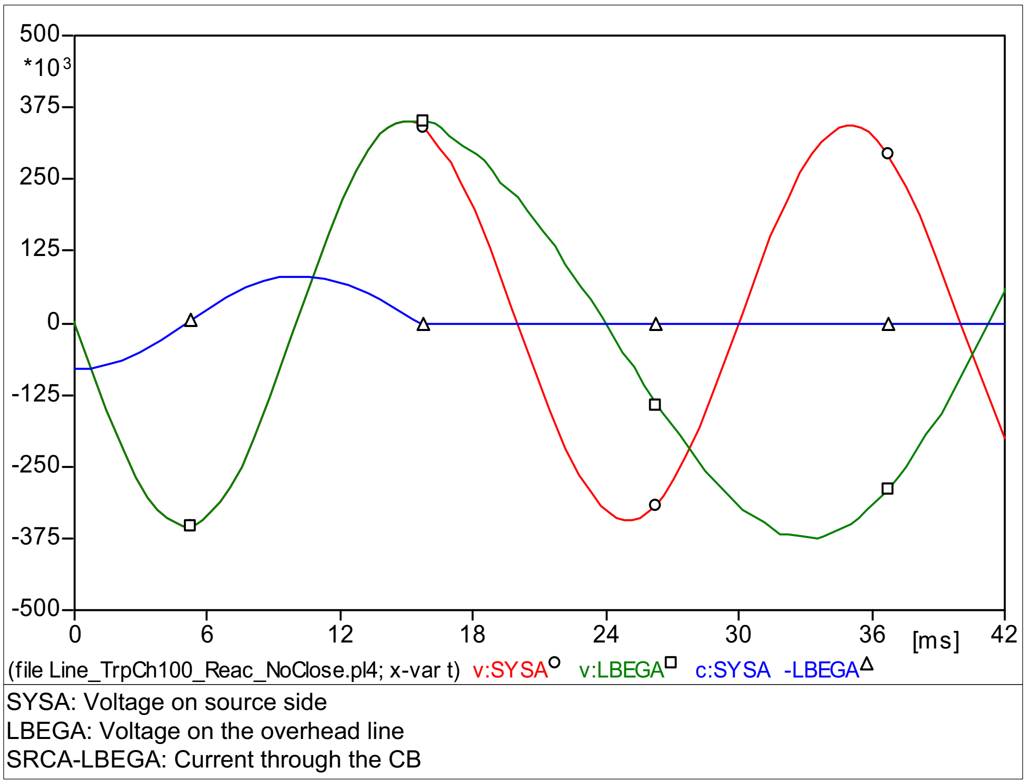


Figure 3.6 – Current and voltage relation in compensated overhead line

3.2.2 – Circuit breaker closing

Circuit breaker closing on an overhead line can result in significant overvoltages, particularly when there is voltage on the line to be energized, which is a commonly encountered situation in fast auto-reclosure applications.

Switching overvoltages generated when energizing an overhead line can be described using the simplified single phase equivalent circuit given in Figure 3.7.

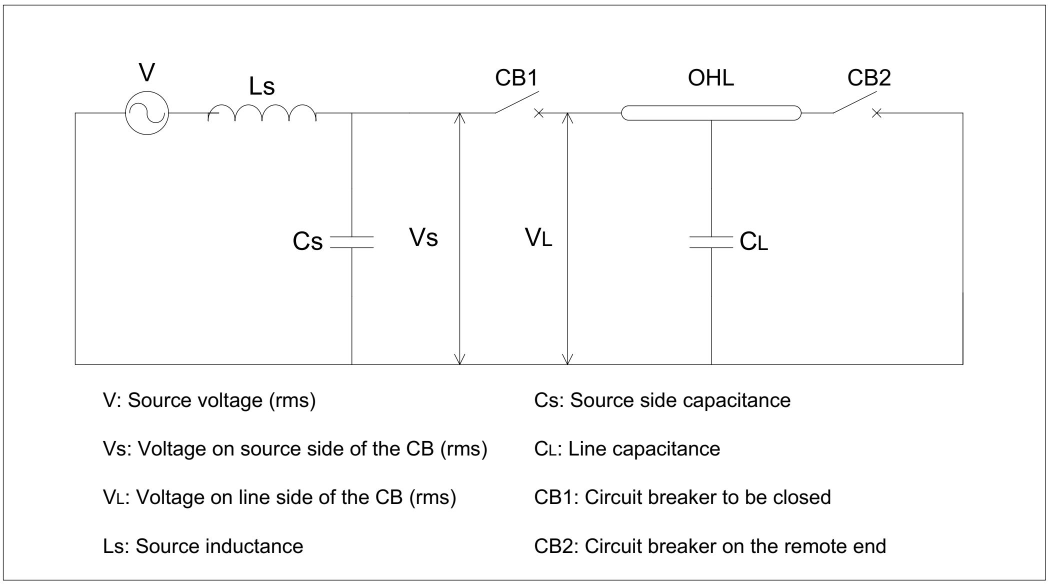


Figure 3.7 – Single phase equivalent circuit of overhead line closing

Before the circuit breaker's contacts touch each other or are joined together by a prestrike, there is a voltage difference on the circuit breaker terminals. At the moment when circuit breaker makes, this voltage is imposed on the line side and source side in the form of travelling waves.

Voltage imposed on the source side and line side are;

$$V_L = \left(\frac{Z_L}{Z_S + Z_L}\right)V \quad \text{and} \quad V_S = \left(\frac{Z_S}{Z_S + Z_L}\right)V \qquad (3.12)$$

where,

V is the voltage between circuit breaker terminals before closing

V_S is the voltage imposed on source side

V_L is the voltage imposed on line side

Z_S is the surge impedance of the source side

Z_L is the surge impedance of the line side

In a heavily interconnected system $Z_L >> Z_S$, hence most of the voltage is imposed on the line side [18]

Severity of the overvoltage generated depends on system conditions. If there is no voltage on the line to be switched, voltage between circuit breaker terminals just before making lies in a range from zero to peak value of the power frequency voltage. Worst case occurs when circuit breaker makes at a point where the source side voltage is at peak value and remote end of the line is open. In such a case reflection of traveling wave from the open line end leads overvoltage on the line to a value approaching 2 p.u. A simple description of the case is given in Figure 3.8

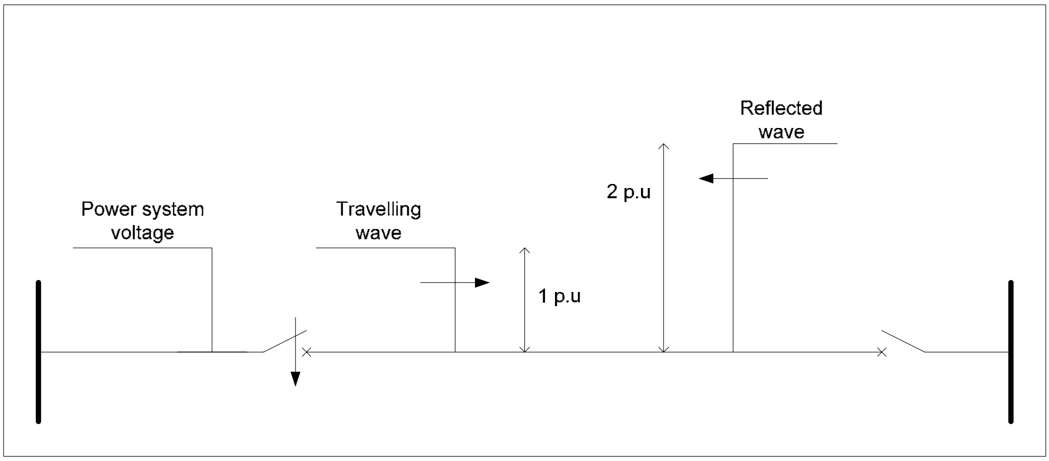


Figure 3.8 – Travelling wave reflection from open line end

If there is trapped charge on the line before closure, which is a possible case as described before, voltage between circuit breaker terminals before making may reach to a value of 2 p.u. in the worst case when the line voltage is at peak value and the source voltage is at opposite peak value. With the effect of reflection when the remote end circuit breaker is open, the overvoltage may reach to a maximum value of 4 p.u. theoretically [8]

Sequence of events for overhead line energization was described using a simplified single phase circuit in the discussions given above. But in the real case all three phases would be involved, and some complicating effects such as auto reclosing and shunt reactor existence should be considered as well. Also in real case discussions some simplifications should be revised, such that damping effects and distributed nature of very long overhead lines are taken into account.

In EHV overhead lines it is a general application to reclose circuit breakers after clearing a fault, in order to improve system reliability. When the circuit breaker clears an asymmetrical fault by three phase operation, healthy phase(s) remains charged. Phase(s) with trapped charge needs a leakage path to discharge. If the line is equipped with a shunt reactor, then the line will discharge through the shunt reactor with the circuits natural frequency as given in Eq. 3.11 and this oscillation will decay in time because of the damping present in the circuit.

In case the line is not equipped with a shunt reactor, which is common for medium length lines (<200 km), leakage path for discharge is limited, since at EHV level capacitive voltage transformers are used instead of inductive voltage transformers and capacitive voltage trasformers do not provide a discharge path for trapped charges. In some cases such as at extremely dry air conditons, voltage on the transmission line may remain almost constant for many seconds after current interruption [18] [19]. Level of trapped charge on an unloaded overhead line is shown in Fig 3.9 [20]

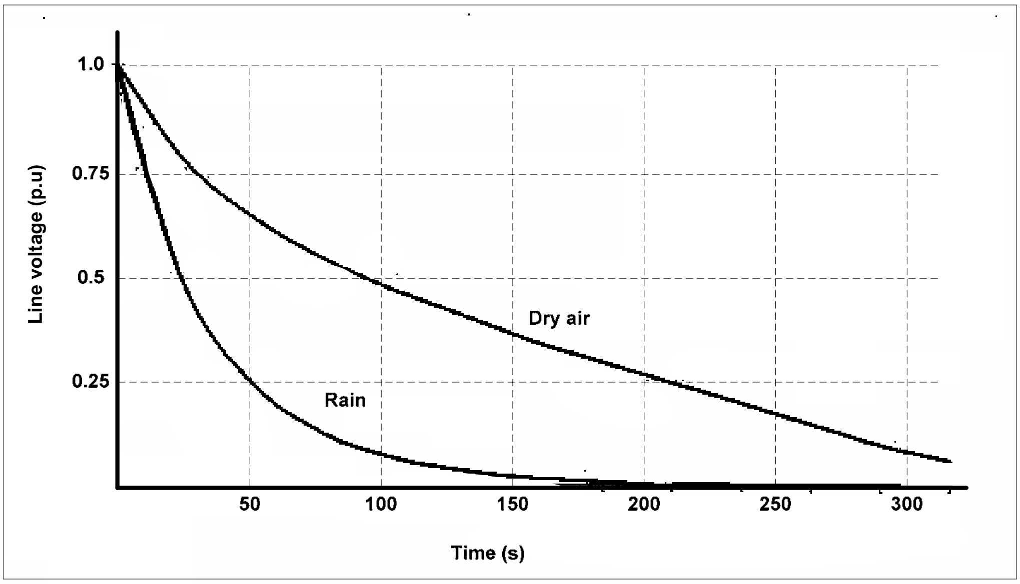


Figure 3.9 – Decay of trapped charge on an unloaded overhead line

At EHV level auto reclosure is applied in a very short time after interruption of fault current. Time between current interruption and initiation of close command, which is called dead time, is generally in a range between 0,3 s to 1s. In such a short time period, trapped charge on healthy phase(s) in worst case may be around peak value of power frequency voltage. If the circuit breaker makes at the opposite voltage peak, then the transient voltage imposed on the line may reach a value of 2 p.u., and if the remote end circuit breaker is open, an overvoltage level around 3,5 p.u may be reached [15]

Complications present in overhead line switching does not cover only auto reclosing application with or without compensation, but it covers many other factors. As an example, after the first pole of the circuit breaker closes, there will be voltage coupling to the other phases. Effects of such complicating conditions are very hard to be predicted by manual calculations and they can mainly be examined by computer simulatons like EMTP-ATP.

It should be noted that, auto reclosure is not applied to cables [21], which means that the possibility of closing on a charged cable is low.

3.3 – Shunt reactor switching

Shunt reactors are used for voltage regulation purpose in EHV networks, especially on very long lines. And they are frequently, often daily, switched to compensate for system loading and configuration changes.

Transient overvoltages are encountered in current interruption. There are transient responses from the system in closing operations as well, but these responses are in the form of overcurrents. Hence main emphasis will be placed on current interruption in the following discussions.

Shunt reactors may be grounded directly or through a neutral reactor, or they may be ungrounded. In the following discussion main emphasis will be placed on directly grounded shunt reactors, since it is the most common application.

3.3.1 – Circuit breaker opening

Shunt reactors are frequently switched equipments as mentioned above. Most of these switching operations are carried as a daily routine, without an existence of a fault in the system. In such cases, current to be interrupted is very small (around 100 Amps) compared to rated short circuit currents which the circuit breakers are designed for. Interrupting such small magnitudes of current is not a heavy task, but the overvoltages generated may be of important severity. Simplified circuit diagram of shunt reactor opening is given in Figure 3.10

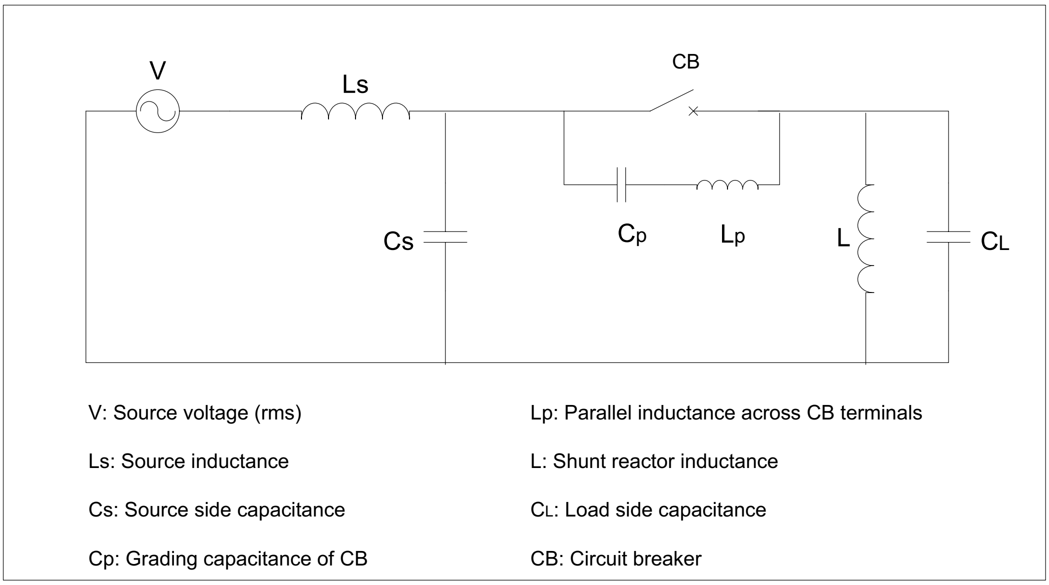


Figure 3.10 – Single phase equivalent circuit of inductive current interruption

Transient overvoltages generated by interruption of small inductive currents can be classified in two groups; chopping and reignition overvoltages.

3.3.1.1 – Chopping overvoltages

Current chopping is defined as "an abrupt current interruption in the circuit breaker away from the natural power frequency current zero of the circuit connected to the circuit breaker" [22]. Possibly the most comprehensive investigation on this phenomena is provided by Working Group 13.02 of CIGRÉ[22][23][24][25][26][27][28][29]

Current chopping is caused by arc instability, which exhibits itself in the form of a negatively damped current oscillation superimposed on the load current. The oscillation amplitude increases rapidly, creating a current zero at which the circuit breaker usually interrupts. The frequency of the oscillation is such that current chopping can reasonably be assumed to be instantaneous [30].

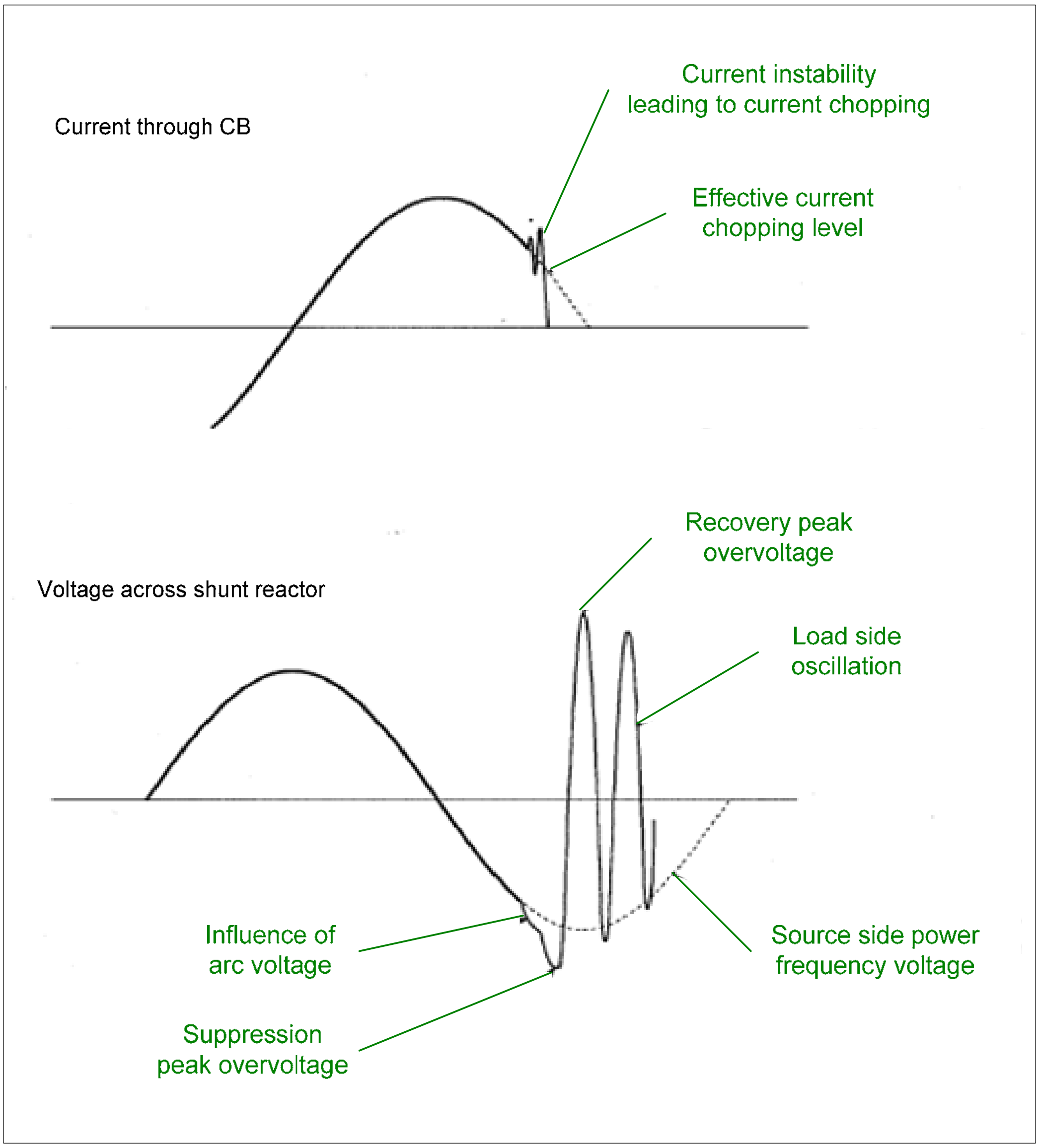


Figure 3.11 – Current chopping during interruption of small inductive currents

Effects of the current chopping phenomena can be seen in Figure 3.11 (redrawn from Fig 2 in [30])

Chopping current level is given by the equation [25] ;

$$i_{ch} = \lambda\sqrt{N\ C_T} \qquad (3.13)$$

where,

i_{ch} is the current level at the instant of current chopping (A)

C_T is total capacitance in parallel with the breaker (F)

λ is the chopping number for a single interrupter ($AF^{-0,5}$)

N is the number of interrupting units per pole

For the circuit given in Figure 3.7, total capacitance C_T is;

$$C_T = C_p + \frac{C_s C_L}{C_s + C_L} \tag{3.14}$$

Assuming $C_s >> C_L$, then

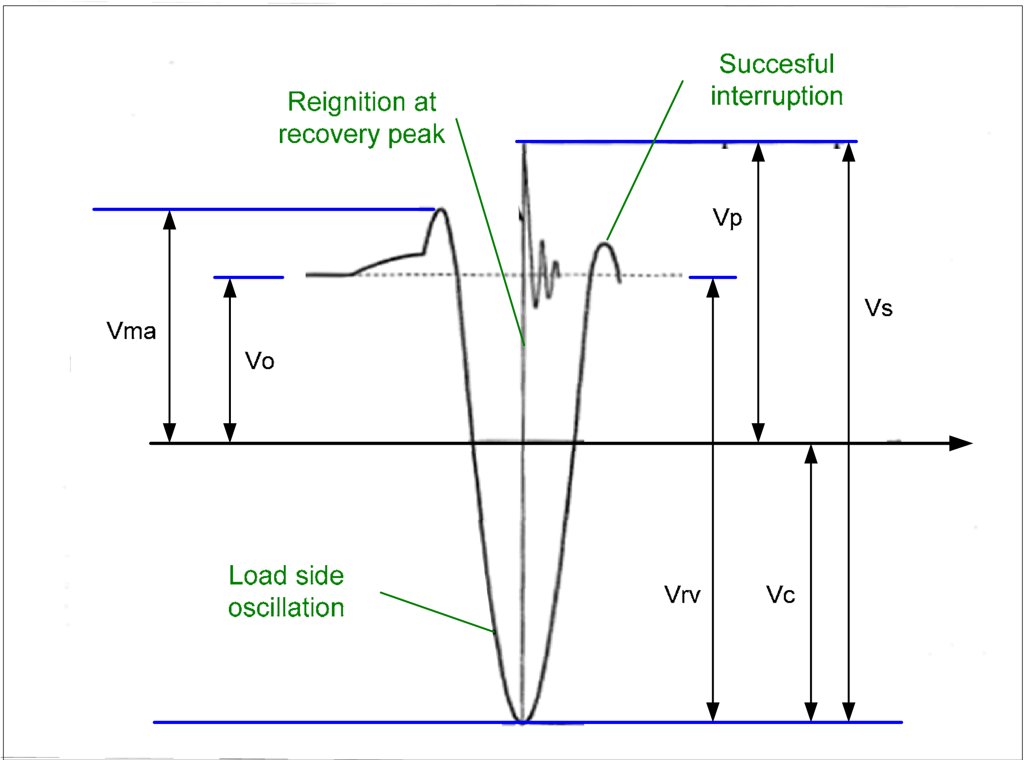
$$C_T = C_p + C_L \tag{3.15}$$

Chopping number is a characteristic of the circuit breaker. Also it depends on the arcing time [31]. Typical chopping numbers of circuit breakers with single interrupting units are given in Table 3.1. (based on data provided in [22])

Table 3.1 – Typical chopping numbers of circuit breakers

Circuit breaker type	Chopping number (λ)
Minimum oil	$7 – 10 . 10^4$
Air blast	$15 – 20 . 10^4$
SF_6	$4 – 17 . 10^4$

Overvoltages generated by interruption of small inductive currents and specific terminology used for referring these overvoltages can be seen from Figure 3.12 (redrawn from [31])



Vo:	Voltage across shunt reactor at instant of current interruption
Vma:	Suppression peak overvoltage to ground
Vc:	Recovery overvoltage peak to ground
Vp:	Reignition overvoltage peak to ground
Vs:	Reignition overvoltage excursion peak to peak
Vrv:	Peak recovery voltage accross circuit breaker

Figure 3.12 – Overvoltages during interruption of small inductive currents

When the current is interrupted at the moment of chopping, trapped energy on shunt reactor inductance oscillates between inductance and load side capacitance, with the circuit's natural frequency;

$$f = \frac{1}{2\pi\sqrt{LC_L}} \tag{3.16}$$

which generally lies in a range between 1 – 10 kHz [32] This oscillation leads to overvoltages at load side, which damps out with the effect of losses in the circuit.

First peak of the oscillation is referred as suppression peak overvoltage, and it has the same polarity with the system voltage at the time of interruption. Second peak of the oscillation is referred as recovery peak overvoltage, and its polarity is opposite to the first one.

Since the frequency of the oscillation is very high in comparison to the power system nominal frequency, voltage of the system can be considered to be constant during the peak values of load side oscillations. Maximum recovery voltage across the circuit breaker generated by chopping overvoltage is encountered in the second peak of load side oscillation. Overvoltage factor in this case is;

$$k_{rv} = \frac{V_{rv}}{V_0} = \frac{V_0 + V_c}{V_0} = 1 + k_c \qquad (3.17)$$

where

k_{rv} is the peak recovery overvoltage factor across circuit breaker terminals

k_c is the recovery peak overvoltage factor and is equal to $\frac{V_c}{V_0}$

V_0 is the voltage across the shunt reactor at the instant of current interruption

Since at the moment of current interruption the load is inductive and current lags voltage by nearly 90°, it is possible to assume that voltage V_0 is equal to power system voltage peak value.

Neglecting damping in first two peaks of oscillation, first and second peaks of load side oscillation may be accepted to be equal in directly grounded shunt reactors. [30]

Then,

$$V_{ma} = V_c \qquad (3.18)$$

$$\frac{V_{ma}}{V_0} = \frac{V_c}{V_0} \quad \Rightarrow \quad k_a = k_c \qquad (3.19)$$

where

k_a is the suppression peak overvoltage factor and is equal to $\frac{V_{ma}}{V_0}$

For the circuit given in Figure 3.10 energy balance equation can be written as;

$$\frac{1}{2} C_L V_{ma}^{\ 2} = \frac{1}{2} C_L V_{CL}^{\ 2} + \frac{1}{2} L\, i_{ch}^{\ 2} \tag{3.20}$$

where

V_{CL} is the voltage across the load side capacitance at the instant of current interruption and is equal to V_0

$$\frac{C_L V_{ma}^{\ 2}}{V_0^{\ 2}} = \frac{C_L V_0^{\ 2}}{V_0^{\ 2}} + \frac{L\, i_{ch}^{\ 2}}{V_0^{\ 2}} \tag{3.21}$$

Then k_a is,

$$k_a = \frac{V_{ma}}{V_0} = \sqrt{1 + \frac{L}{C_L}\left(\frac{i_{ch}}{V_0}\right)^2} \tag{3.22}$$

Assuming $C_s >> C_L$ and $C_s >> C_p$, and combining Eq. 3.13 and Eq. 3.22,

$$k_a = \sqrt{1 + \frac{L}{C_L}\left(\frac{\lambda^2 N C_L}{2\omega Q L/3}\right)} = \sqrt{1 + \frac{3N\lambda^2}{2\omega Q}} \tag{3.23}$$

where

Q is the shunt reactor rating (VA)

ω is the angular power frequency of the power system ($2\pi f$)

As it can be seen from Eq. 3.23, chopping overvoltage is only dependent on chopping number and reactive power of the shunt reactor. And for practical applications k_a factor is generally lower than 1,4 as depicted in [14]

3.3.1.2 – Reignition overvoltages

Small inductive currents may be interrupted with a very short arcing time, since as mentioned before, current magnitudes are very small in comparison to rated short circuit current of the circuit breaker. When the current is interrupted with a very short arcing time, contacts of the circuit breaker may not be apart enough to withstand the recovery voltage generated. In such cases a reignition may occur as shown in Figure 3.12

When a reignition occurs, transient response to equalize load and source side voltage generates an overvoltage referred as reignition overvoltage. Maximum overvoltage factor in such a case is given by the equation;

$$k_p = \frac{V_p}{V_0} = 1 + \beta(1 + k_a) \qquad (3.24)$$

where

β is the damping factor whose value will not normally exceed 0,5. [30]

Oscillating overvoltage generated by reignition has mainly three modes, namely first parallel oscillation, second parallel reignition and main circuit oscillation, which are shown in Figure 3.13 (redrawn from Figure 6 in [30])

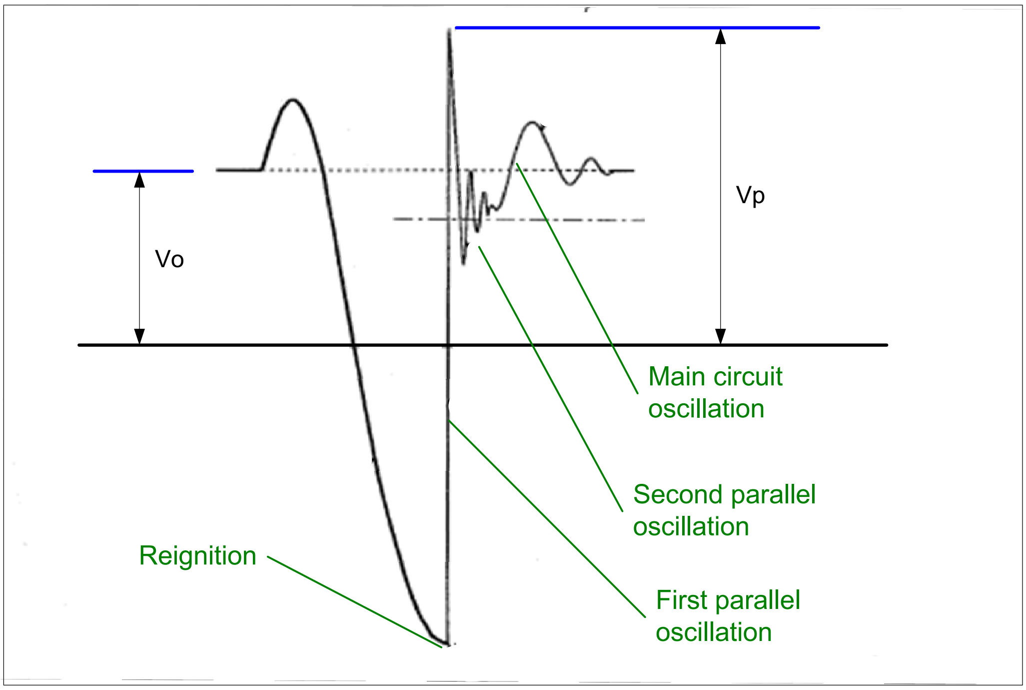


Figure 3.13 – Oscillation modes at reignition

At the instant of reignition grading capacitor C_p discharges through the circuit breaker and generates an oscillation commonly referred as first parallel oscillation with a frequency in a range between 1 – 10 MHz. After this oscillation, another oscillation mode develops to equalize C_s and C_L, which is referred as second parallel oscillation, and its frequency lies in a range between 50 – 1000 kHz.

First parallel oscillation can not be interrupted by circuit breaker because of its very high frequency, but the second oscillation may be interrupted. If not, another mode of oscillation develops, which involves the total circuit both on source and load sides, and is referred as main circuit oscillation. Frequency of main circuit oscillaton is in a range between 5 – 20 kHz [32] [33]

Discussions provided above were based on the assumption that inductive current is interrupted in a very short arcing time, which increases the possibility of reignition. If the current is interrupted with a long arcing time, which provides circuit breaker to increase the gap length between its contacts at the instant of current zero, current interruption can be succesfull, i.e. without reignition. If this is not the case, a reignition would be inevitable. After reignition, oscillating current may be interrupted again during the second parallel oscillation or main circuit oscillation. In such a case load side capacitance C_L is charged to a higher value than before, because of the considerably high rate of change of interrupted oscillating current (di/dt), and load side oscillation starts again, but now with a much higher overvoltage value. Even though contacts of the circuit breaker has seperated further in the mean time, dielectric withstand level of the circuit breaker may not be enough to withstand this dielectric stress, and may lead to a new reignition. If this process repeats itself furher, very high magnitudes of overvoltage may be encountered, which may lead to a flashover out of the circuit breaker and possible damage to the insulation of power system equipment around. This gradual increase in overvoltage level is referred as voltage escallation [34]

Inductive current switching transient overvoltages for ungrounded and reactor ground reactors are somewhat different than the case for directly grounded reactors. In ungrounded and reactor grounded cases, the voltage change in the neutral point after first-pole-to-open is induced to still closed phases [32]. Another important point in inductive current switching overvoltages is the interaction between phases during the load side oscillation, which exhibits itself in the form of beating of the recovery voltage [35] [36].

3.3.2 – Circuit breaker closing

Energization of a shunt reactor does not pose an important problem in overvoltage point of view, but it can cause high inrush currents which may place excessive stress on reactor windings and lead to malfunction of protective relays.

Closing of the circuit breaker to energize a shunt reactor is similar to the occurrence of reignition encountered when interrupting inductive currents. Worst case for energizing a shunt reactor occurs when the circuit breaker makes at source voltage peak. Even in such a case, transient overvoltage does not exceed 1,5 p.u. as it can be deduced from Eq 3.24 with a damping factor (β) value of 0,5.

CHAPTER 4

CONTROLLED SWITCHING APPLICATIONS

4.1 – General Phenomena of Controlled Switching

Controlled switching is a method used to eliminate harmful transients generated by switching operations. In this technique opening or closing commands to the circuit breaker are delayed in such a way that current interruption or initation occurs at a pre-determined point on an electrical reference signal, i.e. voltage or current waveform.

Controlled switching is not a new concept, rather it has been investigated for approximately 35 years. Studies about controlled switching has yielded with a general acceptance that controlled switching is an effective method in reducing switching surges especially for certain application cases. Also it is widely accepted that degree of control possible by use of controlled switching is equal to or better than that achieved by other control methods such as opening or closing resistors. Questions however exist about the reliability of controlled switching, but with the advent of electronics, questions about reliability has decreased considerably. Furthermore controlled switching is an economically feasible application considering the cost and complexity of the methods replaced by controlled switching.

Possibly the most comprehensive review of controlled switching has been conducted by CIGRÉ, through Task Force 13.00.1 Working Group 13.07 under Study Committee A3 (previously designated SC13). This group has produced a number of reports on this topic including a two part state-of-the-art survey [14][15], three application guide reports [1][2][37], a report on the benefits and economic aspects of controlled switching [38] and a report considering "non-conventional" and possible future applications of controlled switching [39].

Controlled switching method can be described basicly with a comparison between controlled and non-controled switching. Figure 4.1 provides an illustrating example for controlled switching in opening operation

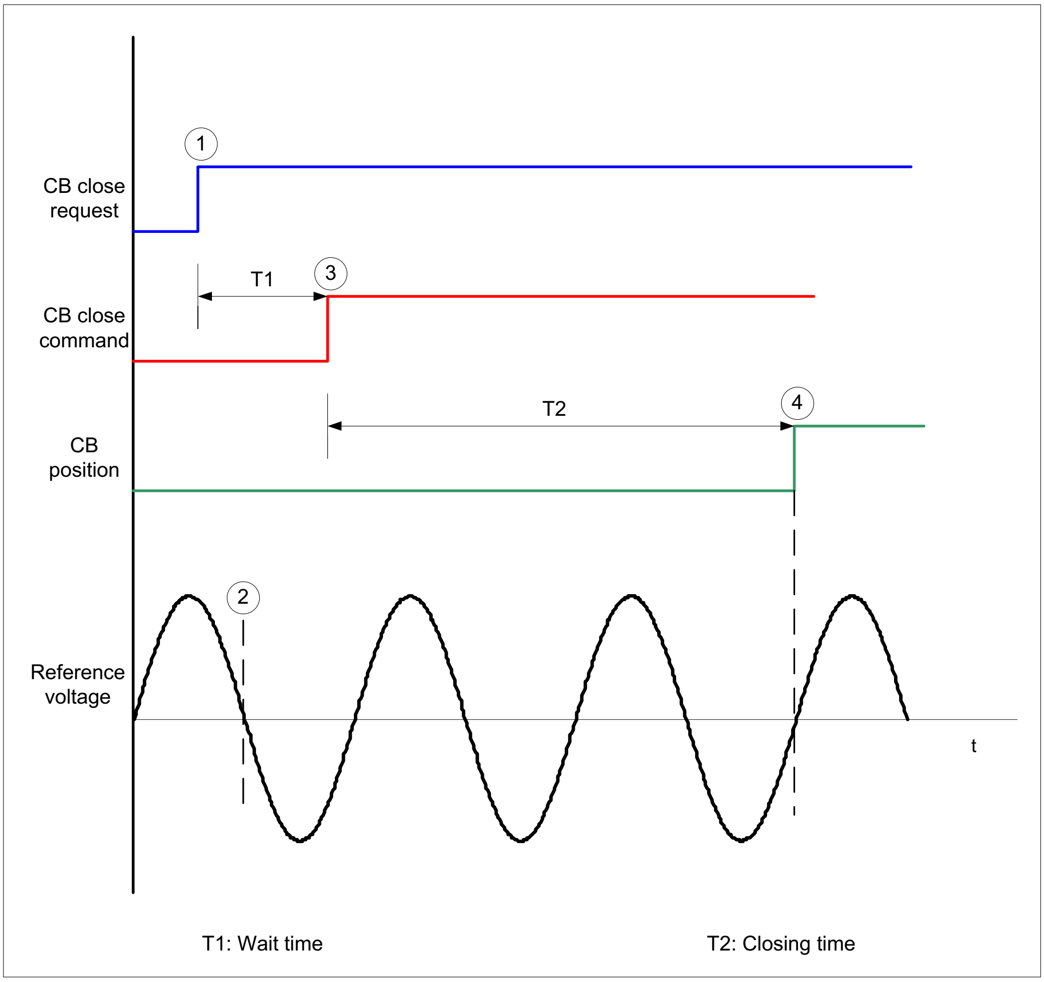


Figure 4.1 – Controlled switching example

In this example optimum instant for contact touch of the circuit breaker is determined to be at a point where the associated voltage wave is at zero. If the close command to the circuit breaker is applied without any means of control, then the actual point on the associated voltage wave at the instant of contact touch would be completely random. In order to achieve a contact touch at voltage zero, a target point should be determined and the time to give close command should be estimated based on closing time of the circuit breaker, which is known by measurements.

Sequence of events for controlled switching in this example is as follows;

- Circuit breaker close request is received at point 1
- In order to determine the target point, next voltage zero is detected at point 2
- Knowing the circuit breaker closing time and power system frequency, target voltage zero is identified
- Time to give close command to the circuit breaker is estimated, and the close command is applied at point 3
- Contacts of the circuit breaker touches at target voltage zero at point 4

The example given above includes following assumptions;

- Operating time of the circuit breaker is constant
- Power system frequency is constant
- RDDS of the circuit breaker is infinite.
- Target point is well defined.

In practice, these assumptions providing an ideal operation can not be met. Real case application considerations will be presented in following discussions.

Transient overvoltages generated by switching operations at EHV level are generally due to overhead line and shunt reactor switching. In the following discussions controlled switching applications for shunt reactor and overhead line switching will be presented.

4.2 Controlled switching of shunt reactor banks

Controlled switching of shunt reactors is a quite mature technology. Extensive number of investigations has been carried out to determine optimum switching instants and controlled switching is accepted to be a standard application in shunt reactor switching within the past decade.

Switching overvoltages generated by shunt reactor switching may be hazardous to power system equipment insulation as described in section 3.2. Overvoltages are generated by both opening and closing operations. However overvoltages generated at opening are more severe than the ones at closing, hence controlled switching for overvoltage reduction purpose is generally applied to opening operations. Overvoltages associated with shunt rector current interruption can be classified in two groups, namely chopping and reignition overvoltages.

At EHV level virtually all circuit breakers used for shunt reactor switching lead current chopping. Overvoltages generated by current chopping can not be avoided since it is a natural result of current interruption process. Nevertheless magnitudes of overvoltages due to current chopping are seldom severe and they are generally less than 1.5 p.u. [2].

Essentially detrimental type of overvoltages encountered in shunt reactor switching is the reignition overvoltages. Magnitudes of reignition overvoltages are higher than chopping overvoltages and typical values of these overvoltages are in the range between 2.0 to 2.5 p.u. Such temporary overvoltage magnitudes can normally be tolerated by the insulation level of the local system, but the rate of change of voltage associated with such events may severely stress the first turns of the reactor windings [2].

Controlled switching can be used to eliminate reignition overvoltages by controlling the opening instant in order to achieve a minimum arcing time such that at the current zero point there is enough distance between circuit breaker contacts to withstand the transient recovery voltage generated.
Controlled switching of shunt reactors can be described using Figure 4.2.

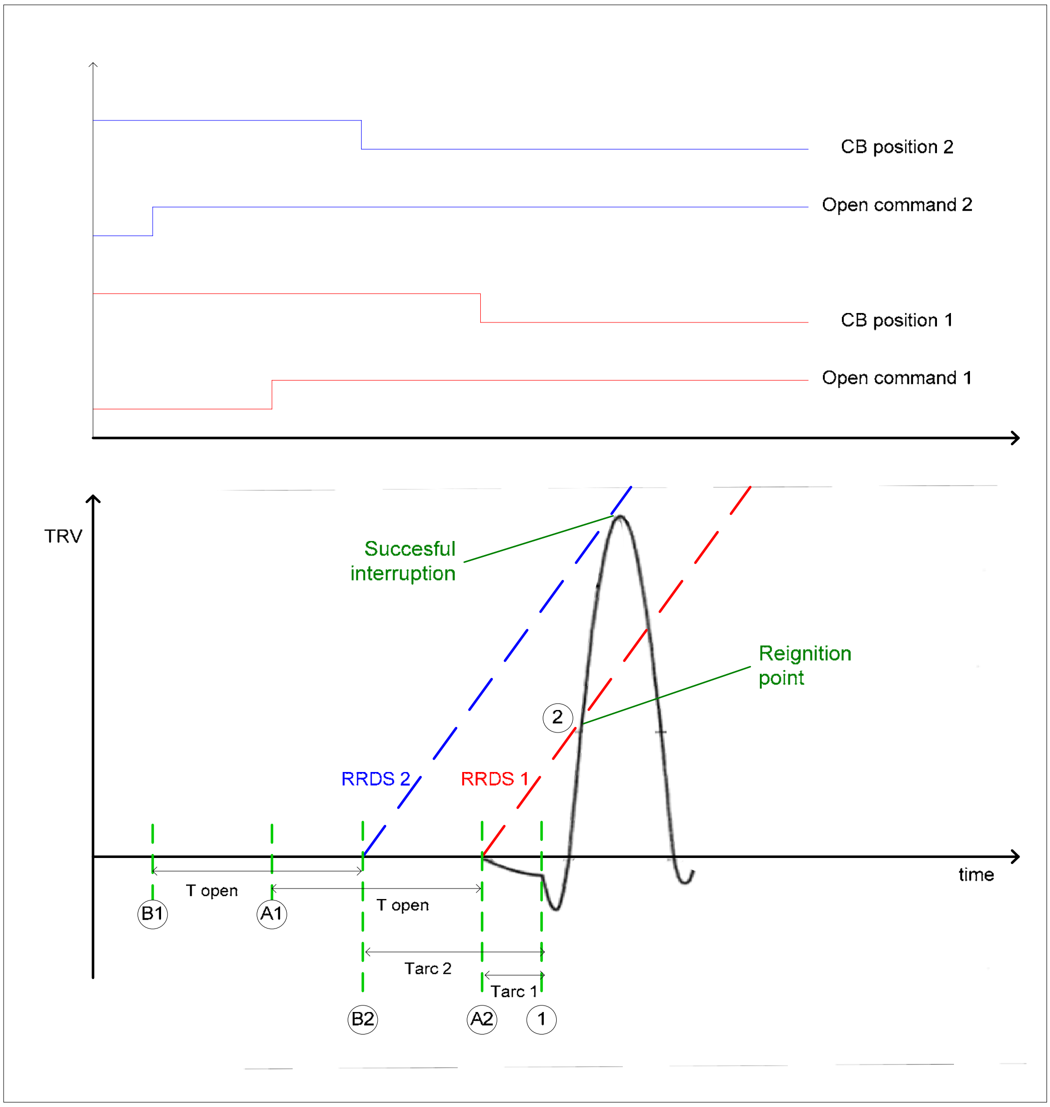


Figure 4.2 – Controlled switching example for shunt reactor opening

In this example the circuit breaker is required to open in an unfaulted situation. And chopping overvoltage experienced between circuit breaker contacts is drawn as in Fig 3.12.

If the open command is applied at point A1, then contact of the circuit breaker seperates at point A2. After an arcing time of Tarc 1 current zero of the associated current wave is reached and current is interrupted at point 1. But the chopping overvoltage generated on load side becomes higher than the dielectric withstand level of the circuit breaker at point 2 and a reignition occurs.

In order to avoid reignition, there should be enough distance between circuit breaker contacts when the transient recovery voltage generated by current chopping is experienced. This can be achieved by extending the arcing time. In the Fig 3.12, if the open command is applied at point B1, circuit breaker contacts seperates at point B2. With the extended arcing time Tarc 2, circuit breaker will develop sufficient dielectric strength to withstand dielectric stress placed by current chopping.

From this example it can be seen that arcing times shorter that Tarc 2 may lead reignitions. Tarc 2 is defined as minimum arcing time of the circuit breaker. Value of minimum arcing time depends on type of circuit breaker (i.e. RRDS characteristics) and overvoltage level expected. As discussed in chapter 3.2, maximum overvoltage to be experienced between circuit breaker terminals is proportional to the chopping number λ of the circuit breaker. Chopping number is an inherent feature of a circuit breaker , and it is determined by a series of experiments in accordance with procedure described in [31]. Experimental results have shown that, chopping number depends also on the arcing time. For example, according to a study about shunt reactor switching transients [40], chopping numbers of modern SF_6 circuit breakers can be approximated by the equation;

$$\lambda_{mean} = (0.22 T_{arcing} + 9) x 10^4 \quad (4.1)$$

for arcing times between 5 ms – 14 ms and with a standard deviation s = 0.8 x 10^4

As chopping number depends also on the arcing time, it can be concluded that higher arcing times cause higher overvoltage levels. Since minimum arcing time depends on several factors, an approprite minimum arcing time should be determined by experiments on a case to case basis. But it is generally accepted that, probability of reignition for arcing times higher than 3 to 5 ms is almost negligible for modern SF_6 circuit breakers [2][14][32].

With this general approval about minimum arcing time, it is possible to define a reignition window as given in Fig 4.3

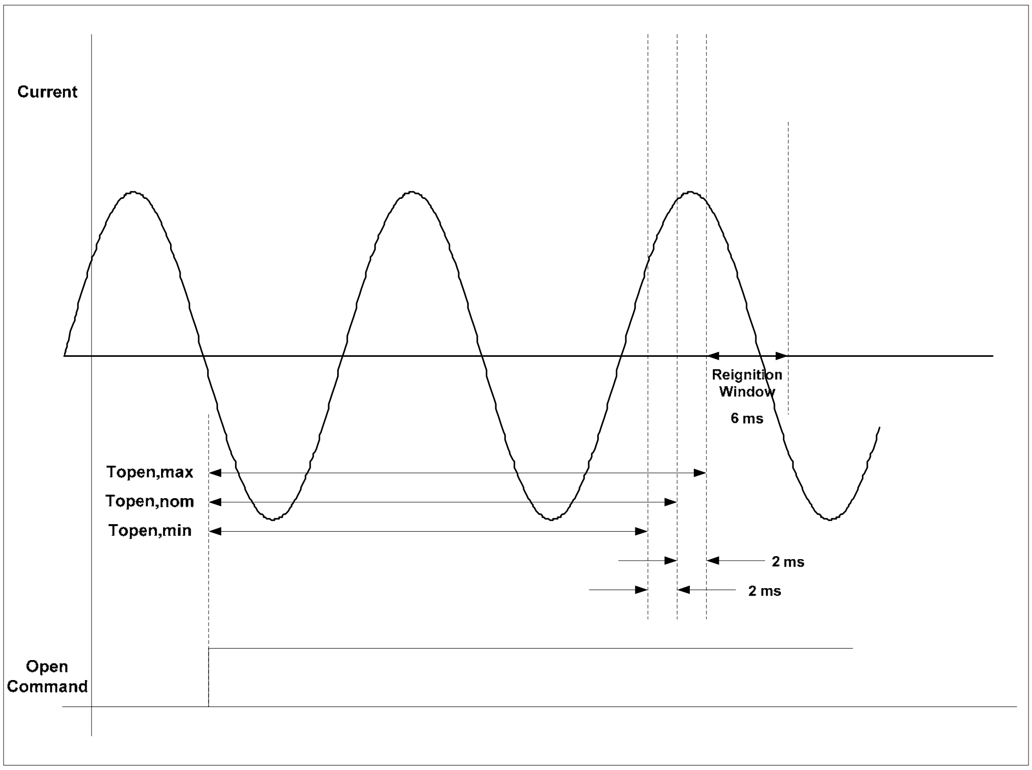


Figure 4.3 – Reignition window for controlled shunt reactor switching

In order to avoid contact seperation in the reignition window, it is important to know the opening time scatter of the circuit breaker. Defining a target minimum arcing time of 6 ms as in Fig 4.3, it can be deduced that contact seperation should occur in a time window of 4 ms, which means that operation accuracy should be at most ± 2 ms. It should be noted that this accuracy constraint can comfortably be accomplished by modern SF_6 circuit breakers.

Three phase shunt reactors may consist of three single phase units or they may be complete three phases units with common core and tank. Three phase common core types may either be of three leg or five leg design. Five leg core design is mainly used at transmission level, and they make the three phases magnetically independent.

Windings of shunt reactors used at EHV level are always connected in Y arrangement. Neutral points of shunt reactors are connected to earth either directly or through an earthing reactor, which is used for the purpose to increase overall zero sequence reactance.

Discussions given above for optimum opening time describe operation in single phase. When three phases are considered, opening time for the first phase to open remains the same. Optimal contact seperation time for the second and third phases to open follow the same constraints about minimum arcing time. But for these phases it is important to estimate relative current zero instants with respect to the current zero instant of the first phase to open. If the shunt reactor is of five leg core type and the neutral is directly grounded, then the current zero instants of second and third phases will follow the power system phase sequence as given in Fig 4.4

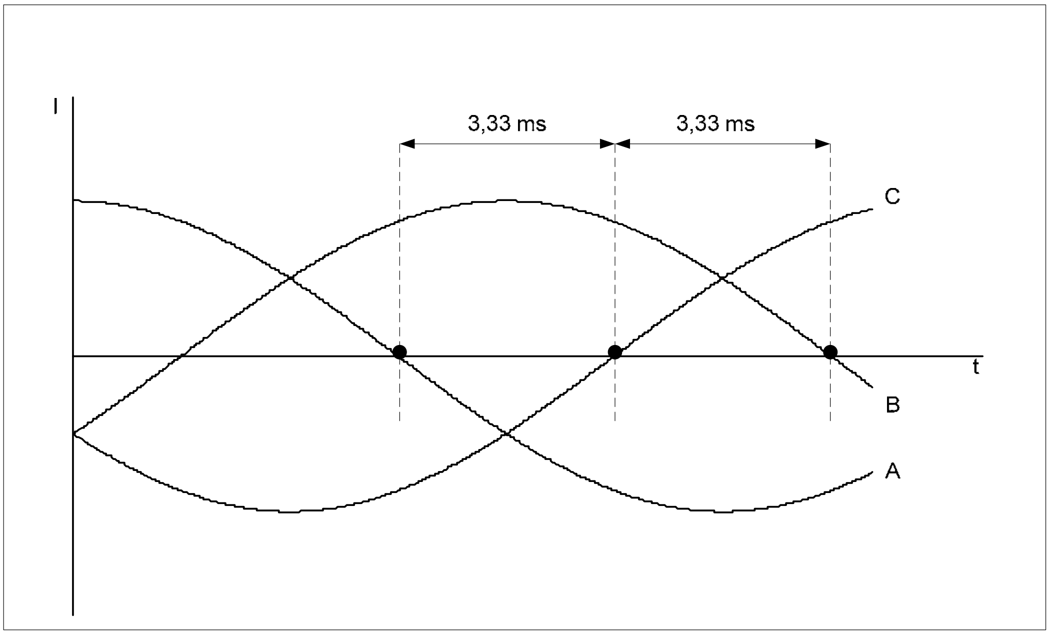


Figure 4.4 – Sequence of current zero instants directly grounded shunt reactors

If the neutral point of the shunt reactor is grounded via an earthing reactor, current zero instants for second and third phases will not be in line with the ones for the case of directly grounded neutral. When the first phase opens, there will be a voltage on the neutral point of the shunt reactor, which shifts the current zero of the second phase to open. In addition, when the second phase opens, voltage on the neutral point changes again and current zero instant of third phase to open shifts further [41]. However it is shown by numerous simulations that deviation for second phase is negligible and for third phase is less than %20, hence it is generally accepted that applications considered for the case of directly earthed neutral suitably applies to the case with earthing reactor as well. (state of art)

4.3 Controlled switching of overhead lines

Reduction of switching overvoltages associated with unloaded line switching is one of the earliest proposed applications of controlled switching [42]. Although there has been extensive studies about controlled switching for unloaded lines, proposed methods has not reached maturity yet and the method is under evolution presently.

Transient overvoltages are encountered in both opening and closing operations in overhead line switching, and controlled switching methods can be applied to both operations. But modern SF_6 type circuit breakers are commonly referred as “restrike free” and they can generally withstand the TRV encountered. Hence controlled switching is generally applied to closing operations rather that opening. In the following discussions main emphasis will be placed on closing control.

In cases where a restrike possibility exists, controlled switching can also be used to eliminate restikes. The method for restrike elimination is the same with the case for inductive load switching, that is by increasing the arcing time. Considerations provided for shunt reactor switching applies to this case also.

As discussed in chapter 3, switching overvoltages experienced when closing into an de-energized overhead line is not particularly significant. However, closing or reclosing into a line having trapped charge may cause destructive overvoltages on the order of 3.5 p.u.

Conventional solution method to eliminate these switching overvoltages is to use closing (or pre-insertion) resistors together with surge arresters. Experience has shown that with appropriate selection of closing resistors and surge arresters overvoltages can be limited to a level below 1.8 p.u. [43]. However closing resistors make circuit breakers mechanically complex and costly. Also decades of operational experience all over the world shows that the reliability of circuit breakers with closing resistors can be fairly lower than the reliability of standard circuit breaker [44]. Hence application of controlled switching is economically feasible since it eliminates the need for closing resistors. Advantages gained by controlled switching is not much more than that gained by closing resistors. But economical feasibility of controlled switching makes it more attractive than conventional measures.

Main idea in controlled closing of unloaded overhead lines is to control closing command such that circuit breaker makes at a point where the voltage across circuit breaker contacts is minimum. Since the voltage across circuit breaker contacts depends not only the source side voltage but also to the line side voltage, strategies for controlled line energization vary according to whether or not the line has shunt compensation and also if there exists any trapped charge on the line (e.g. in the case of automatic reclosing). In the following discussions, controlled switching strategies for different cases will be handled.

4.3.1 – Non-compensated line without trapped charge

The simplest case for controlled switching of an unloaded transmission line is a non-compensated line without trapped charge. Since the line side voltage is zero in this case, closing is ideally targeted on zero source voltage, which corresponds to zero voltage across circuit breaker contacts.

In reality, targeting on zero source voltage does not yield expected result, since the circuit breaker makes before source voltage zero because of closing time variations. This effect is shown in Fig.4.5

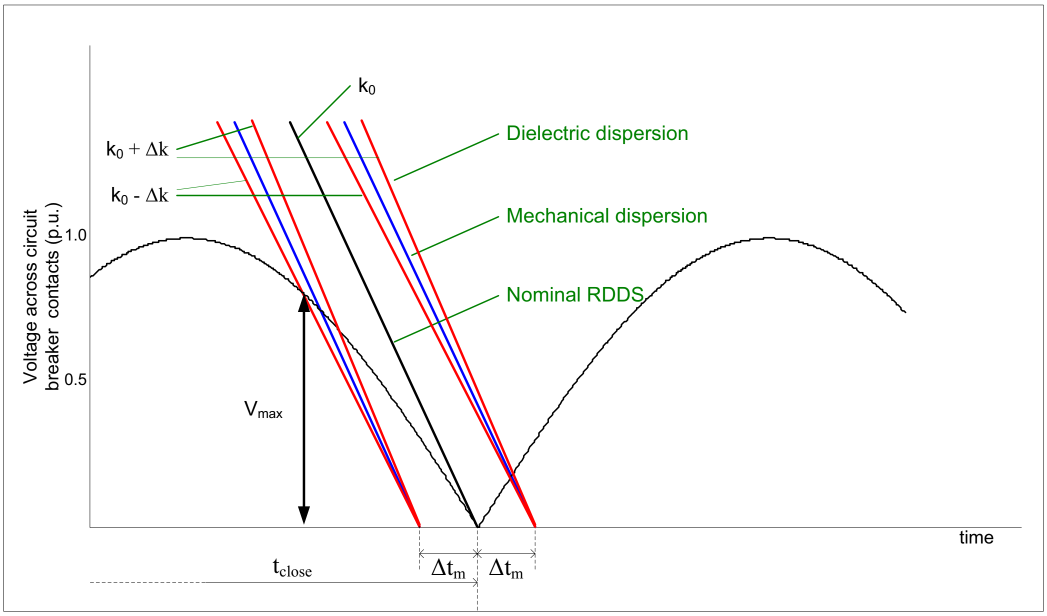


Figure 4.5 – Closing time variation in voltage zero target

In order to have minimum voltage between circuit breaker contacts at the moment of making, target point should be slightly shifted. Effect of this shift is shown in Fig 4.6.

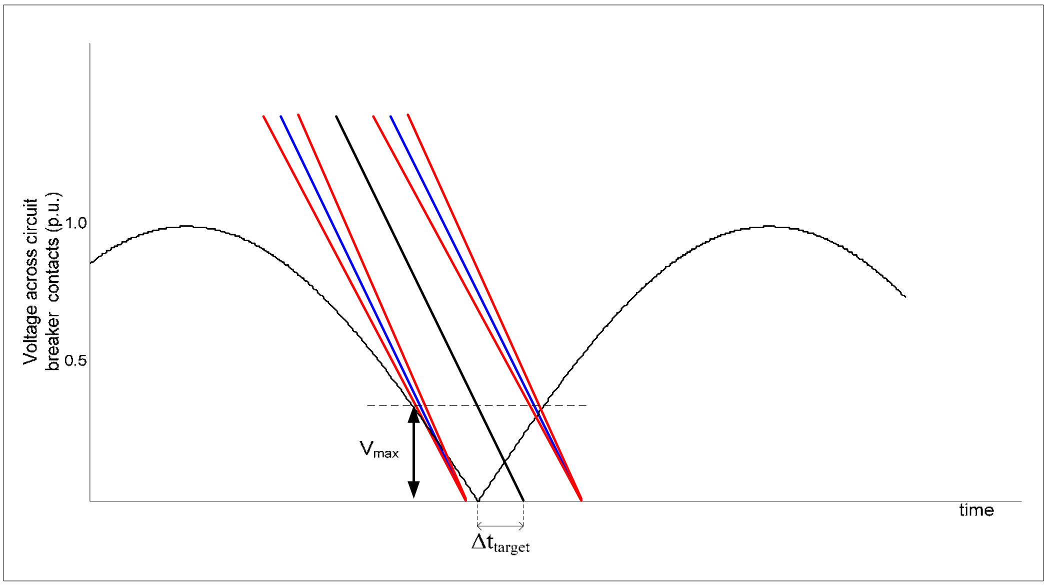


Figure 4.6 – Target shifting for minimum making voltage

Amount of this shift can not be generalized, as it was the case for inductive current switching, since it depends on several factors such as Δt_m, k_0, Δk and power system nominal voltage. In order to determine the amount of the shift, a study on a case to case basis should be conducted.

It should be noted that, detailed investigation which take all variables mentioned above is generally not applied. Rather some assumptions are provided to simplify the investigation. Most effective assumption in this case is the assumption that the RDDS of the circuit breaker is infinite, which is an acceptable assumption for a first approximation study [45]

Discussions given above is applicable to first phase to close. In second and third phases to close, voltage zero points are shifted due to interphase capacitive coupling. This deviation can not be predicted by existing controllers with present controlled switching state of art. In practical applications, it is commonly accepted that, a switching sequence which follows nominal power system phase sequence can be applied.

4.3.2 - Non-compensated line with trapped charge

As it was discussed in chapter 3, closing into an unloaded line with trapped charge may generate high overvoltage levels. Such cases are commonly encountered in transmission lines, especially when high speed auto reclosure is applied. Hence controlled switching can be used to eliminate transient overvoltages encountered in high speed auto reclosure applications. It is noteworthy that, in the following discussions only three phase reclosing will be considered, since it corresponds to worst case in terms of overvoltages and single phase auto reclosure generally leads to lower overvoltages. [1] [46]

Main idea for controlled switching in such cases is control close command to the circuit breaker such that circuit breaker makes at the instant when the voltage between circuit breaker contacts is minimum. Challenging part of this target is to determine the trapped charge on the line at the instant of closing.

Level of trapped charge on the line at the instant of current interruption may be anywhere in the range between -1.2 p.u. to 1.2 p.u., while trapped charge level at the instant of closing depends on the initial value of the trapped charge and its decaying factor. For non-compensated lines, decay of trapped charge may only be through inductive voltage transformers, leakage current on the line insulators and corona losses. At EHV level, it is common to use capacitive type voltage transformers instead of inductive type for economical reasons. Capacitive voltage transformers are not effective in discharging process because of their high ohmic impedance to earth. Other means of discharging have comperatively high time constants and experience has shown that in such cases line voltage is unlikely to fall below %60 of its initial value during an open-close cycle. [1]

In order to adopt a suitable controlled switching application in this case, it is important to measure the line side voltage. Trapped charge on the line can not be measured continuously because of its non-alternating nature. But capacitive voltage transformers measure the DC voltage level related to trapped charge for a certain time interval after interruption, as shown in Fig 4.7 (redrawn from [47]). If the controlled switching application takes this voltage into consideration, making at or very near to voltage zero between circuit breaker contacts becomes possible.

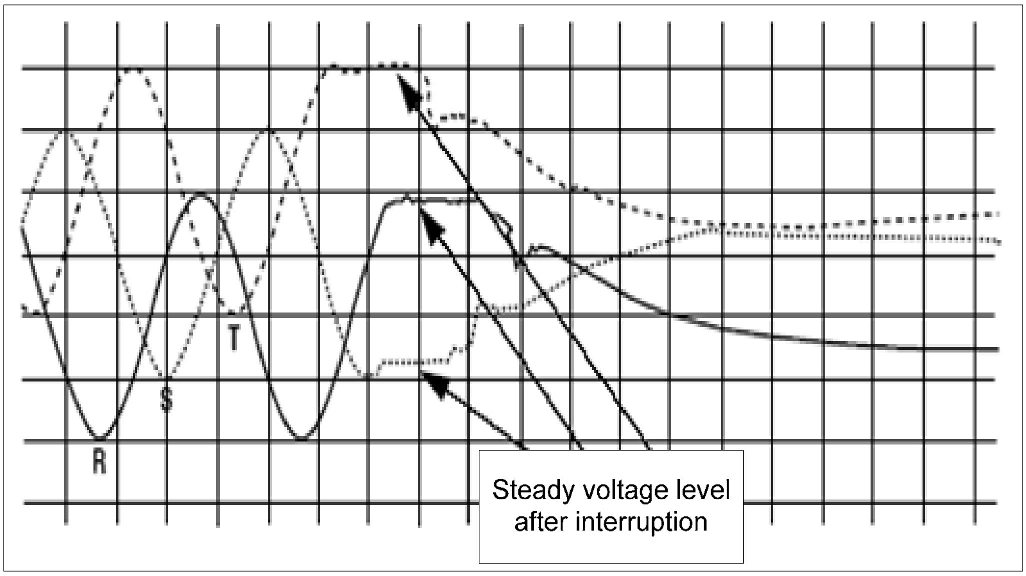


Figure 4.7 – Voltage measurements from a CVT at opening of a healthy OHL

Using the data obtained from capacitive voltage trasformer signals, initial value of the trapped charge can be defined. In order to determine the target instant for closing of each phase, decaying factor of the trapped charge should also be considered. Since it is not possible to measure the instantaneous value of the trapped charge, some assumptions about decaying rate should be provided and these assumptions must be revised in case an unexpected overvoltage level is encountered either in computer simulations or in real operations. Closing target for a non-compensated overhead line with a trapped charge of 1 p.u. is shown in Fig.4.8

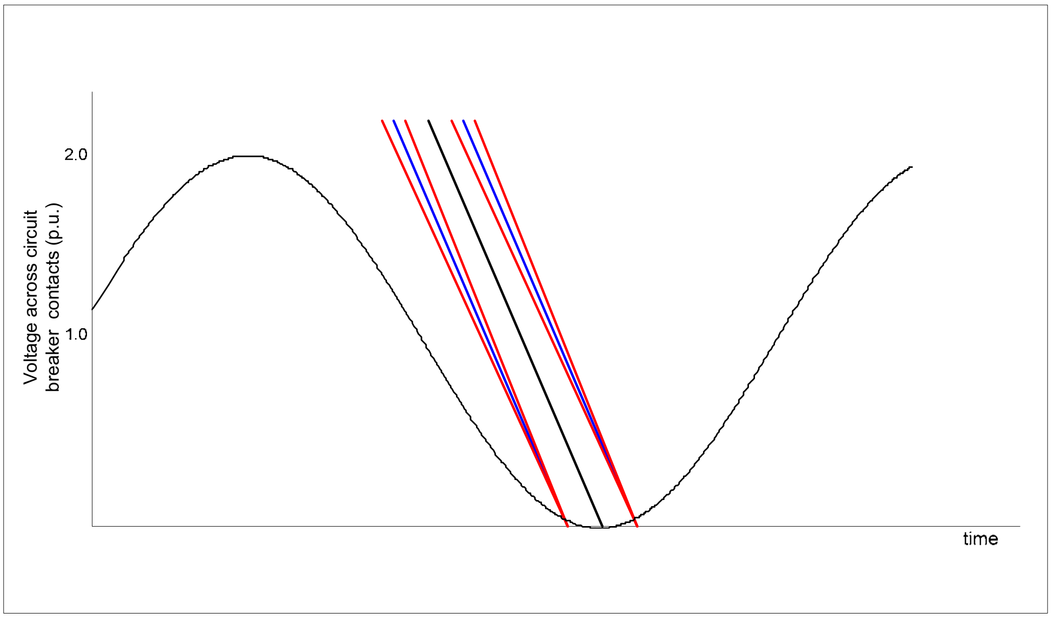


Figure 4.8 – Target instant for non-compensated unloaded OHL with trapped charge of 1 p.u.

An alternative and commony used solution approach for this challenging case is to neglect the line side voltage and define the closing target as source side voltage zero, as it was the case for lines without trapped charge. With this approach, the maximum value of voltage across circuit breaker contacts at the moment of making is 1 p.u. However, experience and site field measurements have shown that overvoltage level can be limited far below 2 p.u. with this simplified approach.(app guide)

4.3.3 - Compensated line with trapped charge

At EHV level it is common to equip long overhead lines (>200 km) with shunt reactors for voltage regulation. When such a line is opened, trapped charge remaining on the line oscillates between line capacitance and reactor with a frequency depending on the compensation factor as discussed in chapter 3. This oscillation damps out with time depending on the damping factor of the citcuit. If the line is reclosed without any means of control before the trapped charge decays, then severe overvoltages may be resulted.

Overvoltages generated in such cases can be eliminated by the use of controlled switching. Target point for this case is the same with the cases discussed above, that is to control making instant of the circuit breaker at a point where a voltage minimum between circuit breaker contacts is achieved. However this is a very challenging task to fulfil, considering the non-periodic voltage across the circuit breaker generated by the load side oscillation and source side voltage.

The degree of compensation has a significant influence on the wave shape across the circuit breaker, as shown in Figure 4.9 and Figure 4.10. For a high degree of compensation voltage wave shape has a pronounced beat pattern, whereas for low degree of compensation beat pattern is less pronounced.

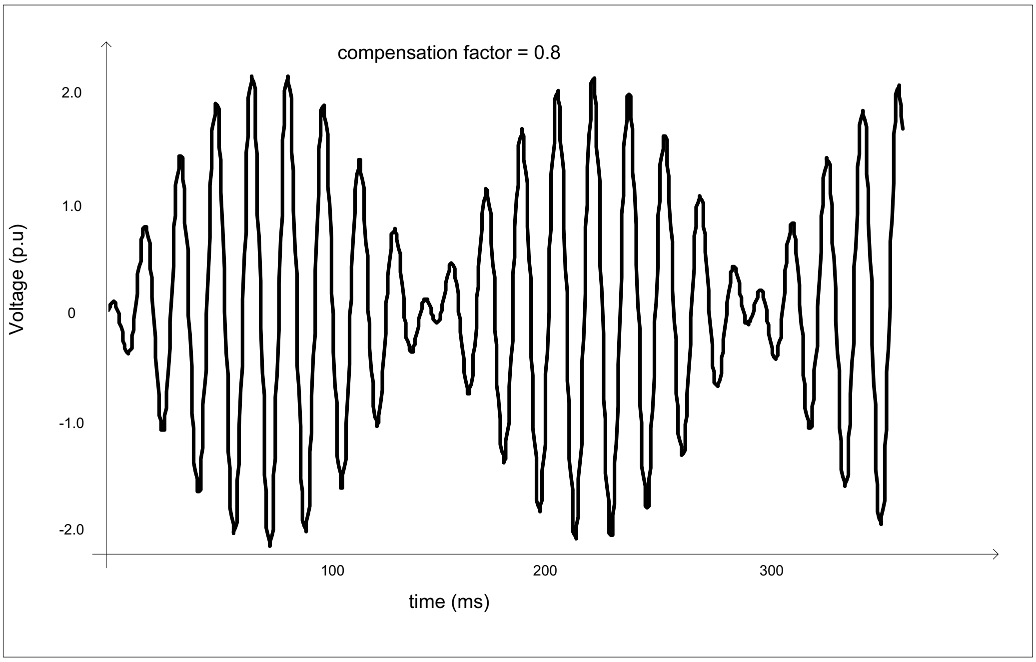


Figure 4.9 – Voltage across circuit breaker for compensated line wth trapped charge (k=0.8)

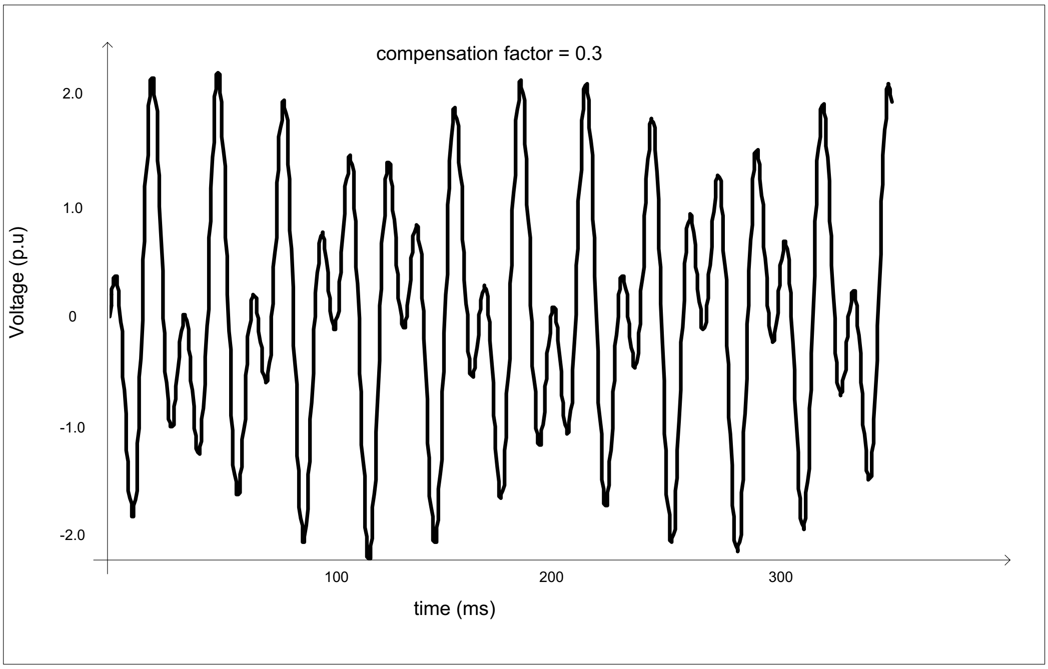


Figure 4.10 – Voltage across circuit breaker for compensated line wth trapped charge (k=0.3)

In order to achieve the target of controlled switching, wave shape of the voltage across interrupter should be defined by means of pattern recognition algorithms, which requires extensive sampling and processing of voltage signals gathered, and next viable closing window should be determined [48][49]. This task becomes even more complicated when the constraint of computation time is introduced, since all these process should be completed in a very short time frame in order to make high speed auto-reclosure possible

Controllers with ability to determine beat minimum are not commercially available because of economical reasons. An alternative method for controlled switching in such cases is to target voltage zero on source side, as it was discussed in previous chapters.

As a result of discussions provided above, it can be accepted that the problem of determining an optimum closing target is analytically and computationally difficult for overhead lines with trapped charge. Hence controlled line auto reclosure tends to become a transient controlled switching problem, in comparison to the more stable and predictable controlled load switching case of shunt reactors described earlier.

4.4 – Other application areas of controlled switching

As stated in chapter 2, any change in the state of a network will be accompanied by a transient response from the system, which may either be in the form of overvoltages or overcurrents. In the discussions given above, use of controlled switching methods for limiting transient overvoltages was described in conjunction with the scope of this thesis study. However, controlled switching can also be used for limiting transient overcurrents as well.

Controlled switching methods can be used for limiting capacitor bank switching overcurrents, which may be of important severity. Target for closing instant in this load case differs according to whether the capacitor bank is earthed or not. If the capacitor bank is grounded, each phase of the capacitor bank is treated as independent. The target instants for closing is the same as the case with closing unloaded overhead line without trapped charge, that is at source voltage zero. In practice target instant is shifted to 1 ms after voltage zero to compensate for mechanical and dielectric dispersions. If the capacitor bank is ungrounded, first phase to close is targeted to close 1 ms after its respective voltage zero. Remaining two phases are treated as one single phase circuit and closed on their respective phase-to-phase voltage zero, which occur 90˚ after the voltage zero of the first phase to close.

Energization of shunt reactors also pose an important problem about high DC biased inrush currents which may cause maloperation of protection relays, and plase excessive electromechancal stress on shunt reactor windings. Controlled switching can be used to eliminate these high magnitudes of overcurrents by controlling the closing instant such that the circuit breaker makes at a voltage peak across each interrupter.

Usage of controlled switching for power transformers is a new and evoluting subject. Aim of controlled switching in this case is to reduce high inrush currents encountered in closing operations. When no means of control is applied in closing operations, inrush current generated in closing at a possible voltage zero instant may cause significant inrush currents of magnitude in the order of 8 – 15 times the transformers full load current [14]. This high inrush current places an excessive electromechanical stress on trasformer windings and may possibly cause maloperation of protection relays. In order to limit high inrush currents, controlled switching can be adopted to control closing instant such that circuit breaker makes at respective voltage peak. Nevertheless this target may not limit the inrush currents to a minimum value, since the remenance flux on the transformer can not be measured. Controlled switching for power transformers remains to be a future study area for the present state of art [50][51].

Another future study area for controlled switching is the controlled fault interruption. The objective in this case is to control opening time in order that a current zero occurs at the beginning of extinguishing window, so that the arcing time and the energy generated during arcing is minimized [37] [52].

4.5 – Benefits of controlled switching

Application of controlled switching provides benefits in both technical and economical aspects. Possible advantages to be gained by controlled switching makes this method attractive, and encourages further researchs about this method.

One of the most important benefits proposed by controlled switching is the circuit breaker lifetime extension. Uncontrolled switching operations lead interrupter wear which refers to arcing contact erosion and nozzle ablation. Arcing contact erosion implies loss of contact material caused by melting and vaporization during arcing across contact gap. Erosion in arcing contact leads distortion in contact shape and thus variation in dielectric withstand characteristics of the circuit breaker. Whereas nozzle ablation implies increase in the internal diameter of the nozzle throat. This causes change in the dynamic gas flow during current interruption and possibly reduced gas density across contacts resulting in degradation of circuit breaker performance in the thermal region.

Controlled switching methods can be used to minimize interrupter wear by controlling arcing and pre-arcing time. Minimizing interrupter wear proposes extension of circuit breaker life, longer maintenance periods and thus lower maintenance costs. Also controlling arcing and pre-arcing times provides a possibility of using more compact and cheaper circuit breaker designs.

Another important benefit proposed by controlled switching is the elimination of costly auxiliary equipments such as closing resistors. Elimination of these auxiliary equipments provides reduction not only in circuit breaker cost but also in maintenance costs.

Benefits mentioned above are directly related to the circuit breaker to which controlled switching method is applied. There are also considerable benefits obtained in other power system equipments by the application of controlled switching. Limitation of switching overvoltages proposes reduction in insulation level and thus cost of power system equipment. This is especially important for overhead lines, where insulation cost is considerable. With the use of controlled switching, it is possible to use more compact tower designs and less string insulators in overhead line construction.

CHAPTER 5

SIMULATIONS ON OVERHEAD LINE SWITCHING

5.1 – Introduction

In this chapter simulations about switching overvoltages generated in overhead line energising (and reclosing) are presented in order to evaluate success of controlled switching technique. In the following simulations switching overvoltages in mainly three cases has been investigated;

1. Uncompensated unloaded overhead line without trapped charge
2. Uncompensated unloaded overhead line with trapped charge
3. Compensated unloaded overhead line with trapped charge

In each case, overvoltages generated by an uncontrolled switching operation has been investigated firstly. Then for each case, success of controlled switching has been investigated by changing three variables;

1. Applied controlled switching method
2. Existence of surge arresters
3. Maximum variation level of circuit breaker operating time

Full range of the cases investigated are listed in Table 5.1. In each individual simulation, overvoltage levels have been recorded and success of controlled switching has been evaluated by comparison.

Table 5.1 – Summary of simulated cases

	Simulation no	**Controlled switching**	**Δt $_{make}$**	**Surge arrester**
Uncompensated unloaded overhead line without trapped charge	1	not applied	-	not used
	2	not applied	-	used
	3	Target: source voltage zero	1,5 ms	not used
	4	Target: source voltage zero	2,5 ms	not used
	5	Target: source voltage zero	1,5 ms	used
Uncompensated unloaded overhead line with trapped charge	6	not applied	-	not used
	7	not applied	-	Used
	8	Target: source voltage zero	1,5 ms	not used
	9	Target: source voltage zero	2,5 ms	not used
	10	Target: source voltage zero	1,5 ms	Used
	11	Target: line voltage	1,5 ms	not used
	12	Target: line voltage	2,5 ms	not used
	13	Target: line voltage	1,5 ms	Used
Compensated unloaded overhead line with trapped charge	14	Not applied	-	not used
	15	Not applied	-	Used
	16	Target: source voltage zero	1,5 ms	not used
	17	Target: source voltage zero	2,5 ms	not used
	18	Target: source voltage zero	1,5 ms	Used

5.2 – Simulation basis

Simulations are performed by using Alternative Transient Program (ATP), which is a version of EMTP (Electro-magnetic Transient Program). Switching overvoltages has been observed for a duration of 0.1 seconds, with an integration time step of 10 µsec.

Simulations are based on a real overhead line in Turkish 400 kV network, which is placed between 400 kV Hisar S/S and 400 kV Kayabaşı S/S and a shunt reactor is connected to the line end on Hisar S/S.

It is important to note that the main objective of this simulation study is not to prepare a feasibility study about switching overvoltages on the mentioned overhead line, but rather to evaluate the success of controlled switching technique in an example circuit. Hence, because of some simplications applied, results obtained from this simulation study may not be entirely applicable to the mentioned overhead line.

Simulated circuit has been prepared by the ATPDraw software, which produces an executable file for ATP-EMTP program. The simulated circuit is given in Figure 5.1

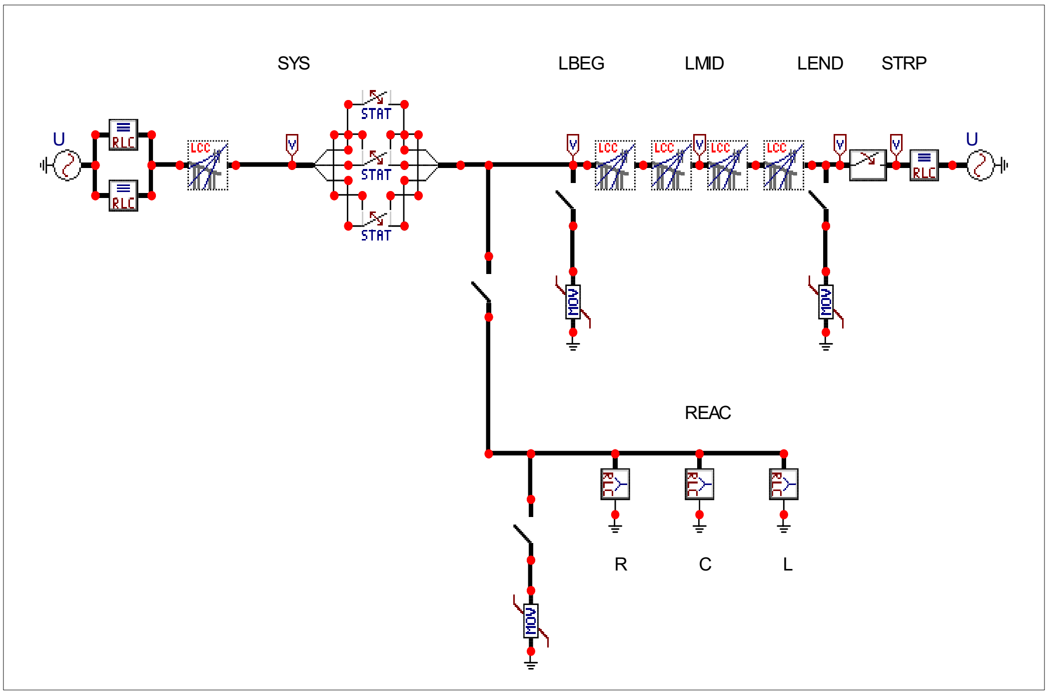


Figure 5.1 – Simulation circuit

In the simulation circuit there are two voltage sources. The first one on the left side represents the Thevenin equivalent of the power system. This voltage source has a peak value corresponding to maximum operation voltage of 420 kV. The source is connected to the system through a lumped linear branch representing the Thevenin equivalent of the source side circuit, in parallel with a lumped resistance representing the surge impedance of the source side circuit. Thevenin equivalent of the source side circuit has been calculated based on the data provided by TEİAŞ [53]. Source side parameters are given in Appendix.

The second voltage source on the right side has been used to provide trapped charge to the line. This voltage source has been disconnected before the operation of the circuit breaker under consideration. By changing the peak value of this source, it is possible to change the trapped charge level on the overhead line.

The overhead line has been divided into four equal sections in order to investigate overvoltages along the line. Each part of the overhead line has been represented by a transposed and distributed model. The model used takes frequency dependency into account (JMARTI model) [54]. Parameters of the model has been calculated by the ATP supporting program LCC (line cable constants). Data used for modelling the overhead line and the output file of the LCC program are given in Appendix.

Shunt reactor is a star connected three phase reactor with directly grounded neutral. Shunt reactor has been simulated by a lumped inductance. Phase to ground capacitance of the reactor has been represented by a lumped capacitance in parallel with reactor inductance. Value of this capacitance has been selected in accordance with the measurements from site tests. Results of these site tests about capacitance measurement are given in Appendix. Also a resistance accounting for the damping effect has been represented by a lumped resistance in parallel to reactor inductance. Shunt reactor parameters are given in Appendix.

A standard metal-oxide surge arrester used at 400 kV voltage level is modelled in the simulation. Details of the model is provided in Appendix.

The circuit breaker used in the simulations is a so called "statistical switch". With this type of switch it is possible to define the closing instants and the standard deviation in closing instants of the circuit breaker poles independently. Also distribution of deviation can be selected as Gaussian or uniform. Another important aspect of this switch type is that, any of the circuit breaker poles can be selected as "master", such that the remaining poles follows this master pole. [55]

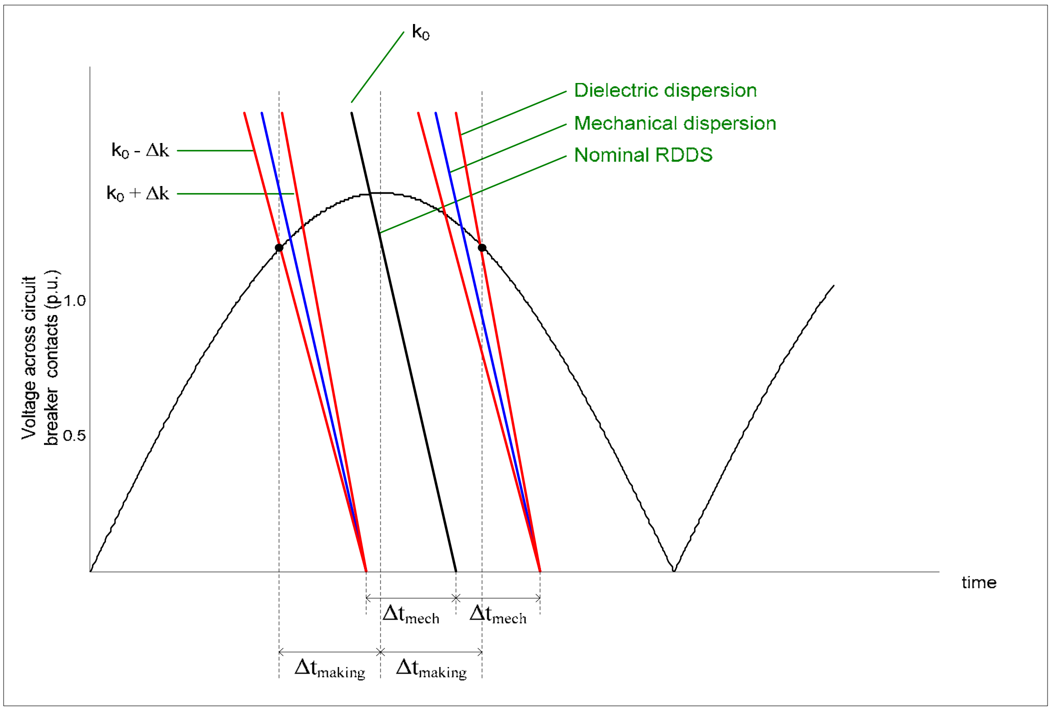


Figure 5.2 – Making time variation

The circuit breaker model used in the simulations has an infinite RDDS characteristics. In order to represent statistical variations in operating time of the circuit breaker, a standard deviation is introduced to the circuit breaker model. Considering the infinite RDDS characteristics of the circuit breaker model, this variation corresponds to the variation in making time, which is different than the mechanical variation as shown in Figure 5.2. In the simulations conducted, a simplified approach for modelling the statistical scatter of circuit breakers has been utilized. With this simplified approach, the standard deviation (σ) referred to in the context of statistical switch corresponds to one third of the making instant scatter (σ = Δt_{making} / 3). This simplification is an easy to implement approach to model related quite complex parameters of a circuit breaker (RDDS, Δs and Δt_{mech}) by means of a circuit breaker model with infinite RDDS slope [1]. In the simulations performed, two different values of Δt_{making} is used, those are 1,5 ms and 2,5 ms, which correspond to maximum pole span of 3 ms and 5 ms respectively.

In the following simulations, closing operations are repeated 100 times by the statistical switch model, in order to have an accurate picture of the overall distribution of the overvoltages due to switching operation. In each simulation, voltages at the beginning, middle and end of the line is calculated. Using an inherent feature of the ATP-EMTP program, a summary of voltages along the line is extracted, which presents a general view of overvoltage level on the overhead line.

Insulation level in power system equipment is determined according to $U_{2\%}$ value, which is defined as the value which statistically is exceeded in 2% of all switching cases. In order present a picture about possible insulation level constraints, simulation results are presented in two forms; frequency of occurance(%) and probability of exceeding overvoltage.

In the following subchapters, results of the each simulation will be provided with its simulation number as given in Table 5.1

5.3 – Simulation results

5.3.1 – Non-compensated line without trapped charge

When the trapped charge on the overhead line to be switched is zero, which is the general case for planned switching operations, $U_{2\%}$ value reaches up to 1.95 p.u.(simulation no:1). If the surge arresters are connected to the line, $U_{2\%}$ value decreases to 1.75 p.u. (simulation no:2)

Application of controlled switching, which targets source voltage zero for closing, reduces the $U_{2\%}$ value 1.50 p.u. even with a Δt_{making} value of 2.5 ms (simulation no:4). When controlled switching and surge arresters are used together $U_{2\%}$ value decreases a little bit further to a value of 1.40 p.u. (simulation no:5)

As it was discussed in Chapter 3, closing into a non-compensated line without trapped charge does not pose an important problem about switching overvoltages. Though application of controlled switching in this case reduces the overvoltage level further, even with relatively high Δt_{making} value.

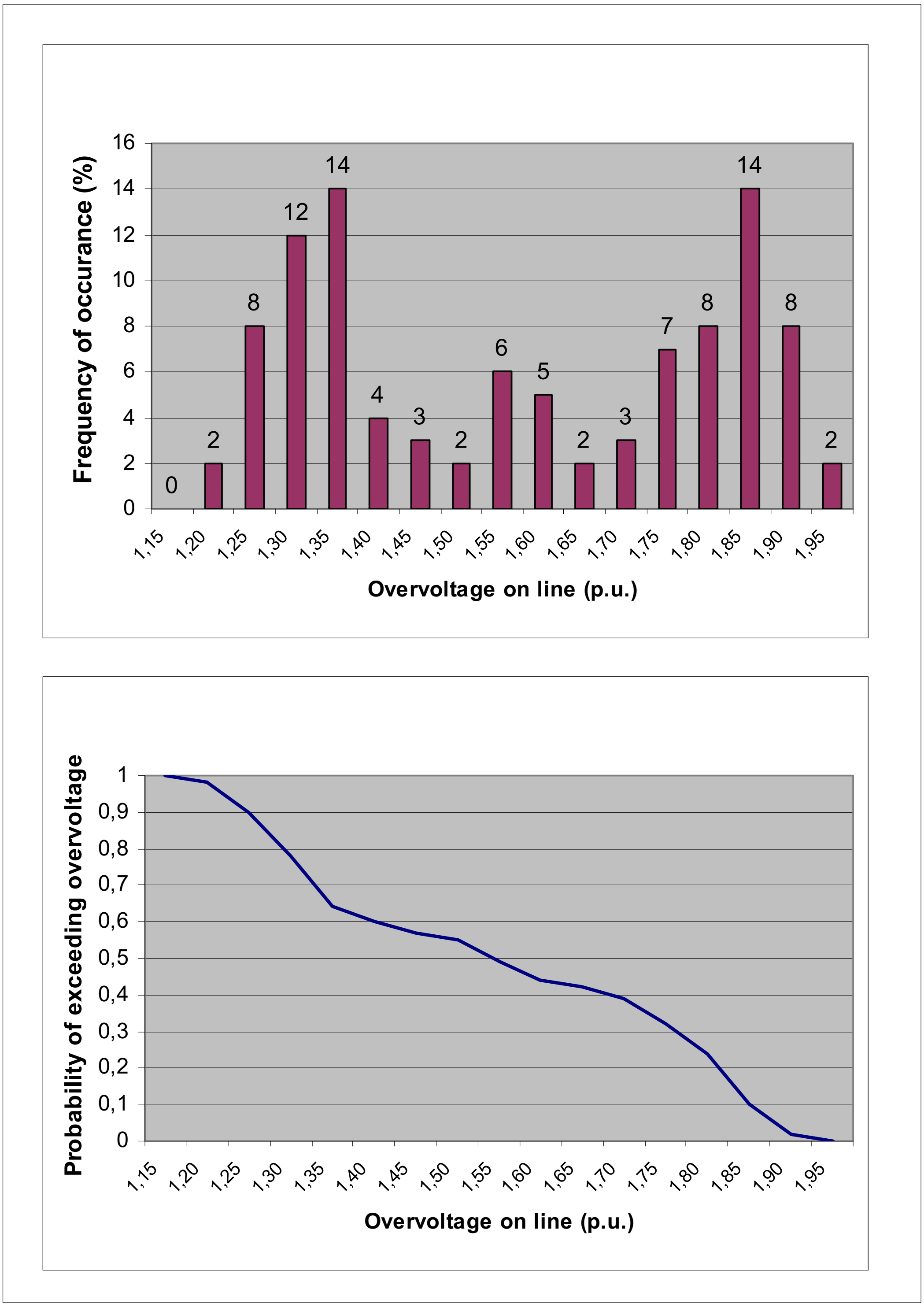


Figure 5.3 – Results of simulation no: 1

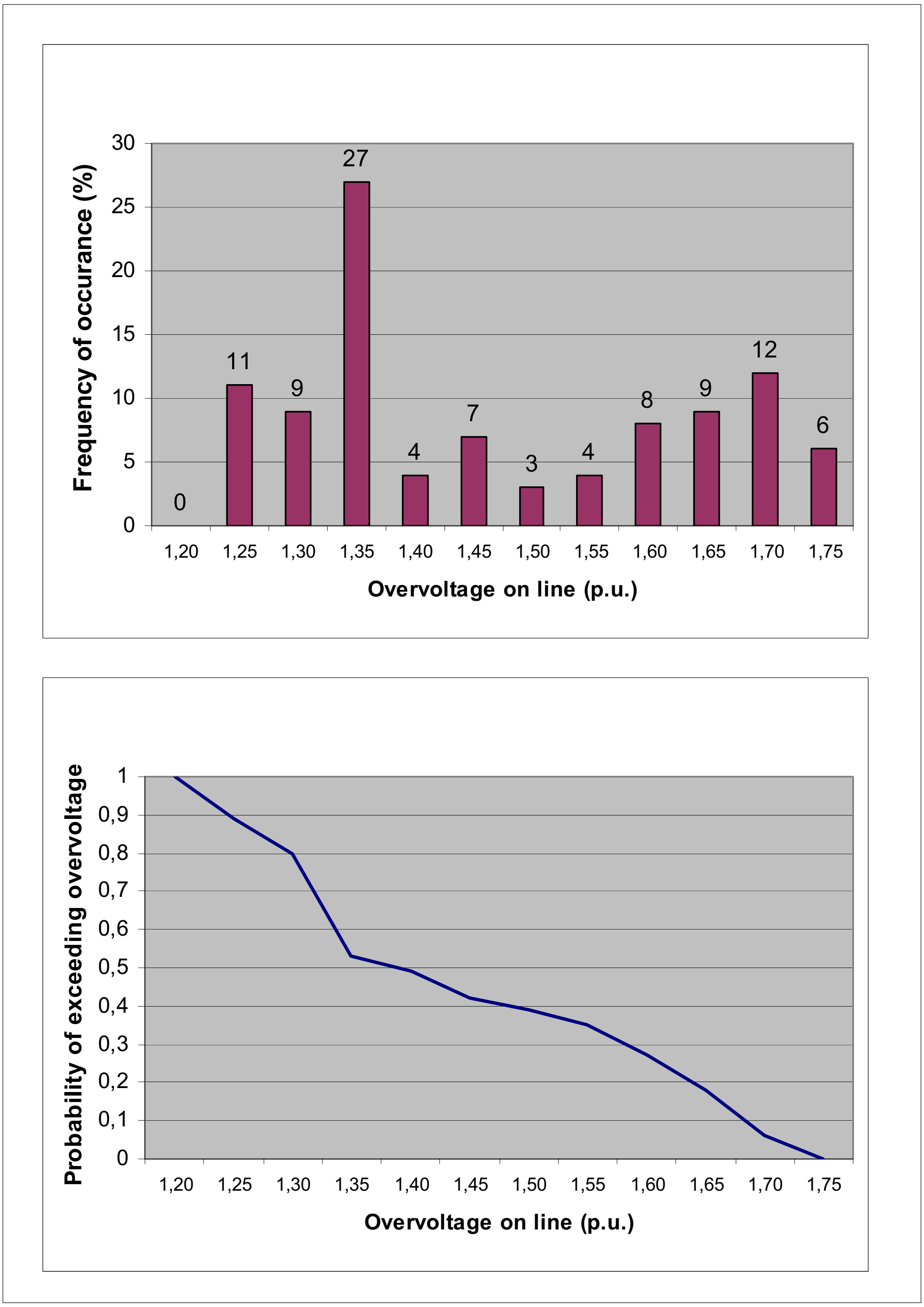


Figure 5.4 – Results of simulation no: 2

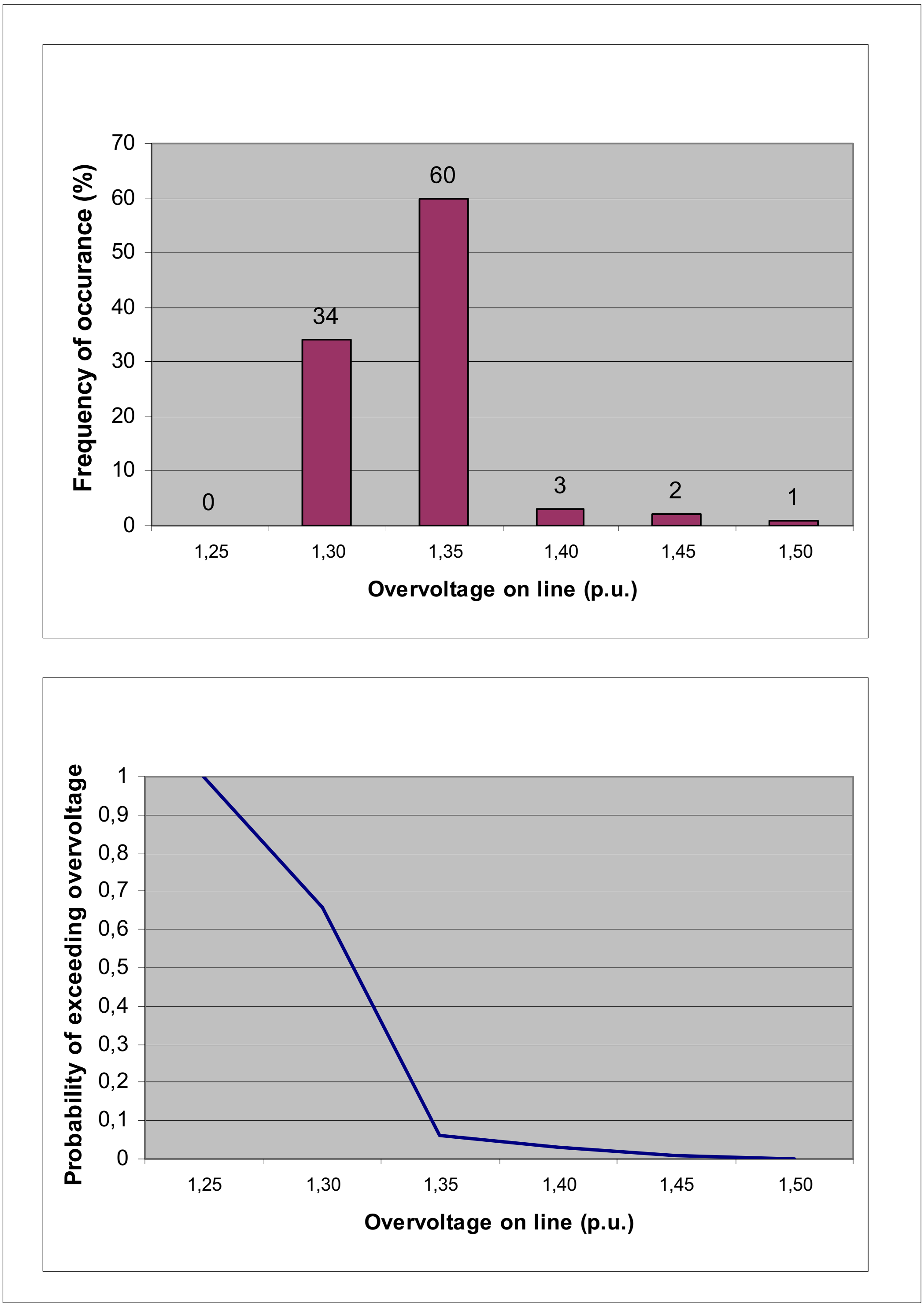


Figure 5.5 – Results of simulation no: 3

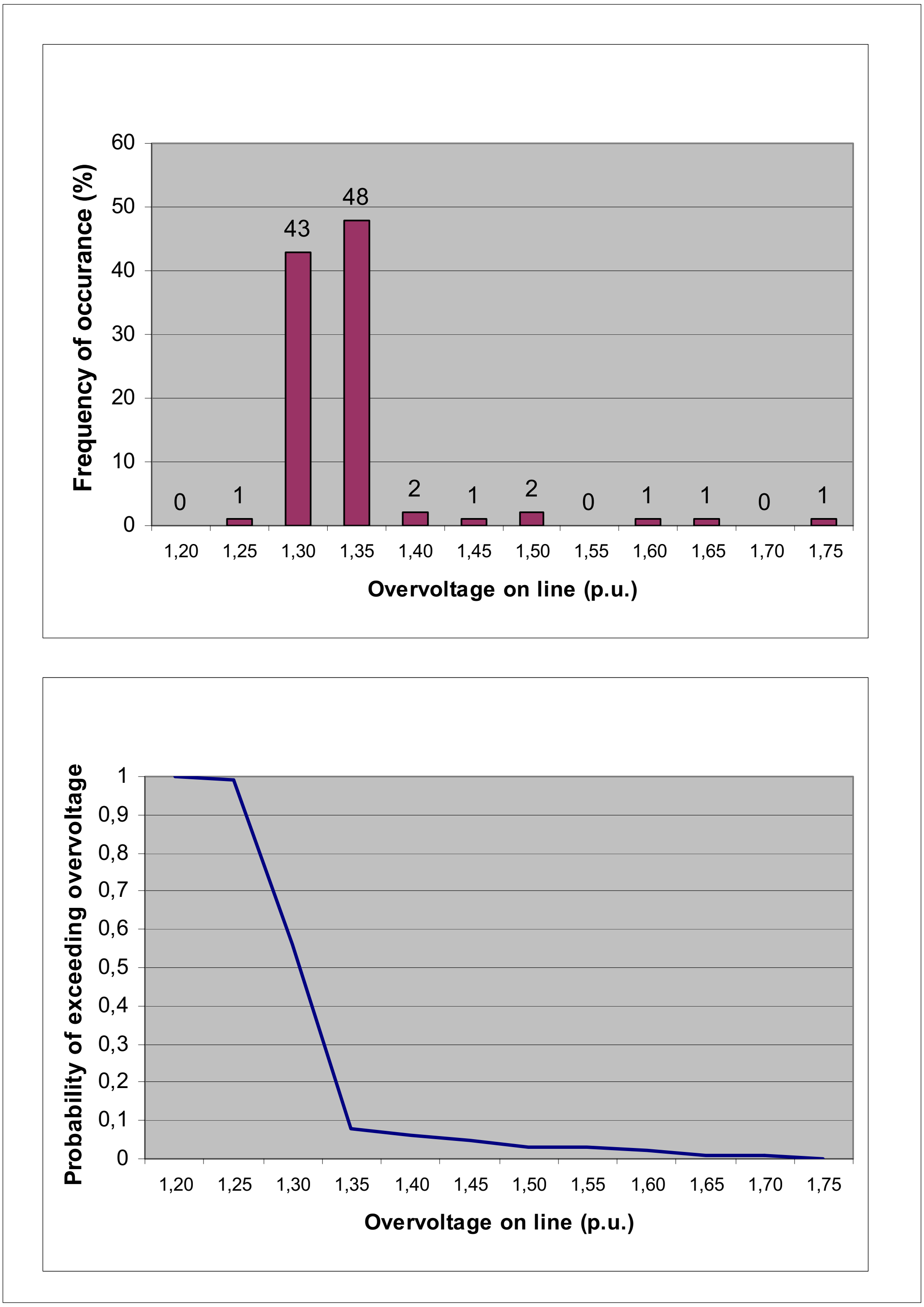


Figure 5.6 – Results of simulation no: 4

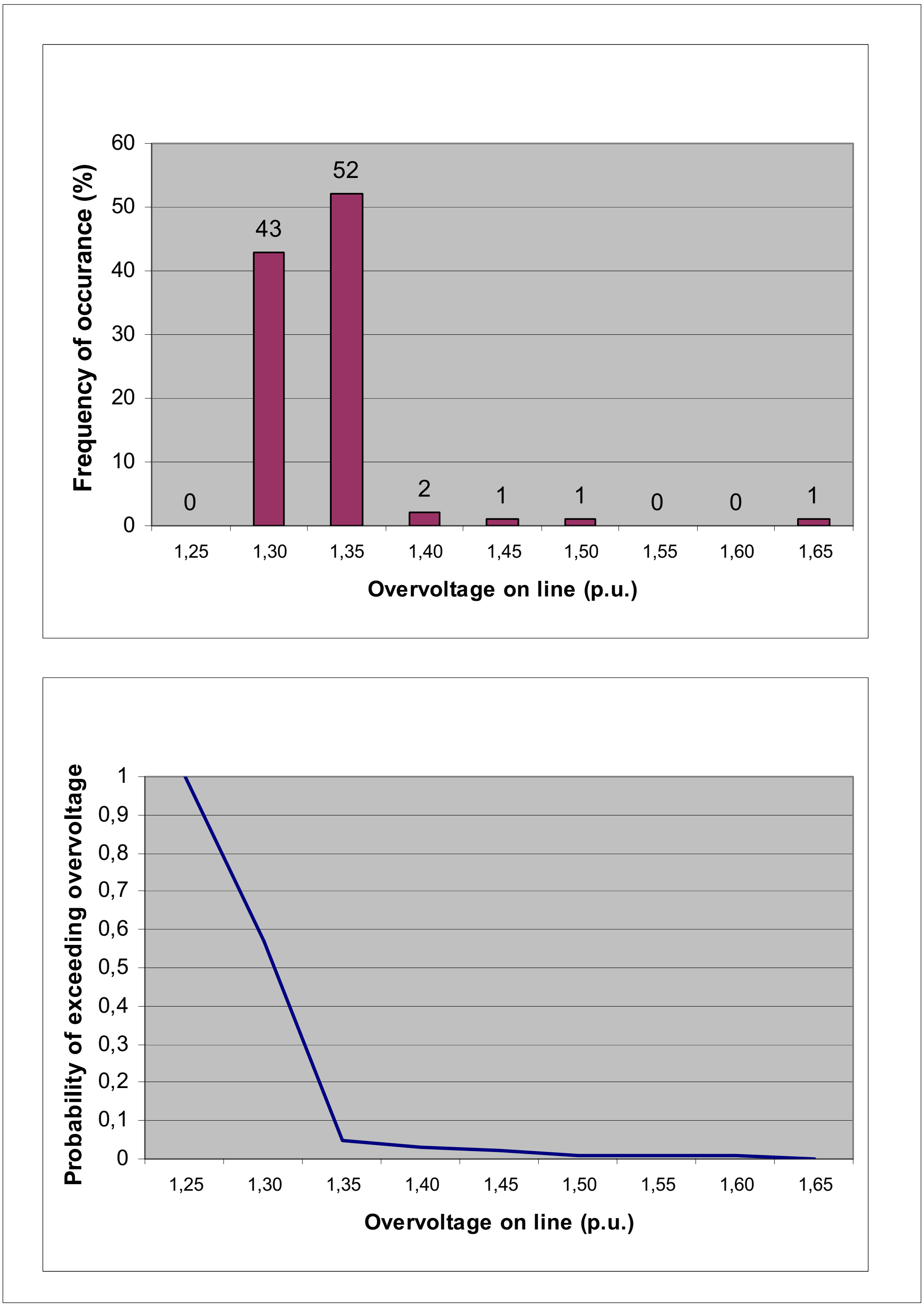


Figure 5.7 – Results of simulation no: 5

5.3.2 – Non-compensated line with trapped charge

When three phase high speed auto reclosure is applied, there is a high possibility that a considerable amount of trapped charge is present on the overhead line at the instant of closing. If the circuit breaker is closed without any means of control, $U_{2\%}$ value reaches up to 2.80 p.u. (simulation no:6). Application of surge arresters in this case reduces $U_{2\%}$ value to 2.15 p.u (simulation no:7)

Application of controlled switching, which targets source voltage zero for closing, reduces the $U_{2\%}$ value 1.90 p.u. for a Δt_{making} value of 1,5 ms (simulation no:8). Even if the making instant scatter is increased to 2.5 ms., the $U_{2\%}$ value increases a little more to a value of 1.95 p.u. (simulation no:9) When controlled switching and surge arresters are used together $U_{2\%}$ value decreases to a value of 1.75 p.u. (simulation no:10)

As it was discussed in Chapter 4, it is possible to obtain trapped charge level on the line from capacitive voltage transformers. If the controller takes trapped charge level into account, $U_{2\%}$ value decreases significantly to 1.25 p.u., even with a Δt_{making} value of 2.5 ms.

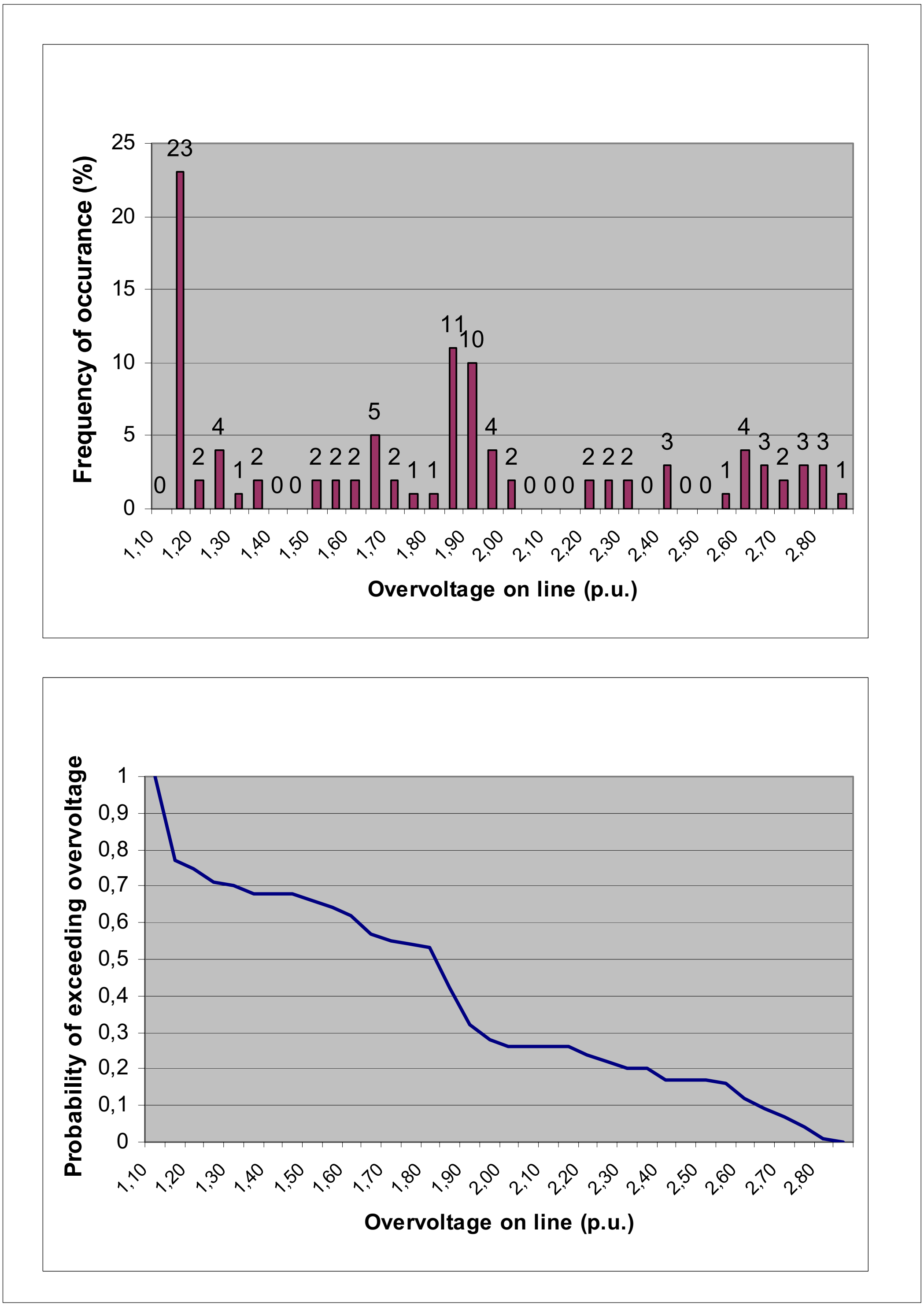


Figure 5.8 – Results of simulation no: 6

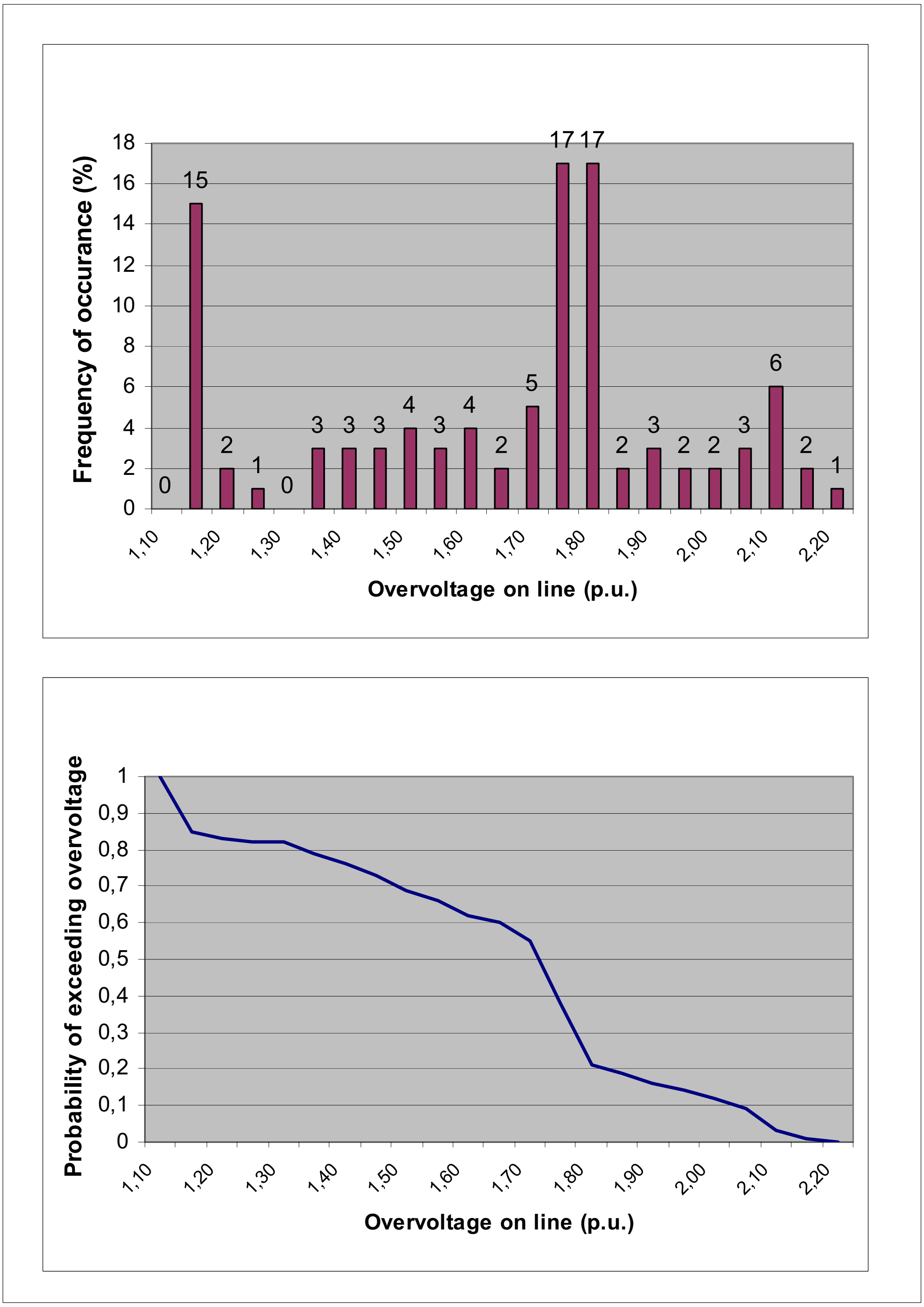


Figure 5.9 – Results of simulation no: 7

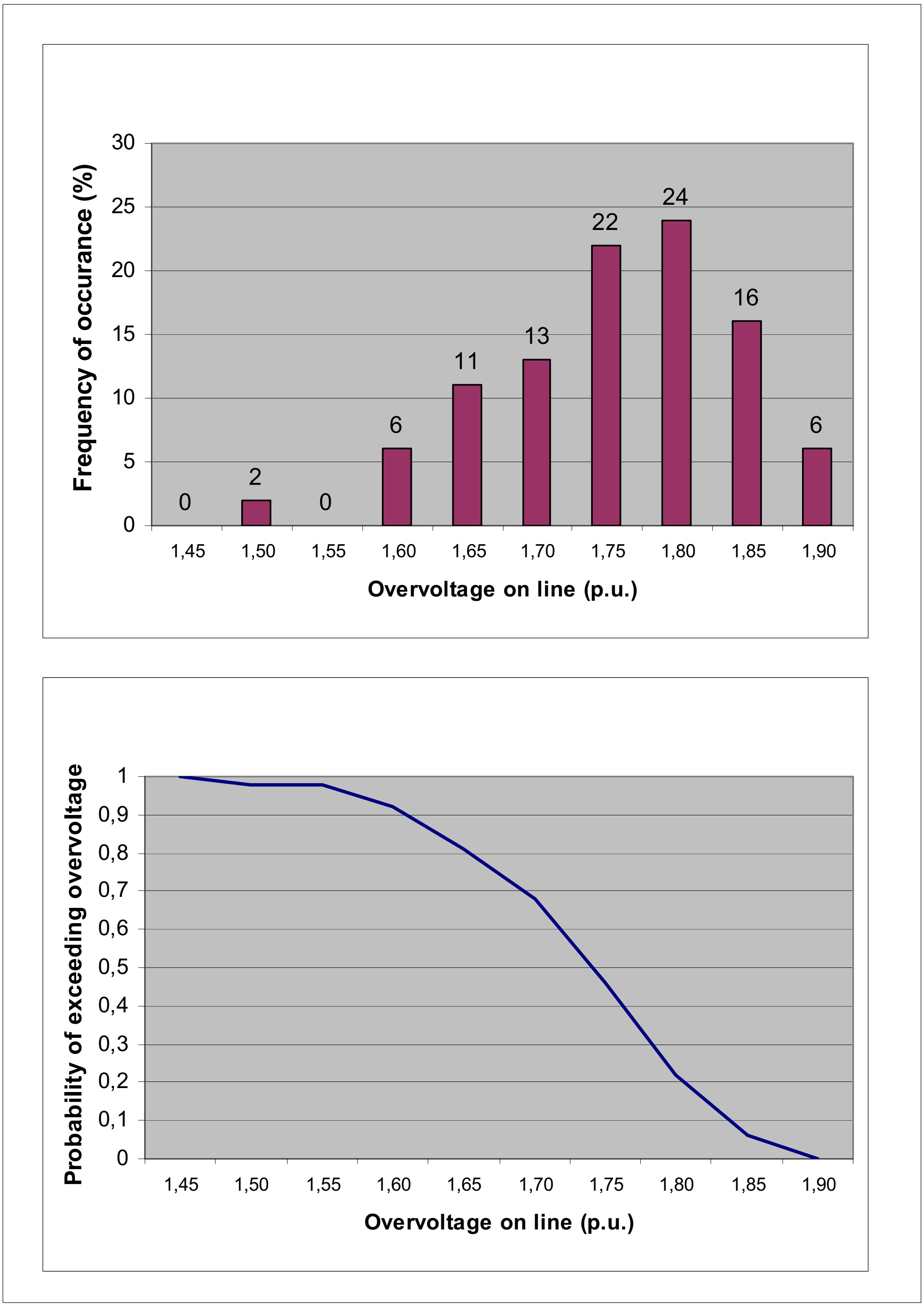


Figure 5.10 – Results of simulation no: 8

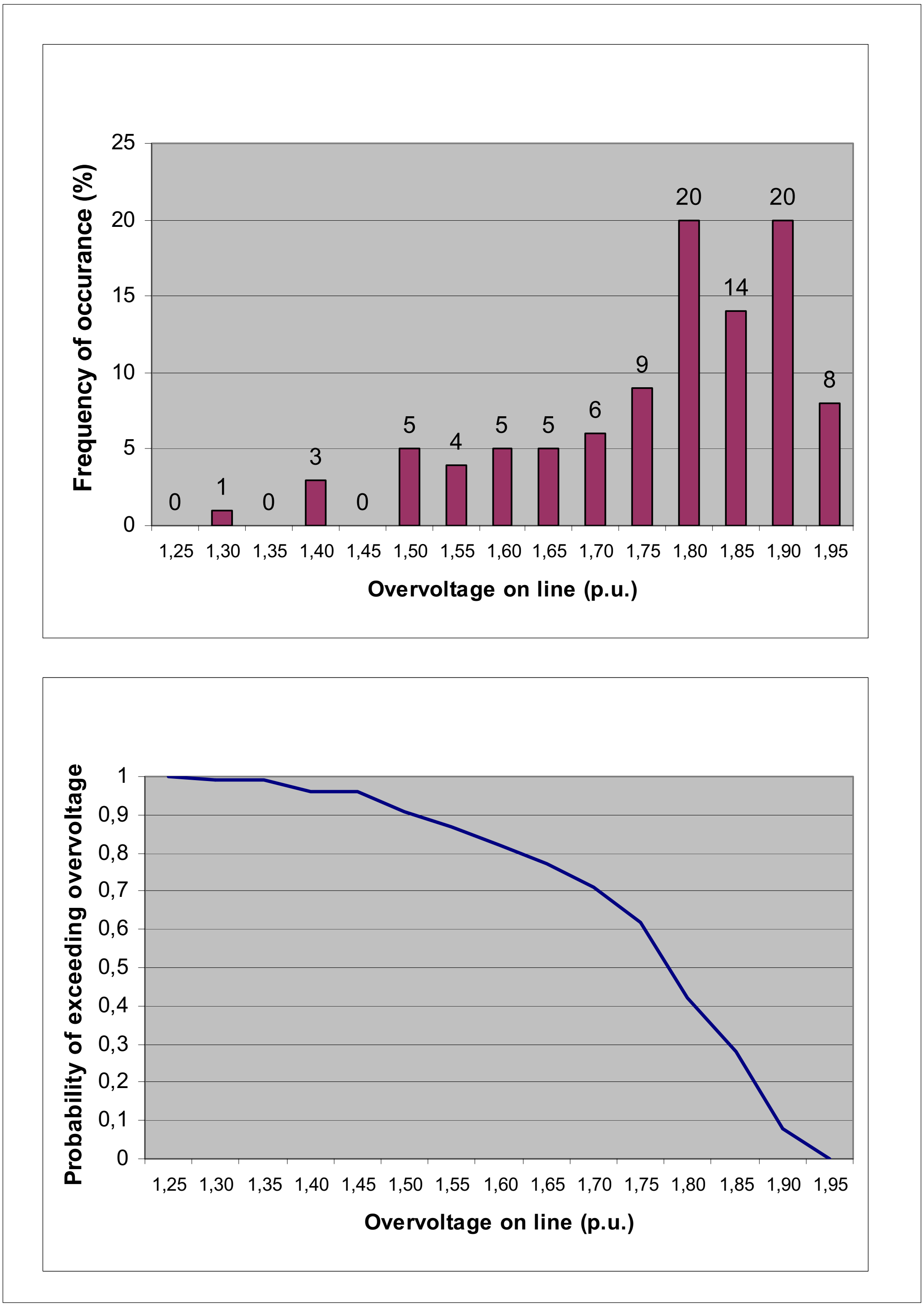


Figure 5.11 – Results of simulation no: 9

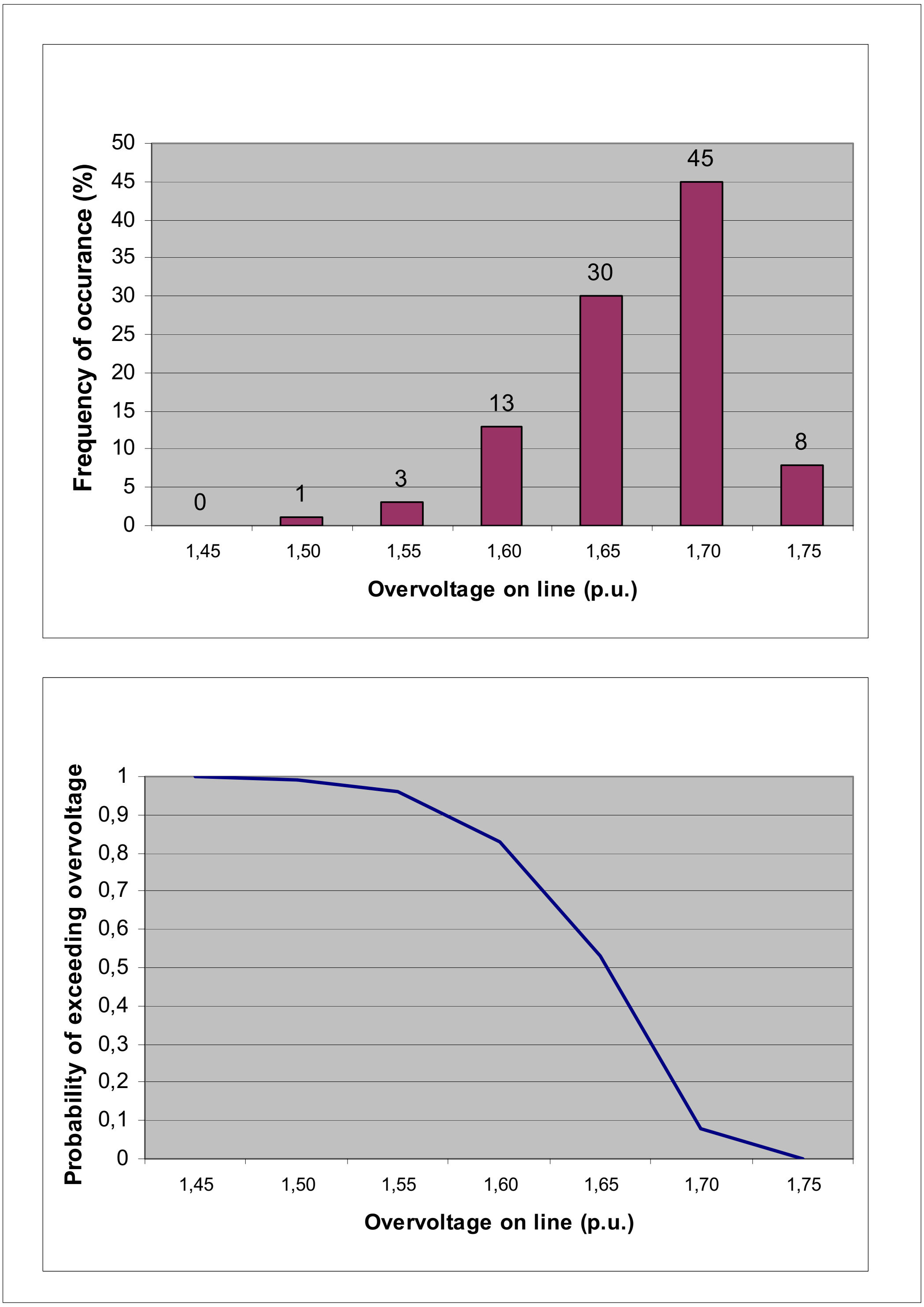


Figure 5.12 – Results of simulation no: 10

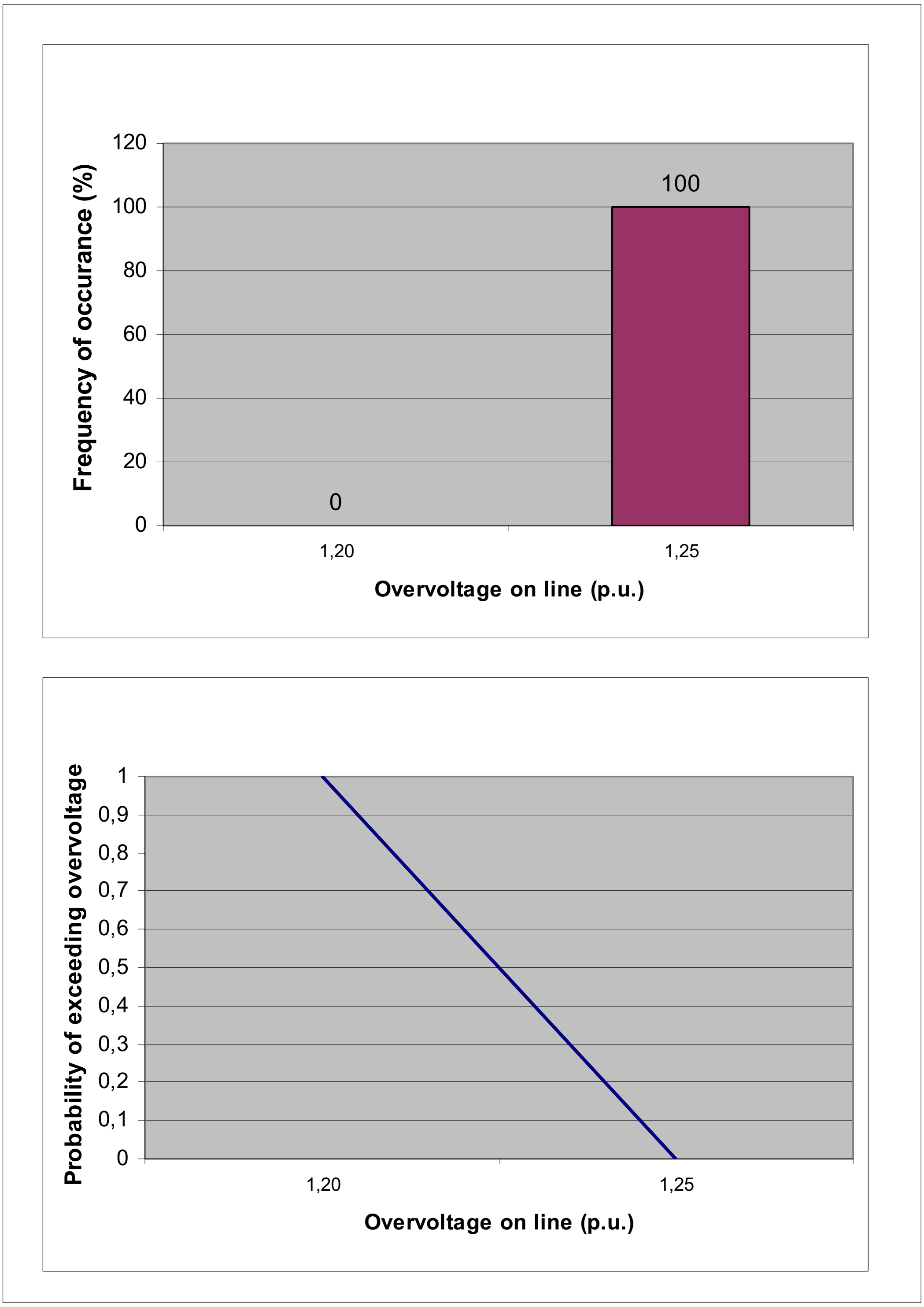


Figure 5.13 – Results of simulation no: 11

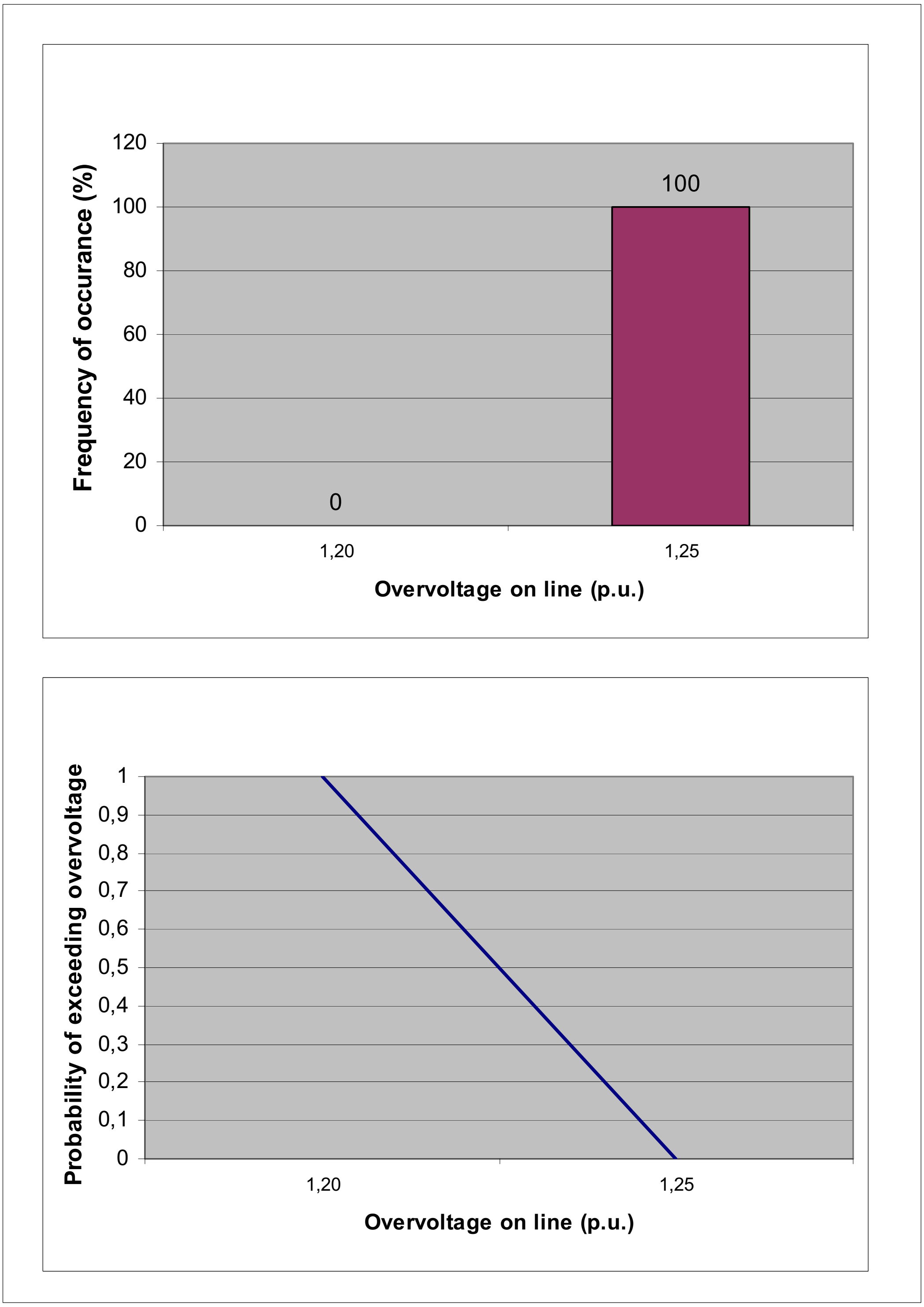


Figure 5.14 – Results of simulation no: 12

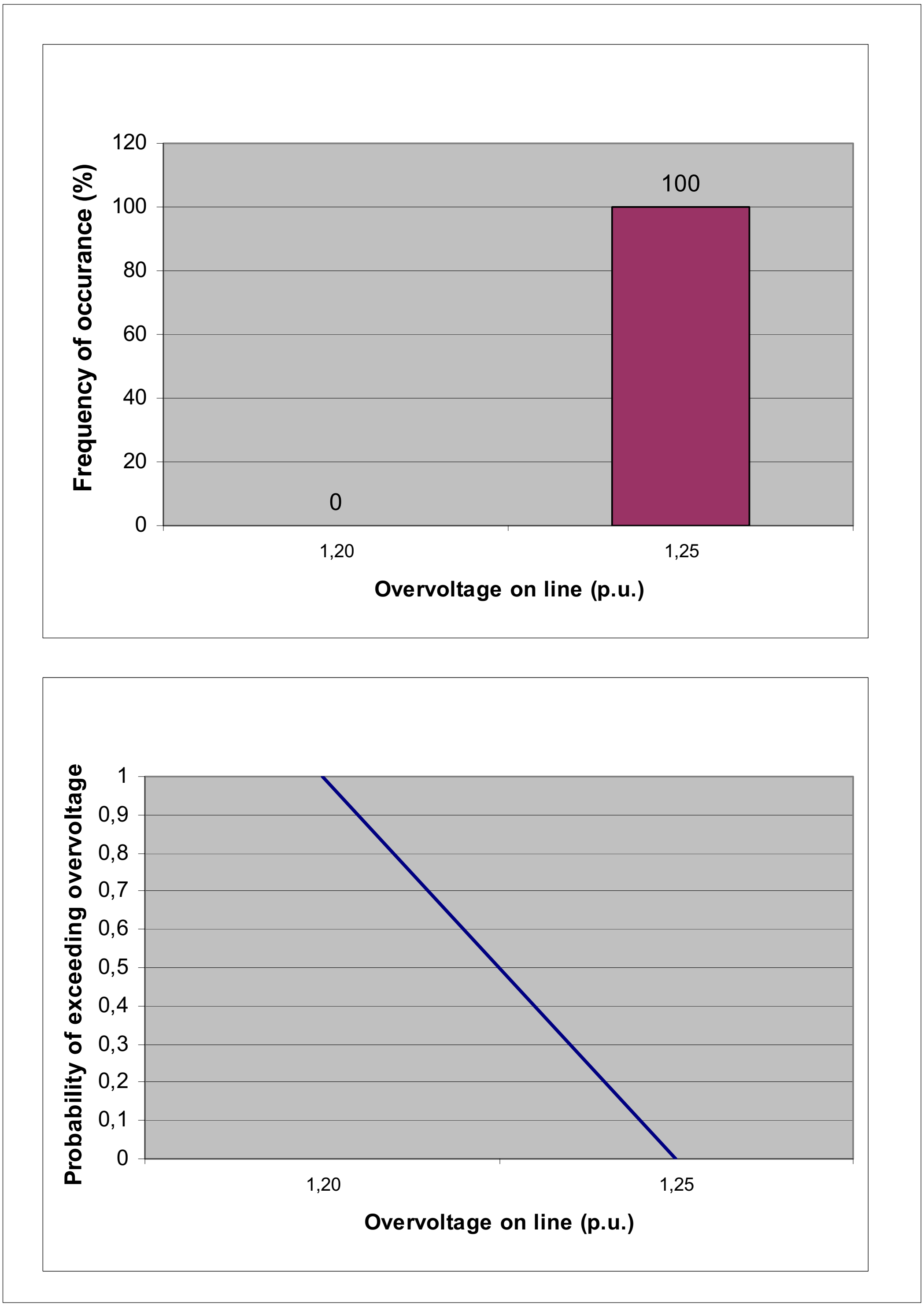


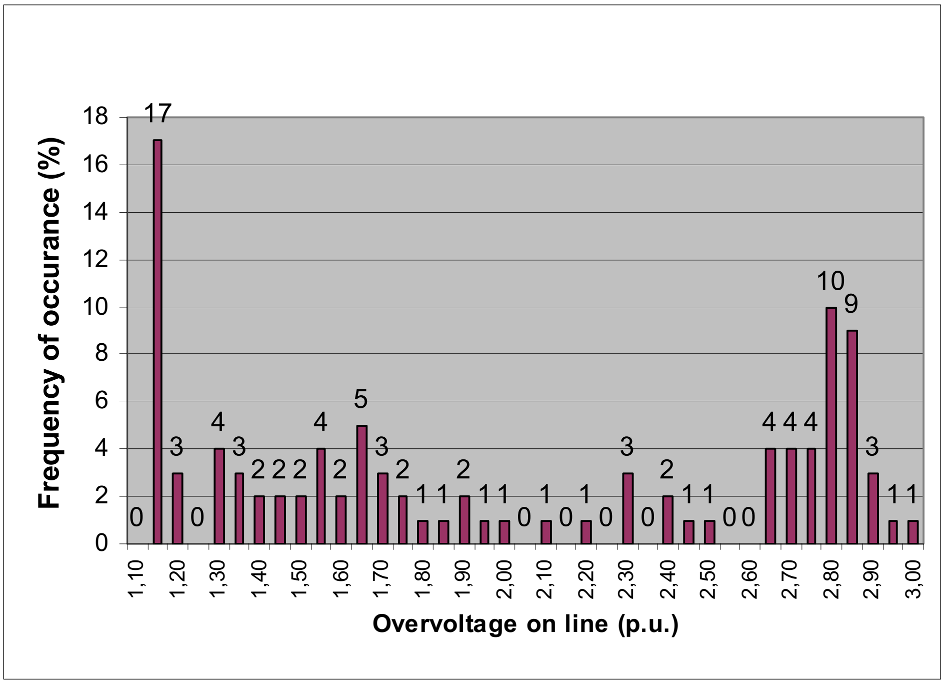
Figure 5.15 – Results of simulation no: 13

5.3.3 – Compensated line with trapped charge

When a shunt reactor compensated line with trapped charge is energised without any means of control, $U_{2\%}$ value reaches up to 2.90 p.u. (simulation no:14). Application of surge arresters in this case reduces $U_{2\%}$ value to 2.30 p.u (simulation no:15)

Application of controlled switching, which targets source voltage zero for closing, reduces the $U_{2\%}$ value 2.40 p.u. for a Δt_{making} value of 1,5 ms (simulation no:16). If the making instant scatter is increased to 2.5 ms., the $U_{2\%}$ value significantly increases to a value of 2.75 p.u. (simulation no:17) When controlled switching and surge arresters are used together $U_{2\%}$ value decreases to a value of 1.85 p.u. (simulation no:18)

As it was discussed in Chapter 4, it is possible to obtain voltage on the line side. Nevertheless obtaining a viable voltage zero between circuit breaker terminals by evaluating both source and line side voltages is very complicated. Since commercially available controllers do not have such features, this case has not been included in simulations.



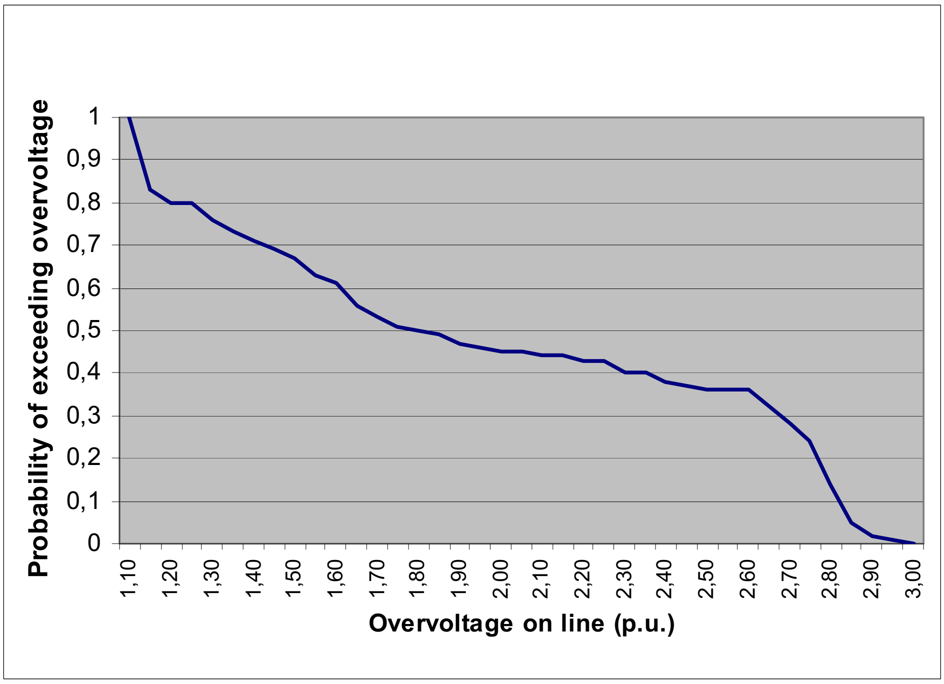


Figure 5.16 – Results of simulation no: 14

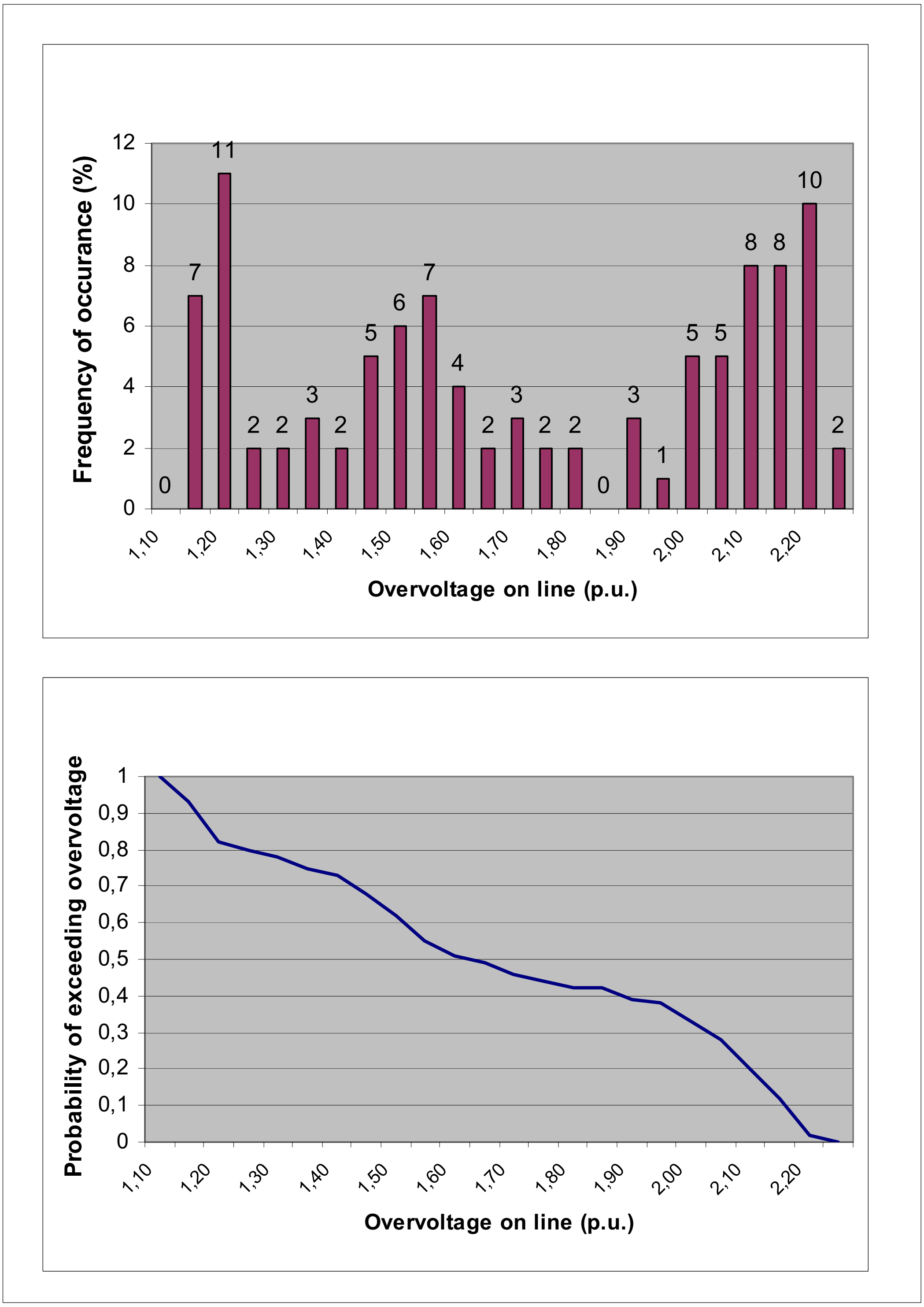


Figure 5.17 – Results of simulation no: 15

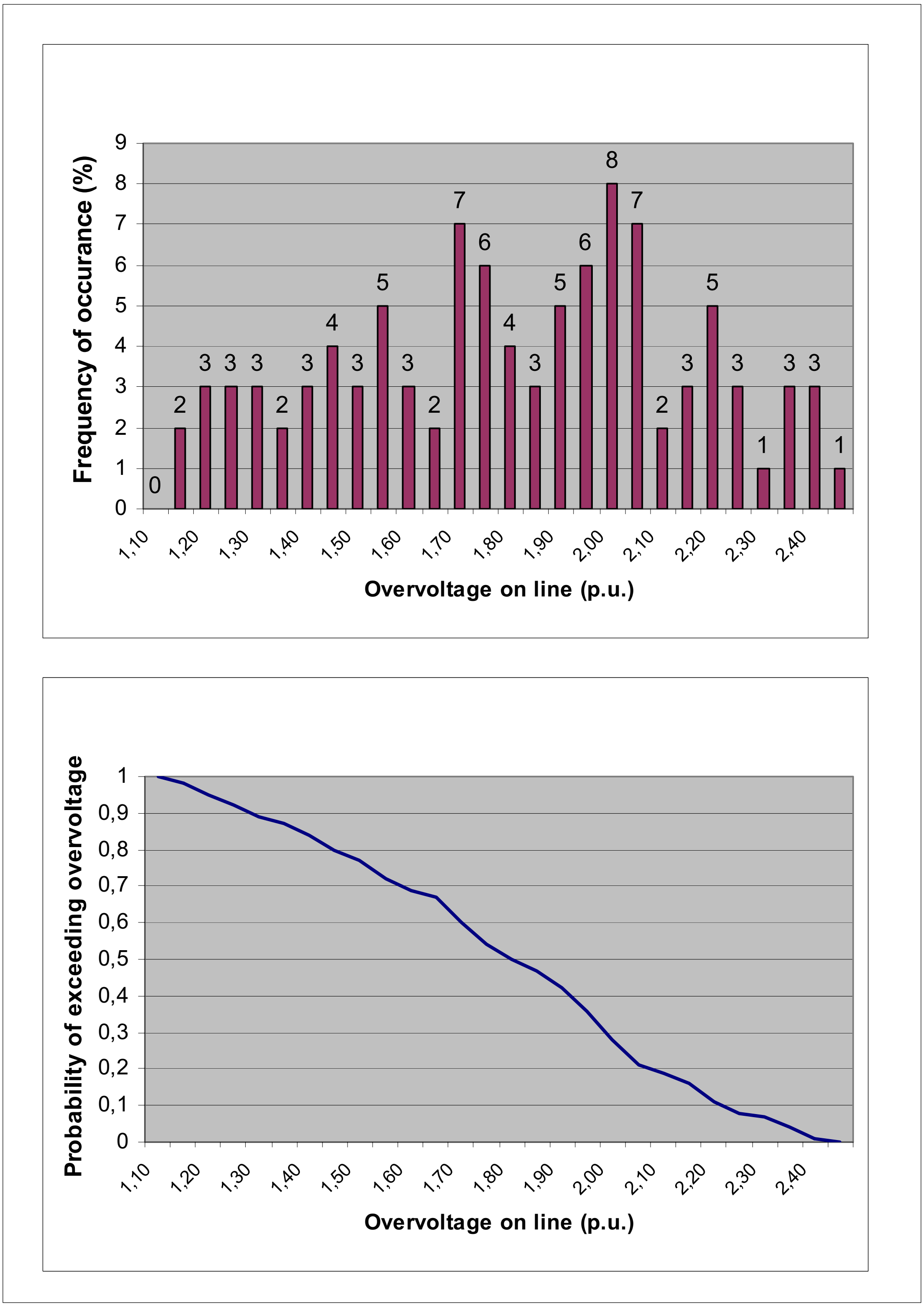


Figure 5.18 – Results of simulation no: 16

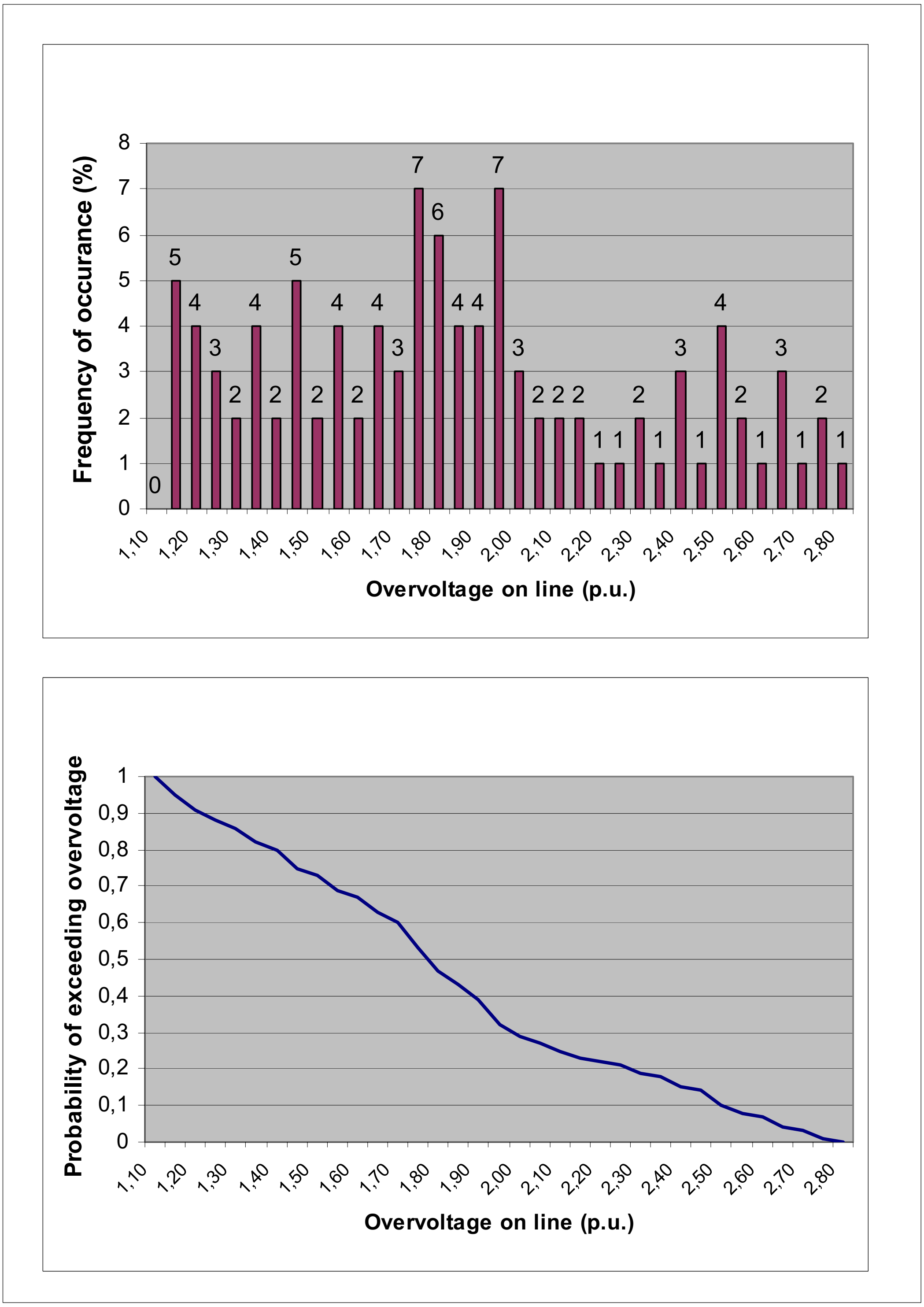


Figure 5.19 – Results of simulation no: 17

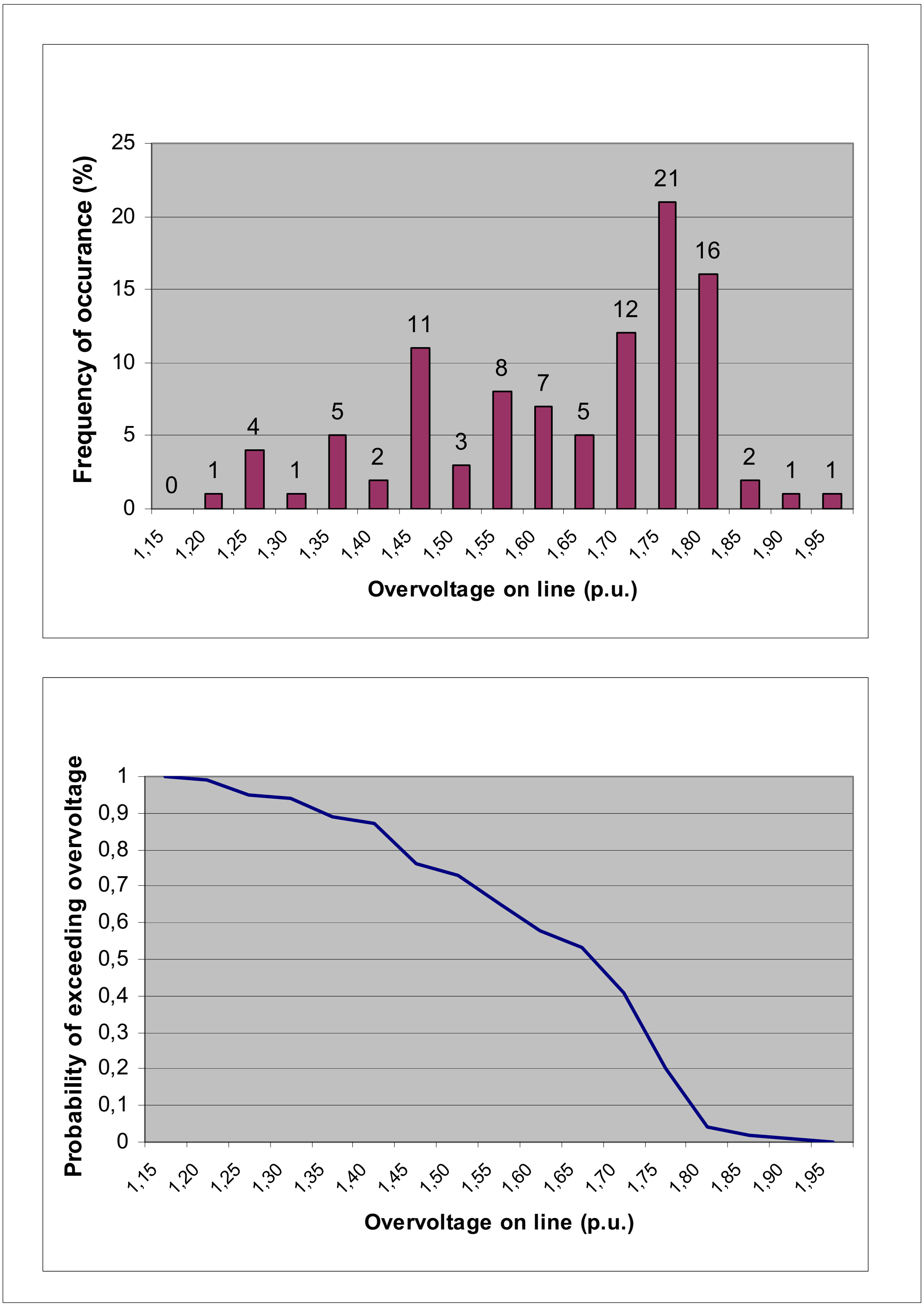


Figure 5.20 – Results of simulation no: 18

CHAPTER 6

CONCLUSION

Controlled switching is a widely applied and continuously improving method used for limiting switching transients encountered in power systems. The method has been investigated for several decades, but its application has become feasible just within past 10-15 years, with the advancements in electronics technology. Today the method has gained its technical maturity especially in some well defined load cases such as shunt capacitor and shunt reactor switching. Possible application areas such as transformer energisation and controlled fault interruption are still under evolution.

Controlled switching method places some requirements on circuit breakers, such as consistent operating times and sufficiently high RRDS and RDDS characteristics. These requirements may in sometimes be very strict, depending on the type of the load to be switched. Presently some circuit breaker types do not fulfill these requirements, hence controlled switching can not be applied to these circuit breakers. But it is expected that, in the near future, the area where controlled switching is applicable will be broadened with the replacement of existing old circuit breakers with modern ones and improvements in algorithms used for controlled switching (operating time compensation, etc).

Controlled switching provides several benefits in both technical and economical aspects. Most important benefits obtained by application of this method is extended lifetime of circuit breakers and lower insulation cost of the power system equipments. Since it is possible to obtain considerable savings with the use of controlled switching, the method attracts notable attention from the users.

Reliability of controlled switching applications can not be assesses for the time being, because of the fact that the wide usage of this method does not reach more than last 10-15 years. But it is expected that the existing reliability of this method, even though it can not be entirely assessed, will be improved with the advance of digital technology and improved technical maturity of controlled switching methods.

On the other hand controlled switching applications are generally backed up by primary protection measures, such as surge arresters, for the purpose of fulfilling redundancy constraints. It has been shown in the simulations that, the protection and control schemes including both controlled switching method and surge arresters provide a better result for transient overvoltage reduction.

Today controlled switching method is applied using an external control device (controller), which takes system voltage and current signals as inputs. Such external applications decrease the reliability of the method, since the cabling and the environmental conditions affect the operation of the controller. In the future it is expected that these controllers will be an internal equipment provided as a standard feature of circuit breakers. Furthermore it also seems possible in the future that, controlling algorithms will be integrated in the substation protection and control systems, which leads to a result that the controlled switching will become a matter of software only.

REFERENCES

[1] CIGRÉ Working Group 13.07, “Controlled Switching of HVAC Circuit Breakers, Guide for application lines, reactors, capacitors, transformers (1st part)” , Electra No 183, April 1999 , CIGRÉ, Paris.

[2] CIGRÉ Working Group 13.07, “Controlled Switching of HVAC Circuit Breakers, Guide for application lines, reactors, capacitors, transformers (2nd part)” , Electra No 185, August 1999 , CIGRÉ, Paris.

[3] CIGRÉ Working Group A3.07, “Controlled Switching: non-conventional applications” , Electra No 214, June 2004 , CIGRÉ, Paris.

[4] Whitaker, Jerry C., “AC Power Systems Handbook” , 2nd edition, CRC Press LLC, 1999.

[5] IEEE Std. C37.100-1992 – IEEE Standard Definitions for Power Switchgear

[6] IEC 62271-100:2001, High-voltage switchgear and controlgear - Part 100: High-voltage alternating-current circuit-breakers, International Electrotechnical Commission, Geneva, 2001.

[7] ANSI C37.06-1987, AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis - Preferred Ratings and Related Required Capabilities, American National Standards Institute, Inc. New York, 1987.

[8] Garzon R. D., High Voltage Circuit Breakers : Design and Applications, Marcel Dekker Inc, New York, 1997

[9] van der Sluis, L., Transients in Power Systems, John Wiley & Sons Ltd, John Wiley & Sons Ltd, Chichester, 2001

[10] SIEMENS “Power Engineering Guide”, 4th edition, Chapter 2, Circuit Breakers for 72 kV up to 800 kV, Figure 18

[11] Knobloch H. et al, “Technological Trends in High-Voltage Circuit-Breakers”, Paper 13-106, CIGRÉ, Paris, Aug 2000

[12] IEEE Std C37.011-2005, IEEE Application guide for transient recovery voltage

[13] IEEE Std C37.012-2005, IEEE Application guide for capacitance current switching for AC high voltage circuit breakers

[14] CIGRÉ Task Force 13.00.1 of Study Committee 13, “Controlled Switching – A State of the Art Survey (1st part)”, Electra No. 162, October 1995, CIGRÉ, Paris

[15] CIGRÉ Task Force 13.00.1 of Study Committee 13, “Controlled Switching A State of the Art Survey (2nd part)”, Electra No 164, February 1996, CIGRÉ, Paris

[16] Hermosillo V. F., “Controlled Switching Circuit Breaker Considerations”, Seminar/Workshop on Controlled Switching, CIGRÉ WG A3.07, IEEE/PES Switchgear Committee Meeting, St. Pete Beach, Florida, May 2003

[17] CIGRÉ Working Group 13.04, “Capacitive Current Switching – State of the Art” , Electra No 155, August 1994 CIGRÉ, Paris

[18] Flurscheim C.H. , “Power Circuit Breaker Theory and Design”, 1975

[19] Beehler, J.E. , ”Weather, Corona and the Decay of Trapped Energy on Transmisson Lines” , IEEE PAS, Vol.83, No.5, pp 512-520, May 1964

[20] Froechlich K., “Introduction to Controlled Switching”, Seminar/Workshop on Controlled Switching, CIGRÉ WG A3.07, IEEE/PES Switchgear Committee Meeting, St. Pete Beach, Florida, May 2003

[21] IEEE Std C37.104-2002, IEEE Application guide for automatic reclosing of line circuit breakers

[22] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapters 1 and 2)” , Electra No 72, October 1980, CIGRÉ, Paris

[23] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 3, Part A)” , Electra No 75, March 1981, CIGRÉ, Paris

[24] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 3, Part B)” , Electra No 95, June 1984, CIGRÉ, Paris

[25] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 4, Part A)” , Electra No 101, July 1985, CIGRÉ, Paris

[26] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 4, Part B)” , Electra No 113, July 1987, CIGRÉ, Paris

[27] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 5, Part 1)” , Electra No 133, December 1990, CIGRÉ, Paris

[28] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 5, Part 2)” , Electra No 134, February 1991, CIGRÉ, Paris

[29] CIGRÉ Working Group 13.02, “Interruption of small inductive currents (Chapter 6)” , Electra No 138, October 1991, CIGRÉ, Paris

[30] IEEE Std C37.015-1993, IEEE Application guide for shunt reactor switching

[31] IEC TR 1233, High-voltage alternating-current circuit-breakers-Inductive load switching , International Electrotechnical Commission, Geneva, 1994.

[32] Morais S.A. , “Considerations on the specification of circuit breakers intended to interrupt small inductive currents” , Electra No 147, April 1993, CIGRÉ, Paris

[33] Greenwood, A., “Electrical Transients in Power Systems,” *Wiley-Interscience* , New York, 1971.

[34] Ishikawa, M., Kosakada, M., Okabe, S., Suzuki, K., and Toda, H., “Investigations of Multiple Reignition Phenomena and Protection Scheme of Shunt Reactor Current Interruption in GIS Substations,” IEEE Transactions on Power Delivery, vol. 8, no. 1, pp. 197–202, Jan. 1993

[35] van Den Heuvel, W.M.C., Papadias, B.C. , “Interaction between phases in three-phase reactor switching, part I: Grounded reactors”, Electra No 91, October 1983, CIGRÉ, Paris

[36] van Den Heuvel, W.M.C., Papadias, B.C. , “Interaction between phases in three-phase reactor switching, part II: Ungrounded reactors”, Electra No112 , May 1987, CIGRÉ, Paris

[37] CIGRÉ Working Group A3.07, “Controlled Switching of HV AC Circuit Breakers : Guidance for further applications including unloaded transformer switching, load and fault interruption and circuit-breaker uprating”, January 2004, CIGRÉ, Paris.

[38] CIGRÉ Working Group A3.07, “Controlled Switching of HV AC Circuit Breakers :Benefits & economic aspects”, Jan 2004, CIGRÉ, Paris.

[39] CIGRÉ Working Group A3.07, “Controlled Switching: non-conventional applications”, Electra No 214, Jun 2004, CIGRÉ, Paris.

[40] Uglesic, I., Hutter, S., Krepela, M., Grcic, B.F., Jackl, F., “Transients due to switching of 400 kV shunt reactor”

[41] Lee, W.Y., Park, K.Y., Chong, J.K., Lee, B.Y., Kim, H.J., "A method to decide the switching instants of controlled switching circuit breaker for shunt reactors" , 2002

[42] Maury, E., "Sysnchronous closing of 525 and 765 kV circuit breakers: A means of reducing switching surges on unload lines", CIGRÉ session 1966 , report 143, CIGRÉ, Paris

[43] Fernandez, F.C., Esmeraldo, P.C.V., Filho, J.A., Zani, C.R., "Use of controlled switching systems in power system to mitigate switching transients. Trends and benefits – Brazilian experience", IEEE/PES Transmission & Distribution Conference & Exposition: Latin America, 2004

[44] Janssen A.L.J., Degen W., Heising C.R., Bruvik H., Colombo E., Lanz W., Fletcher P., Sanchis G., "A Summary of the Final Results and Conclusions of the Second International Enquiry on the Reliability of High-Voltage Circuit Breakers", Paper 13-202, CIGRÉ, Aug 28 - Sept 3, 1994, Paris.

[45] Carvalho, A., Hofbauer, W., Hogg, P., Froechlich, K., "Controlled switching as a reliable mean to reducestresses imposed to the circuit breaker and to the network", Paper 13-95, CIGRÉ SC 13 Colloquium, 27-28 Sept, 1995, Florianopolis, Brazil.

[46] Koschik, V., Lambert, S. R., Rocamora, R. G., Wood, C. E., and Worner, G., "Long line single-phase switching transients and their effect on station equipment", IEEE Transactions on Power Apparatus and Systmes, PAS-97, 1978.

[47] ABB , "Controlled Switching – Buyer's Guide, Application Guide – Edition 1", 2004-05

[48] Froehlich, K., Hoelzl, C., Stanek, M., Carvalho, A.C., Hofbauer, W., Hoegg, P., Avent, B.L., Peelo, D.F., Sawada, J.H. , "Controlled closing on shunt reactor compensated transmission lines, Part I: Closing control device development", IEEE Transactions on Power Delivery, Vol.12, No 2, April 1997.

[49] Froehlich, K., Hoelzl, C., Stanek, M., Carvalho, A.C., Hofbauer, W., Hoegg, P., Avent, B.L., Peelo, D.F., Sawada, J.H. , "Controlled closing on shunt reactor compensated transmission lines, Part II: Application of closing control device for high speed autoreclosuring on BC Hydro 500 kV transmission line", IEEE Transactions on Power Delivery, Vol.12, No 2, April 1997.

[50] Brunke J. H., Fröhlich K. J., "Elimination of transformer inrush currents by controlled switching - Part I: Theoretical considerations", IEEE Transactions on Power Delivery, Vol. 16, No. 2, April 2001.

[51] Brunke J. H., Fröhlich K. J., "Elimination of transformer inrush currents by controlled switching - Part II: Application and performance considerations", IEEE Transactions on Power Delivery, Vol. 16, No. 2, April 2001.

[52] Thomas R., Sölver, C.E., "An adaptive self-checking algorithm for controlled fault interruption", International Conference on Power System Transients (IPST), June 2005, Montreal, Canada.

[53] TEİAŞ Yük Tevzi Dairesi Başkanlığı Etüd ve Raporlama Müdürlüğü, "2003 puant yük şartlarında yük akışı, üç faz ve faz toprak kısa devre etüdü, SE-2004/1"

[54] Rule Book – ATP – Alternative Transient Program, XVI Jmarti setup

[55] Rule Book – ATP – Alternative Transient Program, VI.B.Statistic and systematic switches

APPENDIX

SIMULATION DATA

A.1 - Source side parameters

Peak value of source voltage;

$(420000 / \sqrt{3}\ ) . \sqrt{2}\ = 343000$ V

Thevenin equivalent values provided by TEİAŞ (380 kV Sincan S/S);

R= 0.00125 p.u. = 2 Ω (primary)

X= 0,00642 p.u. =10,272 Ω (primary)

L= 32,69 mH

Resistance representing surge impedance of the source side circuit;

R= 400 Ω

A.2 – Overhead line parameters

Table A.1 – Overhead line data

General	
Tower geometry	Given in Figure A.1
Sag, m	10
No of conductors in each bundle	3
Bundle spacing, mm	45,7
Conductors	
Phase conductors	ACSR 954 MCM
No of aluminium strands	54
No of steel strands	7
No of aluminium and steel layers	3 Al + 1 Steel with a central wire
No of outer layer strands	24
Strand diameter, mm	3,38
Conductor diameter, mm	30,42
DC resistance, Ω/km at 20˚C	0,0597
Earth wires	
Type	1. wire: Galvanized steel wire 2.wire: Optical ground wire (107/44)
No of conductors	1 GSW + 1 OPGW
No of steel strands	1. wire: 7 2.wire: 9 (with central tube)
No of layers	1. wire: 1 2.wire: 1
Strand diameter, mm	1. wire: 4,19 2.wire: 4
Ground wire diameter, mm	1. wire: 12,6 2.wire: 15,3
DC resistance, Ω/km at 20˚C	1. wire: 2,132 2.wire: 3,42

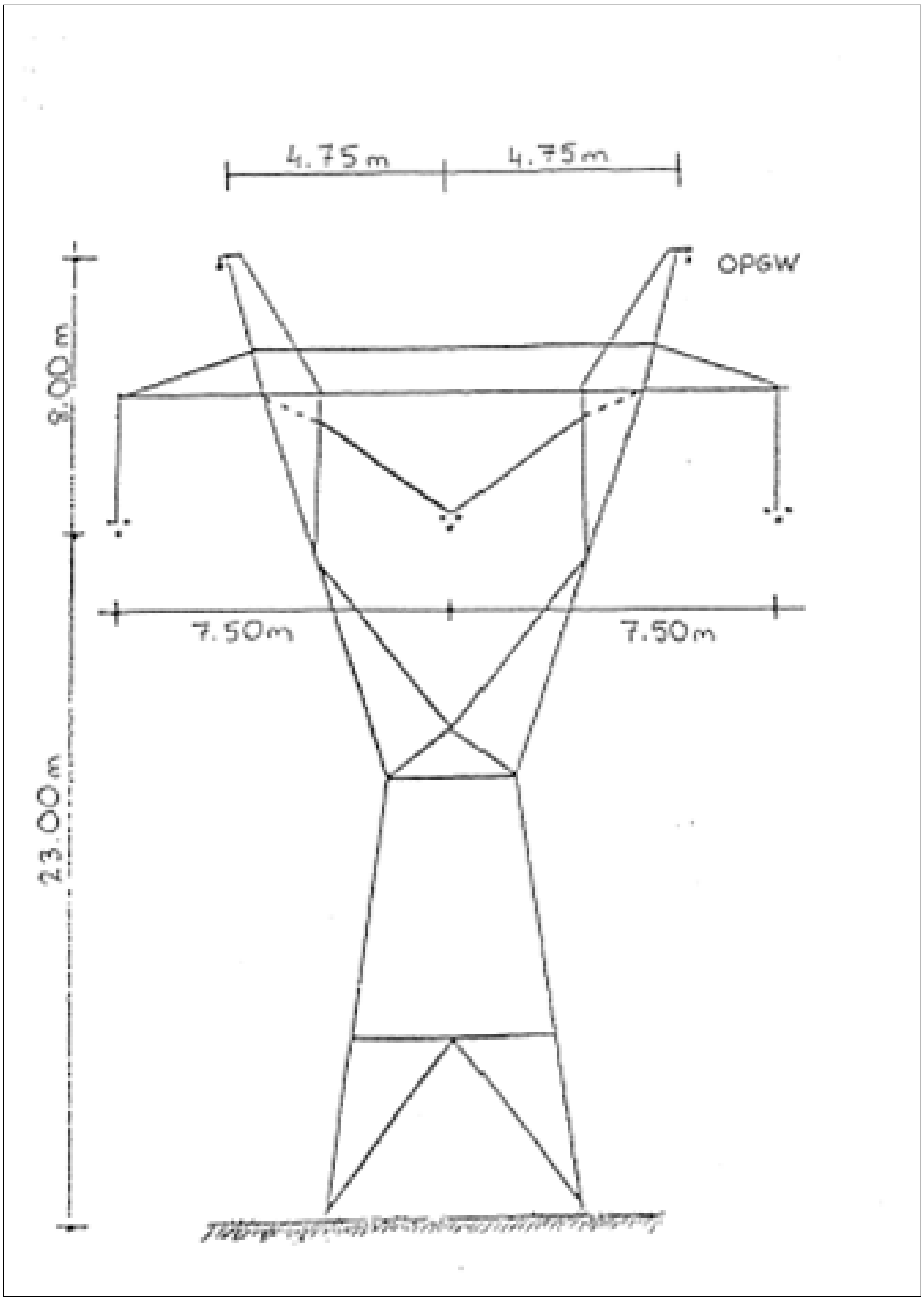


Figure A.1 – Overhead line tower data

```
BEGIN NEW DATA CASE
JMARTI SETUP
$ERASE
BRANCH  IN___AOUT__AIN___BOUT__BIN___COUT__C
LINE CONSTANTS
METRIC
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901243567890123456789012345678901234567890
C
C CONDUCTOR DATA
C
C p    s       r                 d       h       v       v       s      a     n n

C h    k       e            cm   i       o       t       m       e      l     a b
C a    i  ohms s            in   a       r       o       i       p      p     m u
C s<---n<------i          <------m<------i<------w<------d<------a<----h<----e<n

C
C 1. GROUND CONDUCTOR:
  0 0.50   2.132 4           1.260   -4.75   31.00   21.00
C 2. GROUND CONDUCTOR:
  0 0.50   3.420 4           0.400    4.75   31.00   21.00    0.40   40.0       9
C
  1 0.50 0.05970 4           3.042   -7.50   23.00   13.00    45.7   60.0       3
  2 0.50 0.05970 4           3.042     0.0   23.00   13.00    45.7   60.0       3
  3 0.50 0.05970 4           3.042    7.50   23.00   13.00    45.7   60.0       3
C
BLANK
C End of Conductor Cards
C
C FREQUENCY CARDS
C                f          C print> print> I      d      IM     I    U
C ohm-mr    Hz   r          a inv       inv c      i  prntsu     p    n
C      h         e          r CCCCCC ZZZZZZ a      s  YYZZet     n    t
C -----o<--------q          s  es es  es es p <----t   s sgu<-c<-t    r
     50.      50.          1                     66.              1
     50.    0.005          1                     66.        8  5    1
BLANK
C End of Frequency Cards
BLANK
C End of Case
DEFAULT
$PUNCH, G-TBA.pch !
BLANK card ending  JMARTI SETUP  data cases
```

Figure A.2 – Input file of the overhead line

A.3 – Reactor parameters

Rated power of reactor: 73,3 MVar

Frequency: 50 Hz

L = 7,66 H

C = 10615 / 3 = 3538 pF

R = 2 MΩ

Date (DD/MM/YY)	30/11/05	Time	11:25
Company	SIEMENS		
Location	380 kV Hisar TM Kayabasi-Reaktor		
Equipment	Reaktor		
Serial Number	7106353		
Manufacturer	ASEA		
Year	1979		
Type	XMY45		

Test Results

No	Test ID	L C	Circ. Desc.	kV	mA	Watts	Meas. %PF	Corr. Fctr	Corr. %PF	Cap./ Ind.	R T
1	CH	B	GND-RB	10,00	33,348	1,212	0.364	1.00	0.364	10615 pF	
3	A Fazi Bushing							1.00			
4	C1	B	UST-RB	10,00	1,674	0,087	0.520	1.00	0.520	532,7 pF	
5	C1	B	UST-RB	1,500	1,670	0,110	0.660	1.00	0.660	531,6 pF	
6	C2	B	GAR-RB	1,500	2,260	0,085	0.375	1.00	0.375	719,4 pF	
7	C1+C2	B	GND-RB	1,500	3,930	0,161	0.409	1.00	0.409	1251,0 pF	
8	B Fazi Bushing							1.00			
9	C1	B	UST-RB	10,00	1,687	0,083	0.491	1.00	0.491	536,9 pF	
10	C1	B	UST-RB	1,500	1,685	0,103	0.611	1.00	0.611	536,3 pF	
11	C2	B	GAR-RB	1,500	2,220	0,087	0.391	1.00	0.391	706,5 pF	
12	C1+C2	B	GND-RB	1,500	3,905	0,178	0.455	1.00	0.455	1243,0 pF	
13	C Fazi Bushing							1.00			
14	C1	B	UST-RB	10,00	1,665	0,084	0.507	1.00	0.507	530,0 pF	
15	C1	B	UST-RB	1,500	1,662	0,099	0.598	1.00	0.598	529,1 pF	
16	C2	B	GAR-RB	1,500	2,298	0,091	0.395	1.00	0.395	731,4 pF	
17	C1+C2	B	GND-RB	1,500	3,956	0,150	0.380	1.00	0.380	1259,1 pF	
18	Nötr Bushingi							1.00			
19	C1	B	UST-RB	10,00	0,818	0,041	0.497	1.00	0.497	260,5 pF	
20	C1	B	UST-RB	1,500	0,819	0,040	0.493	1.00	0.493	260,9 pF	
21	C2	B	GAR-RB	1,500	1,344	0,017	0.124	1.00	0.124	427,7 pF	
22	C1+C2	B	GND-RB	1,500	2,163	0,064	0.296	1.00	0.296	688,6 pF	

Figure A.3 – Shunt reactor site test report

A.4 – Surge arrester parameters

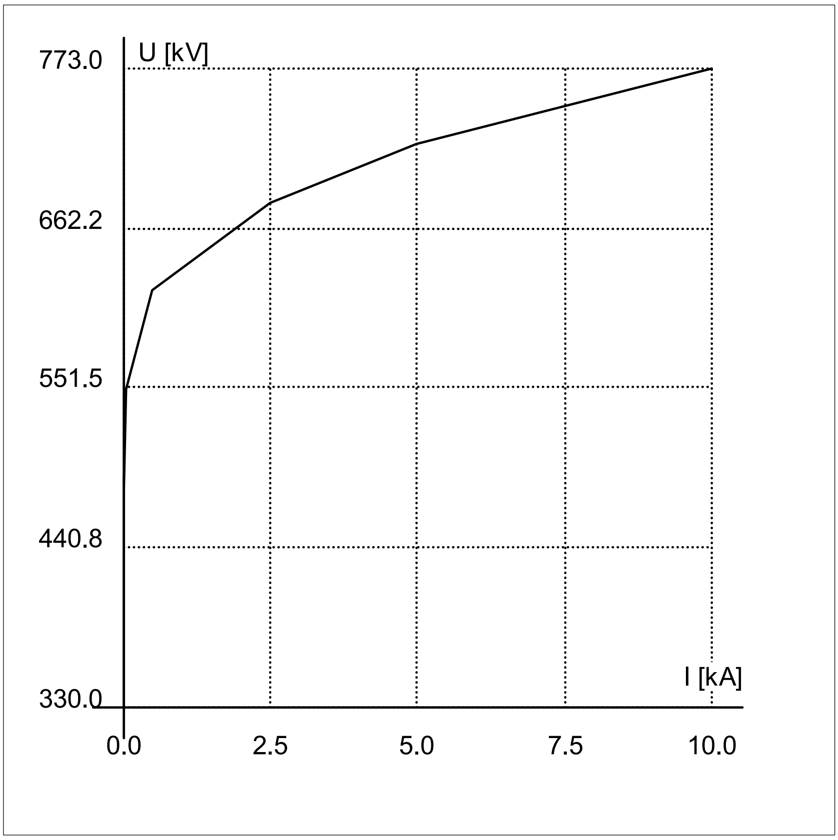


Figure A.4 – Surge arrester characteristics