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Controlled Switching of Reactive Loads and Commisioning Regimes

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material to a substantial extent has been accepted for the award of any other degree or diploma by university of higher learning, except where due acknowledgement has been made in the text.

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Date: ______________________________

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Publications & Industry Contribution

1. Cowhey, Eoin, O'Donovan, Michael, Connell, Dr Joe, *Performance & Analysis of Controlled Switching on a Transmission System*, 51st Universities Engineering Power Conference (UPEC 2016), Coimbra, Portugal, 2016.

2. Cowhey, Eoin, O'Donovan, Michael, Connell, Dr Joe, Kearns, Niall, *Utility Experience of Commissioning Controlled Switching Devices on Transmission Shunt Reactors*, 52nd Universities Engineering Power Conference (UPEC 2017), Heraklion, Crete, 2017.

3. Member of CIGRÉ Working Group A3.35, *Best Practices for Commissioning of Controlled Switching Projects*.

Abstract

Switching is a vital task in any power system for ensuring its safe and reliable operation. Switching may be necessary for fault clearance, to ensure wider system stability and to prevent damage to plant. It is essential for isolation, to allow technicians to carry out maintenance tasks safely. Also, switching of reactive loads such as shunt capacitor banks and shunt reactors, is crucial for controlling system voltage.

Switching of some loads however, may produce voltage transients and heavy transient inrush currents which can impact on wider system power quality, impact customers and cause damage or deterioration of the insulation of HV equipment. Therefore, it is important to provide some form of measure to control or mitigate transients caused by switching. The main control measures include: metal oxide surge arrestors, pre-insertion resistors, current limiting reactors and synchronised or controlled switching. Controlled switching is the favoured solution for frequently switched loads such as reactive plant, for economic benefits and as it reduces transients in the first instance.

Controlled switching is defined as the use of electronic equipment to control the making or breaking of high voltage circuit breakers at pre-determined points on the system voltage and current waveforms. It has been implemented in Ireland for over 30 years for the energisation of shunt capacitor banks. Over the last two years, the benefits of controlled switching for different applications has become ever more apparent, with increased use such as switching of transmission shunt reactors and the energisation of large power transformers, particularly in remote areas of the network such as wind farm interfaces.

The aim of this thesis is to provide a complete overview of the stages concerned in implementing controlled switching schemes, from examining the impacts of switching certain loads, to performing systems studies, up to site commissioning stage. The research in this thesis looks at both the theory and practice. It draws together the published work, manufacturers guidelines, international standards and simulation results, to give the total awareness of the issues involved in reactive load switching and commissioning regimes.

The various solutions and strategies associated with controlled switching schemes are examined, to ensure that the best and most economical solution has being implemented. Several recent projects where controlled switching has been implemented for switching of transmission reactors and power transformers are also investigated.

List of Abbreviations

A	Ampere
BCU	Bay control unit
CB	Circuit breaker
CIGRÉ	Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)
CS	Controlled switching
CSD	Controlled switching device
CT	Current transformer (instrument transformer)
DC	Direct current
EMTP-ATP	Electro Magnetic Transients Program – Alternative Transients Program
EHV	Extra high voltage
FACTS	Flexible AC transmission systems
HV	High voltage
HVDC	High voltage direct current
IEC	International Electrotechnical Commission
IEEE	Institution of Electrical and Electronic Engineers
IPP	Independent Power Producer
kV	Kilo-volts
MVAr	Mega volt amps reactive
MW	Mega watt

OTLC	Onload tap changer
p.u.	Per-unit value
r.m.s	Root-mean-square value
RDDS	Rate of decrease of dielectric strength
RRDS	Rate of rise of dielectric strength
SF_6	Sulphur hexafluoride
STATCOM	Synchronous static compensator
SVC	Static Var compensator
TACS	Transient analysis of control systems
TRV	Transient recovery voltage
VT	Voltage transformer (instrument transformer)

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1. Introduction

1.1 Overview

In recent years the Irish power system has become considerably more complex with the increasing penetration of generation from renewable energy sources, mainly wind along with more complex customer loads.

Many of these new connections saw an increased use of underground cables rather than the traditional overhead line conductors in order to minimise the visual environmental impact. Some of these connections can be a considerable distance from existing transmission stations, up to 40 km for certain 110 kV renewable connections. Shunt reactors were necessary to limit the capacitive voltage rise. Also, in some of these installation types, it is becoming common to install harmonic filters to mitigate any possible sub harmonic distortion arising from ferro-resonance.

In major urban areas which are located in more prominent parts of the network, the use of underground cables is considerably more prevalent due to safety, visual impact and reliability. Again, owing to the capacitive nature of cables, there are issues with voltage rise during low load periods, so it was necessary to install larger shunt reactors to clamp voltages to acceptable levels.

Conversely, to boost and maintain acceptable voltage levels in weaker parts of the network, with little or no generation sources in proximity, it was necessary to install shunt capacitor banks to supply the local reactive power needs. There have been more than 40 shunt capacitor banks installed in locations throughout Ireland in the last thirty years.

Industrial customers' loads have also become increasingly more complex with the use of sensitive electronic equipment such as, variable speed drives for motors, advanced manufacturing process such as semiconductor production, communications equipment and in recent years there has being a major influx of data centres to Ireland. At present there is 250 MVA of installed data centre connections and this figure is likely to expand over the next 10 years by 1000 MVA, with 600 MVA connection offers currently in place [1]. See Figure 1.1.

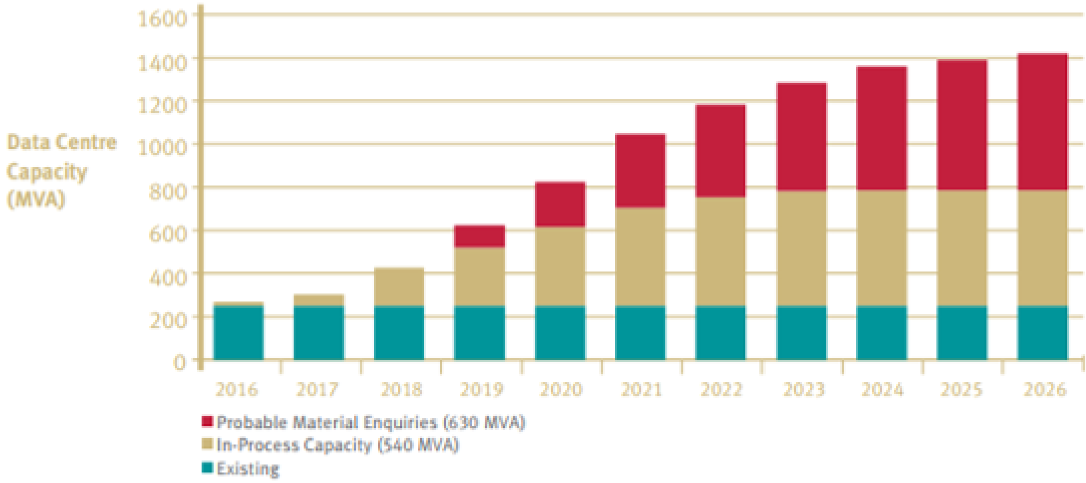


Figure 1.1: Demand Expected from Assumed Build of New Data Centres [1].

Therefore, as customers' loads are sensitive, they require a constant clean electricity supply source within acceptable voltage and frequency thresholds, so reactive and filtering plant are vital in achieving this. While at the same time they are highly susceptible to switching events on the power system, which can produce transient oscillations and impact quality of supply.

Reactive components such as shunt capacitor banks and reactors which are used to control voltage levels, are switched remotely by system operators depending on the system voltage requirements and many of these components may be switched daily. The main issue with switching this type of equipment is that, heavy transient inrush currents and transient over voltages can occur during energisation and transient over voltages may occur during de-energisation. These transients may:

- Propagate through the network and can result in interference with customers equipment.
- Immediately damage or de-grade over time the insulation of HV equipment, leading to the unavailability of key infrastructure used to enhance quality of supply.

Therefore, to prevent and mitigate the occurrence of transient currents and voltages during switching, it is necessary to introduce a means of controlling and damping. The most common methods of managing transients include:

- Metal oxide surge arrestors.
- Pre-insertion resistors.
- Current limiting reactors.
- Controlled or synchronised switching of circuit breakers.

Controlled switching (CS) is the preferred method for frequent switching of loads as it can prevent occurrence of transients in the first instance.

1.2 Motivation and Research Objectives

CS has been utilised for the energisation of shunt capacitor banks on the 110 kV transmission system for almost 25 years now. The Irish electrical utility has had negative experience in the past with CS whereby, almost all of the early generation of Controlled Switching Devices (CSD) have failed in service from 1995 on. This left the transmission system operator in a position where they had to adopt a limited switching regime of shunt capacitor banks at off peak times to prevent any interference to customers [2]. Uncontrolled switching eventually resulted in deterioration of many of the circuit breaker interrupters, and from 2012 to 2015 over 30 of these CSDs along with their associated circuit breaker have been replaced.

In the last 2 years, the application of CS has been further utilised for switching of filter banks, shunt reactors and also for the energisation of large power transformers on weaker parts of the network such as wind farm interface transformers.

The main motivation for this research is to investigate the current suitability and effectiveness of the CS strategies implemented for existing shunt capacitor bank installations in Ireland, and also for the implementation of CS for shunt reactor and transformer switching applications. These were introduced to the Irish transmission over the duration of this research.

This research will examine:

- Power quality issues associated with switching of predominately reactive loads.
- CS methods for the energisation and de-energisation of HV plant and equipment.
- The pertinent circuit breaker characteristics, both internal and external which may influence the performance of the circuit breaker.
- Most effective CS strategies for the 3 main switching applications; shunt capacitor banks, shunt reactors and power transformers.
- Proposed improved practical methods of commissioning CS schemes.

1.3 Contribution of Thesis

The main contribution of this research is to provide a complete insight of the stages in implementing CS scheme from examining the theory, to simulation studies, up to the site commissioning stage. The major stages in realising this outcome are to:

1. Investigate the current state of the art of CS as applied in the Irish transmission system and examine how effective current CS strategies for a number of different applications are and make recommendations for any improvements if necessary.
2. Demonstrate the importance of system studies and analysis when considering CS. Outline the pertinent information required for modelling and build a number of standard EMTP-ATP models which can be utilised for similar studies in the future.
3. Examine the best method of commissioning, testing and validating the operation of these type of schemes to ensure the best performance of the CS scheme over its lifecycle.

1.4 Thesis Structure

This thesis is composed of eight main components and is structured as follows:

- Switching in the power system and circuit breaker technology (Chapter 2).
- Mitigation measures (Chapter 3).

- System modelling using EMTP-ATP to simulate load switching (Chapter 4).
- Capacitive load switching (Chapter 5).
- Shunt reactor switching (Chapter 6).
- Switching of unloaded power transformers (Chapter 7).
- Conclusions and further research (Chapter 8).

Chapter 2 deals with the theory of switching and examines the different types of transients, how they are produced and impacts to equipment and customers. In this chapter current sulphur hexafluoride (SF_6) circuit breaker technology for load switching is also discussed.

Chapter 3 outlines the current state of the art of CS on the transmission system in Ireland. Selected methods of mitigating switching transients are discussed here, including metal oxide surge arrestors, pre-insertion resistors and current limiting reactors. A detailed insight of CS and how it is implemented is included, along with various external influencing factors such as temperature and control voltage and how they affect the circuit breaker performance.

Chapter 4 examines EMTP-ATP, which is an industry standard software tool for analysing and simulating switching transients. It is demonstrated here, how the modelling of the main network components such as shunt capacitors banks, shunt reactors and power transformers is achieved. Methods of modelling of the switching arc is also introduced here.

Chapter 5 examines methods of eliminating transient inrush currents and high transient voltages that occur during shunt capacitor bank switching. Also discussed here are the different methods of controlled switching, strategies to be employed and other considerations with this type of load and physical arrangement, including switching near previously energised capacitive loads. This section includes a case study on the commissioning practice surrounding shunt capacitor banks in Ireland.

Chapter 6 gives an overview of the problems that occur when switching transmission shunt reactors and how CS can be employed to eliminate unsymmetrical energisation current and prevent current chopping during de-energisation. A case study of the commissioning of a 220 kV, 50 MVAr shunt reactor is also discussed.

Chapter 7 deals with the energisation of unloaded power transformers. This presents issues for localised system voltage limits, particularly at independent power provider (IPP) interfaces. Here controlled switching as a solution is discussed, and the most appropriate switching strategy for the winding configuration, grounding method and core type is also examined. A case study of where CS was implemented on a 220 kV: 21 kV, 500 MVA power transformer is also presented.

Chapter 8 concludes the thesis by discussing the most appropriate methods of mitigation, downfalls with current methods and how controlled switching should be considered for each application, with a studied approached and robust commissioning procedure. Future research proposals are also discussed.

1.5 Literature Review

The main gap in this subject exists around the complete implementation of CS schemes from start to finish. Therefore, as an objective of this research, an attempt is made to tie all the different stages in implementing CS, with a particular focus on applications on the Irish transmission system. The core steps in employing a CS scheme are:

- Understanding the problem and how CS schemes can improve power quality.
- Perform simulation studies to investigate the most appropriate strategy.
- Specification of hardware, including CSD and CB, including the application of compensation measures and CB dielectric strength to ensure a robust scheme.
- Implementation in practice, commissioning of these schemes, understanding the correct operation and ensuring its correct performance.

To date there has been much investigation into how CS can improve power quality for different applications. CS has always been recognised as a method of reducing switching transients and increasing power quality, but only in recent years with advances in more robust CB technology can it be efficiently implemented. The following are the main literature sources used for the basis of this research:

Power Quality

- Duggan, R.C. et al (2004), outlines a general overview of the types and classifications of transients that occur during switching. The main sources of transients investigated in this literature are based on utility capacitor switching and unloaded power transformer switching [3].

- IEEE standard 1195 (1995), provides concise definitions and classifications of power quality anomalies including switching impulse and oscillatory transients based on frequency, durations and causes [4].

Switching Technology

- Smeets, R. et al (2015), systematically discusses all aspects of electrical load and fault switching based on load type, CB technology and provides guidance on how to mitigate unacceptable switching transients. Much of this literature is supported with practical examples of switching phenomena based on real life measurements [5].
- IEEE standard C37.012 (2014), provides detailed guidance in relation to CBs designated for capacitive load switching and details capacitive load types including shunt capacitor banks, high voltage (HV) cable and unloaded transmission lines. Methods of analysing and calculating peak inrush currents and oscillatory frequencies that the switching device has to handle, are also demonstrated here [6].
- IEEE standard C37.015 (2009), sets out the standard requirements for CBs intended for shunt reactor switching applications. Methods of calculating and analysing the various voltage peaks and oscillatory modes following current interruption and re-ignition are also provided here [7].
- IEC 622271-110 (2009), details the requirements for CBs and their duty for inductive load switching. Also detailed here are the factory test requirements for CBs intended for inductive load switching, including the method used to determine the CBs minimum arcing time (MAT) and re-ignition region on the voltage waveform [7].

System Simulation

- Akihiro, A. at al (2015), provides a complete and practical overview of the main simulation software tools available for transient studies which include EMTP-RV, EMTP-ATP and EMTDC/PSCAD. Detailed here are practical methods used for arc modelling including EMTP-ATP MODELS Thevenin type 94 component [8].

- Haginomori, E. at al (2016), gives practical guidance and examples on the use of EMTP-ATP for transient studies including the modelling switching transient for capacitive and inductive load switching. Demonstrated in this literature is the method of using an integrated EMTP control strategy for the purpose of simulating dynamic switching arcs and also more practical approaches [9].
- Pinceti, P et al (2009), propose a solution to model metal oxide surge arresters based on their electrical characteristics. This in contrast to the IEEE frequency dependent model which is based on the physical characteristic [10].

Controlled Switching

- CIGRÉ WG A3.07 (2004), provides much detail and experience on all aspects of controlled switching. This technical brochure details of benefits and economical aspects of CS per load type, including the more common applications, such as shunt reactors and capacitors, to the more specialised including power transformer switching and CS for fault clearance. Also outlined here are the CB requirements and compensation measures [11] [12].
- Goldsworthy, D. et al 2008, describes the internal philosophy used by CSDs in calculating the switching target for both controlled energisation and de-energisation, taking into account the various compensation measures and practical case studies of CS as applied by Bonneville Power Administration for the main CS load types [13].
- Brunke, J. et al (1998), details both the rapid switching and delayed controlled switching strategy for controlled switching of unloaded power transformers, outlining the importance of both the residual and dynamic fluxes in the transformer core [14].

Commissioning of Controlled Switching Schemes

- Currently CIGRÉ A3.35 working group has been set up to investigate the best practices for commission of controlled switching schemes, a general overview of all the main applications are included by load type, particularly at extra high voltage (EHV) transmission voltage levels where plant failures as a result of switching transients are more prevalent.

2. **Switching**

2.1 Switching in the Power System

Switching is a vital task to ensure the safe and stable operation of any transmission system. Switching may be an automated task, such as:

- Selective fault isolation of equipment following short circuits for safety, and to ensure the stability of the system.
- Load shedding operations, to ensure wider system stability during major voltage or frequency perturbations, and to provide automated restorations upon system normalisation.

Switching may also be a manual task:

- Certain plant or equipment may have to be isolated for safe maintenance when technicians are working in close proximately to live equipment. Consequently, parts of the network may re-distributed to allow this.
- Switching may also be performed by system operators for voltage control, i.e. switching of reactive components such as shunt reactors and capacitor banks.

However, switching of certain components can be an onerous task for the switching circuit breaker to handle, and high frequency transients in the current and voltage waveforms may also be produced in the process.

The main concern in this thesis, is switching of reactive loads. These loads may be particularly onerous for the power system to handle, due to heavy inrush currents while energising and high frequency oscillatory transient over-voltages when plant is being de-energised. Examples of these load types include:

Capacitive Loads

- Unloaded cables and long overhead lines.
- Shunt capacitor banks or harmonic filter plant.

Inductive Loads

- Shunt reactors.
- Unloaded power transformers.

2.2 Transients

Transients, also known as surges or spikes are short momentary changes in voltage or current over a very short period, typically in the order of µs to ms. Transients can be very large in magnitude and can typically be divided into two classifications:

- Impulse transients.
- Oscillatory transients.

2.2.1 Impulse Transients

Impulse transients can be defined as a sudden non-frequency change in the steady state order of current and voltage waveforms that is essentially one direction, either a positive or negative impulse [4]. This is simply a single high frequency spike in voltage, typically less than 5 µs. This type of transient may be many times the nominal peak magnitude.

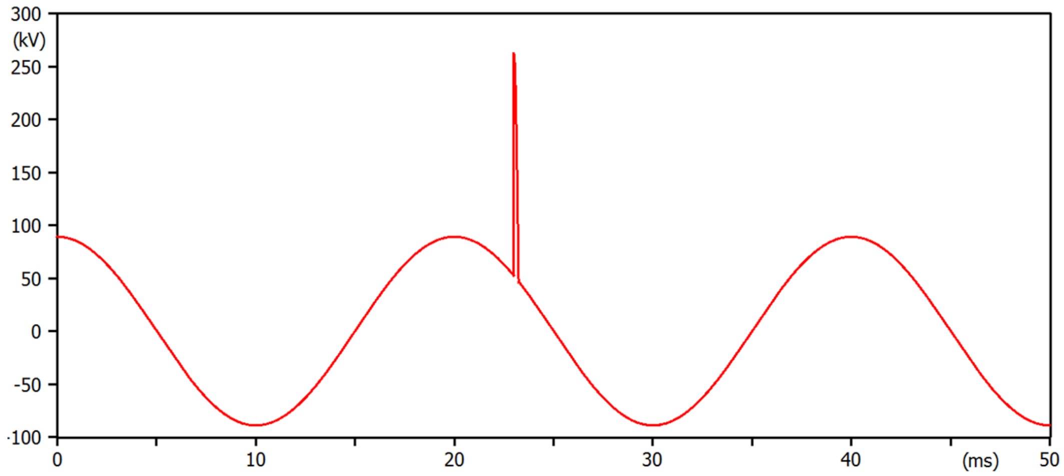


Figure 2.1: Impulse Transient.

Impulse transients are most commonly caused by direct or indirect lightning strikes inflicted into overhead line conductors. Direct lightning may result in an impulse up to, 2000 kA and 1 MV. Indirect strikes occur when a large electric field from the lightning strike couples into the power network. In this instance an impulse of up to 2 kA at 100 kV can be induced in the overhead line conductors.

2.2.2 Oscillatory Transients

Oscillatory transients are typically defined as, a sudden non-frequency change in the steady state condition of voltage and current of both positive and negative polarity values [4]. Oscillatory transients are typically 5 µs to 50 ms in duration and are mainly caused by switching events in the power system.

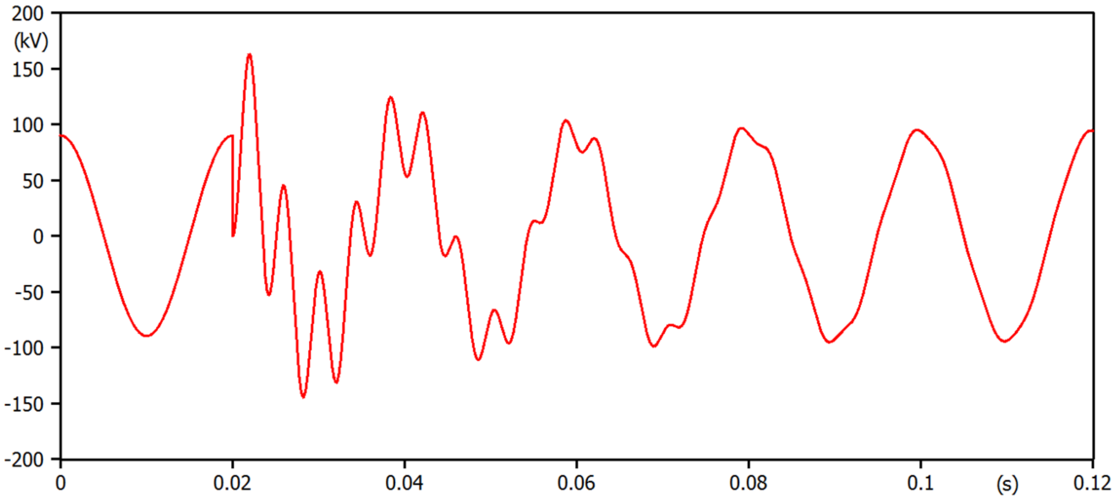


Figure 2.2: Oscillatory Waveform Applied to Fundamental Voltage.

Oscillatory transients can be divided into 3 main categories depending on the frequency, potential magnification and duration [3].

Table 2.1: Oscillatory Transient Categories.

Oscillatory Transient	Frequency	Duration	Voltage Magnitude
Low frequency	< 5 kHz	0.2 – 50 ms	0 – 4 pu
Medium frequency	5 – 500 kHz	20 µs	0 – 8 pu
High frequency	0.5 – 5 MHz	5 µs	0 – 4 pu

2.2.2.1 Low Frequency Transients

Mainly a result of single capacitor bank switching and can produce voltage transients in the range of 300 – 900 Hz and can in theory be as high as 2 pu, but practice is limited to 1.3 – 1.5 pu. due to system damping.

2.2.2.2 Medium Frequency Transients

Occurs during back to back switch of capacitive loads, where a shunt capacitor bank is energised near a previously energised capacitive load. A high frequency, high magnitude discharge current from the previously connected bank is supplied to the capacitor bank being energised.

2.2.2.3 High Frequency Transients

Can be produced during line or cable switching. Switching of GIS (gas insulated switchgear) substations are also a source of high frequency transients.

2.2.3 Propagation of Transients

Transients move through the network in different ways depending on frequency content. High frequency and impulse transients are more influenced by system stray and distributed capacitance and reactance than lower frequency oscillatory transients. These transients move through the system as travelling waves of current and voltage. These waves travel at or near the speed of light in both directions away from the disturbance.

Lower frequency transients propagate through the network in essentially the same way as the power frequency fundamental voltage waveform and can pass through components such as step-down transformers with little attenuation.

2.2.4 Effects of Transients

Transient voltages caused by lightning or switching operations can result in degradation or immediate dielectric failure in all classes of equipment. High magnitude and fast rise time contribute to insulation breakdown in electrical equipment like rotating machinery, transformers, capacitors, cables, instrument transformers, and switchgear. Repeated lower magnitude application of transients to these equipment types cause slow degradation and eventual insulation failure. In electronic equipment, power supply component failures can result from a single transient of relatively modest magnitude. Transients can also propagate to consumers' equipment and can cause nuisance tripping of variable speed drives (VSD) for motors, due to the VSD's DC link over-voltage protection circuitry [5].

2.3 Circuit Breaker Technology

In Ireland, almost all load switching is performed using sulphur SF_6 circuit breakers. SF_6 circuit breakers have excellent dielectric properties, are thermally stable and have excellent regeneration characteristics following the presence of arcing.

Older circuit breaker (CB) technologies such as oil insulated and air blast insulating mediums are also used. However, in the last 30 years these technologies types have almost become redundant. This is due to their increased costs associated with maintenance and plant outage time. Also, there is an increased demand for switchgear with higher ratings and faster operating times, which older technology types cannot fulfil. SF6 insulated CBs are much more beneficial in these regards.

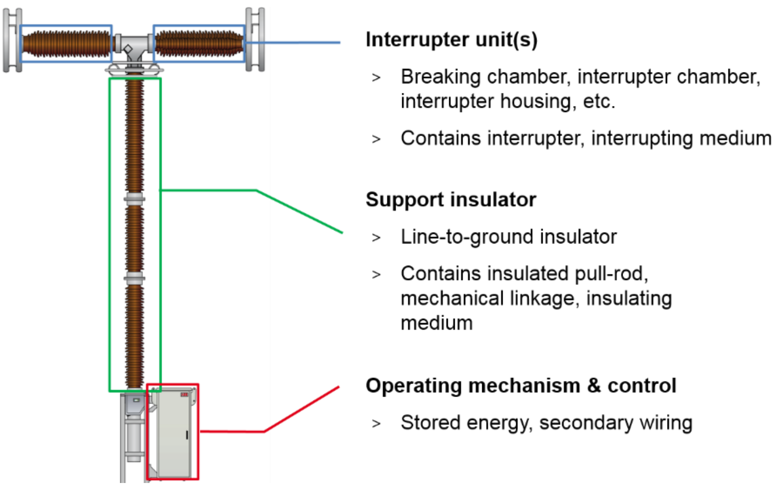


Figure 2.3: SF_6 CB Overview with Dual Interrupters [15] .

2.3.1 Circuit Breaker Construction

CB may be of live tank or dead tank construction, where the physical tank of the breaker is considered electrically live or dead at earth potential. At higher voltage levels, CBs may have multiple interrupters or breaks per phase for insulation purposes. In these situations, grading capacitors are necessary across each interrupter to ensure even distribution of rated voltage. Typical values of grading capacitors are between 900-1600 pF [5]. Many SF_6 circuit breakers operating up to 220 kV on the Irish transmission systems have only a single interrupter per phase, this significantly reduces the CBs cost and size.

The majority of SF_6 circuit breakers have spring operating mechanisms and some older SF_6 types have hydraulic or air operated mechanisms. Spring designs are considered more reliable and have more consistent operating times.

2.3.2 SF_6 Circuit Breaker Arc Quenching

The puffer type interrupter forces a blast of SF_6 over the parting contacts to provide additional arc cooling. This design has excellent arc quenching abilities, but the downside is that the same cooling blast of SF_6 is applied over low energy arcs that occur during switching, as that for a short circuit current interruption. This may lead to current chopping.

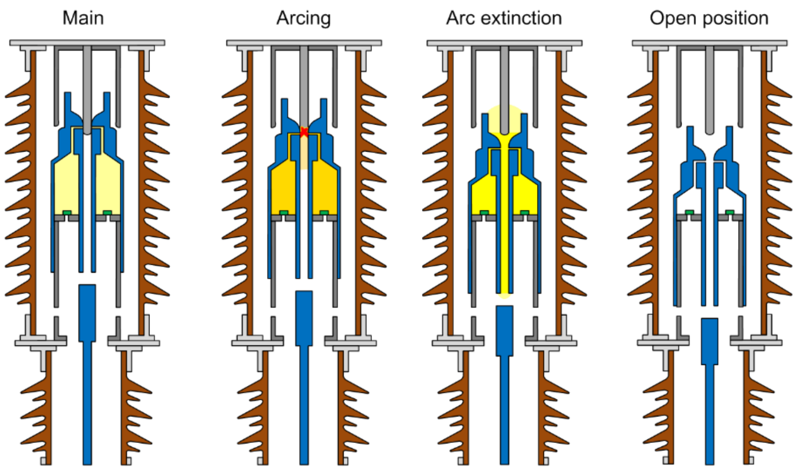


Figure 2.4: Puffer Type Interrupter [15].

2.3.3 Circuit Breaker Switching Definitions

2.3.3.1 Re-ignition and Restrike

As defined by the International Electrotechnical Commission (IEC) in standard IEC 62271-110 [7]:

- A re-ignition refers to a voltage breakdown in the circuit breaker within a quarter of a cycle from attempt to interrupt.
- A re-strike is defined as a voltage breakdown in the circuit breaker at a time equal to or exceeding a quarter of a cycle after attempt to interrupt.

To prevent the occurrence of re-ignitions or re-strikes it is important to consider the thermal and dielectric stresses that the circuit breaker must handle.

2.3.3.2 Transient Recovery Voltage

The transient recovery voltage or TRV is the voltage immediately seen across the parting CB contacts. This voltage is the difference between the phase to earth voltage on the source side, to the phase to earth voltage on the load side.

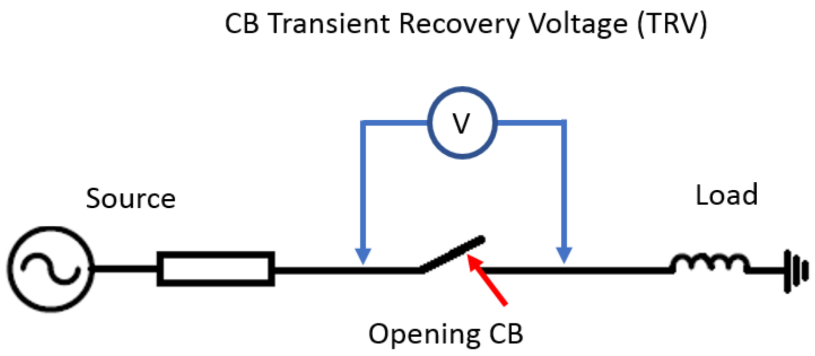


Figure 2.5: Transient Recovery Voltage.

Depending on the load type interrupted, TRV's can be oscillatory, exponential or can be combinations of both. The shape of the TRV wave is determined by the connected lumped and distributed inductive and capacitive elements in the surrounding equipment. The TRV starts from current zero following arc extinction and trails an oscillatory motion along the power frequency voltage until the steady state recovery voltage is reached. The rate at which the oscillation decays depends on damping in the load circuit.

If the dielectric strength of the CB cannot withstand the TRV, then re-ignitions or restrikes may occur. In very extreme cases this can lead to a situation where the CB cannot interrupt the current. To prevent the occurrence of re-ignitions, the dielectric strength of the parting CB contacts must always be higher, even in face of TRV's with very fast rates of rise such as that observed in heavy inductive load switching.

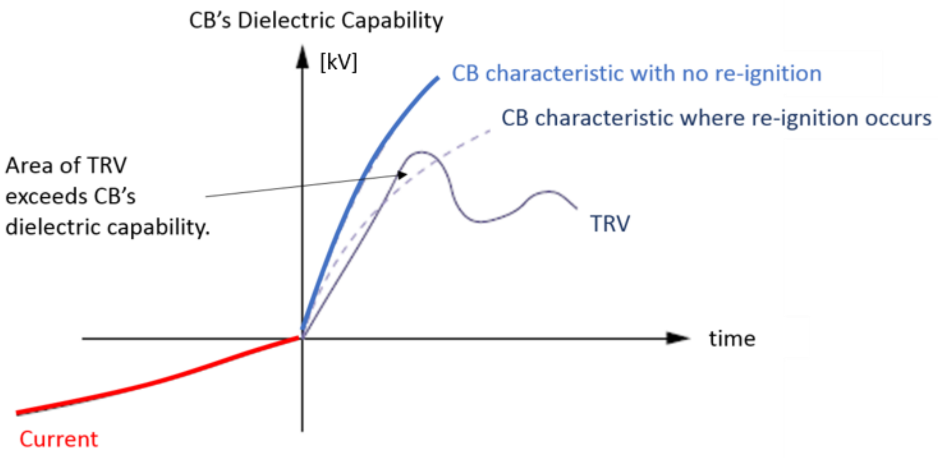


Figure 2.6: Dielectric Withstand Capability.

2.3.3.3 Circuit Breaker Arcing Process

During contact separation, an electric arc is established which allows conduction of electric current across the SF_6 insulating medium. When the circuit breaker physical contacts are parting, the decreasing surface area results in a high current density on that area, this causes the contact material to melt to a liquid state. There is a further temperature increase as more energy is added and this results in the liquid converting to a gaseous state. At a molecular level, the temperature increase gives the individual molecules so much energy that they disassociate into separate atoms and if the thermal energy is increased further, the electrons in the outer shell of the atoms acquire so much energy they become free electrons leaving the positive ions behind [5].

The mixture of free electrons and ions is called the plasma state, where a certain portion of the particles are ionised. This plasma is highly conductive and allows current to flow through the arc plasma after separation.

Current interruption can be achieved by cooling this arc plasma around its most crucial part of existence which is around the current zero. Although current zero is the only opportunity for a switching device to interrupt, it does not imply that every current interruption is finally successful. The arc may have disappeared but the ionised gas in the CB gas chamber will reduce its dielectric strength and its capability of withstanding the CBs transient recovery voltage, see Figure 2.6. Conversely during low energy switching, the CB quenching process may chop the current prior to its natural current zero crossing.

3. Mitigation Techniques

There are a number of methods which can be considered for the reduction of transient over voltages and inrush currents that occur during switching. The main methods that have been used on the Irish transmission system to date include:

- Pre-insertion resistors and current limiting reactors, which can dampen and limit transient currents produced.
- Controlled switching, which can help avoid energisation and de-energisation at non-optimal points on the voltage and current waveforms, hence preventing transients in the first instance.

3.1 Metal Oxide Surge Arrestors

Surge arrestors are designed to insulate normal voltage levels, but also to breakdown and provide a direct current path to earth during over voltages, thus protecting the system from harmful voltage transients. Surge arrestors have an extremely non-linear V/I characteristic. An ideal surge arrestor should only absorb the energy associated with the over-voltage. It starts to conduct current at a specific over-voltage level, holds its rated voltage without variation and ceases conduction upon normalisation of the system voltage, typical surge arrestor breakdown characteristics are shown in Figure 3.1 and 3.2. They are normally located as close as possible to the protected object (transformer/ reactor bushings, CB, etc.) to afford maximum security.

However, surge arrestors cannot reduce the steepness of the voltage swings associated with re-ignitions such as that experienced during inductive load switching [15].

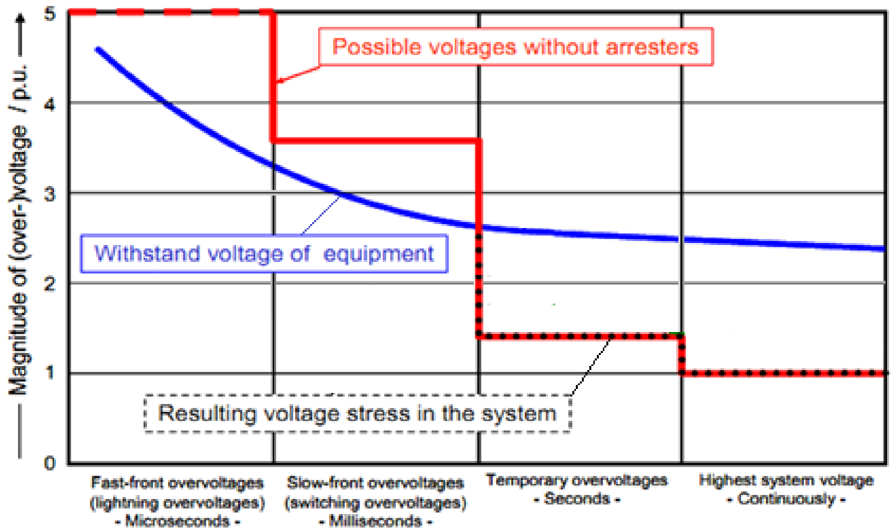


Figure 3.1: Potential Stress on Equipment without Surge Arresters [16].

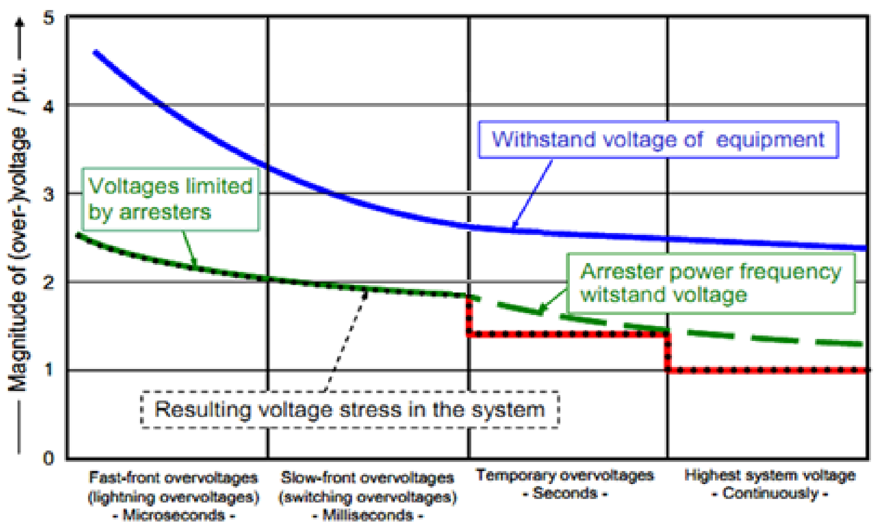


Figure 3.2: Reduction of Stress on Equipment with Surge Arresters [16].

3.2 Pre-Insertion Resistors

During energisation, a resistance is placed in series with the load for a temporary period to provide additional damping to the circuit, which helps limit the energisation current. After a short period, typically 10 – 12 ms, the resistance is bypassed by an additional shorting contact, either on the CB or a completely separate time delayed CB depending on the voltage level. The value of the resistance is typically in the order of the surge impedance of the load [15].

While pre-insertion resistors are an excellent method of reducing transient inrush currents, there are a limited range of circuit breakers on the market designed for use with pre-insertion resistors and therefore the cost is significant. The typical cost of a special breaker with a separate break designed to short out a pre-insertion resistor could be an additional 10 % - 30 % of a conventional breaker depending on voltage level [11], while a separate CB may double the cost of the CB installation. Also, there are increased maintenance costs and the complexity of the CB installation is an issue.

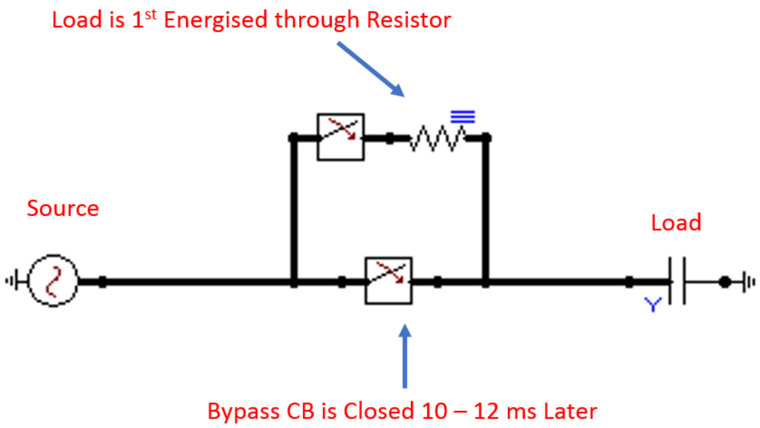


Figure 3.3: Pre-Insertion Resistor Switching Arrangement.

3.3 Current Limiting Reactors

Current limiting reactors, are fixed inductors placed in series with certain loads. They provide a low resistance path for nominal power frequency currents and provide high resistance in the presence of high frequency transient currents. In Ireland they are a requirement for shunt capacitor banks when situated near other capacitive loads to prevent the high frequency transient inrush currents as a result of so called back to back switching. Usually they are of air core construction and maintenance free, however they do not limit the occurrence of remote transient over voltages.

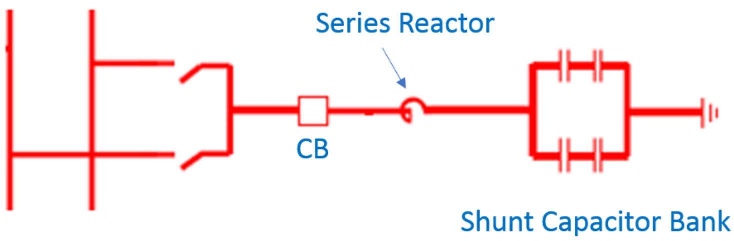


Figure 3.4:Shunt Reactor fed through Series Reactor.

3.4 Controlled Switching

Controlled switching is also referred to as point-on-wave control and can be defined as the use of electronic equipment to control a HV circuit breakers operating time, which allow the making or breaking of a particular load at pre-determined points on the voltage or current waveforms. Controlled switching devices normally monitor a reference voltage quantity from an adjacent, in service item of plant to which the switched load is to be connected or disconnected. By examining the reference waveform, the CSD can calculate the optimum instant that the circuit breaker should be switched, along with additional considerations such as:

- Load type, e.g. capacitive or inductive.
- Duty, e.g. opening, closing or both.
- External influencing factors, e.g. control voltage level, operating mechanism temperature, air or hydraulic pressure.
- CB characteristics, e.g. mechanical scatter, idle time between operations and contact wear over time.

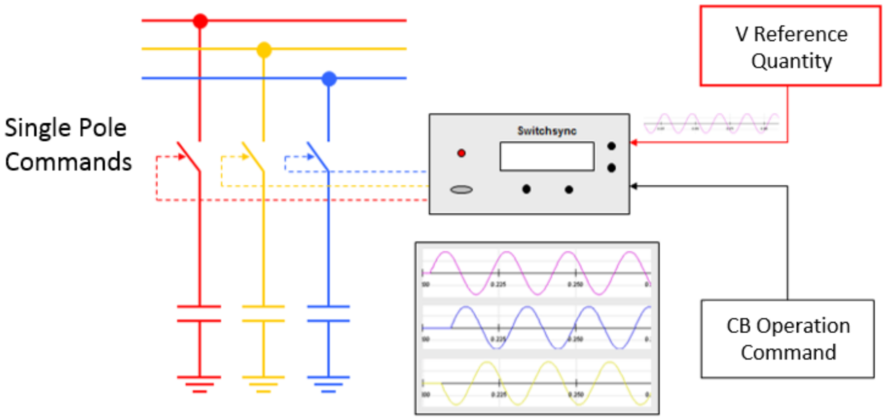


Figure 3.5: CSD Configuration Overview for CB with Individual Mechanism per Pole.

The CSD normally switches each individual pole of the circuit breaker separately, but some CBs have a single operating mechanism for all three poles. These CB types must have separate adjustable linkages so that the opening or closing of each of these poles can have a staggered operation. Implementation of CS with mechanically staggered CB poles is rare and can be difficult to commission. Also, they do not lend well to CSD adaptive control for contact wear, as over the life time of the equipment an electronic adjustment due to wear of an individual CB pole will be applied to all poles, which may not be necessary.

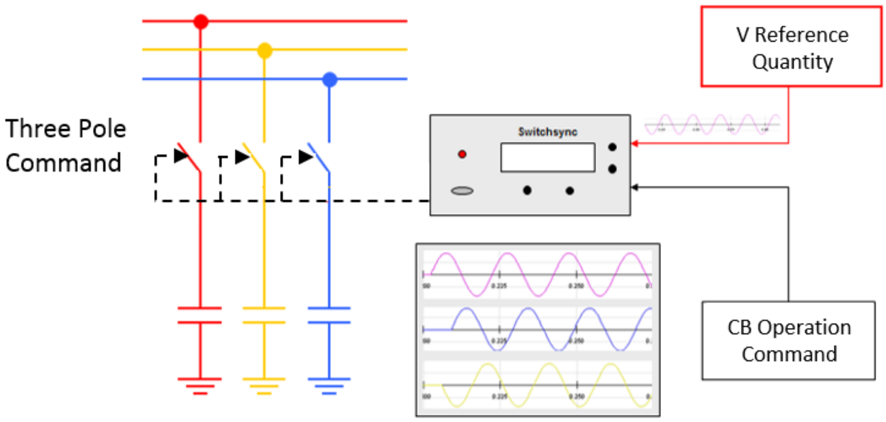


Figure 3.6: CSD Configuration Overview for Mechanically Staggered CBs.

3.4.1 Key Benefits of Controlled Switching

CS has many technical and economic benefits and is an effective method of eliminating the occurrence of transient overcurrent and over voltages that occur during switching. By eliminating the occurrence of transients in the first instance [17], this had added benefits for the overall power system and consumers such as:

- Reduces stress on the insulation equipment and CB contact erosion.
- Prevents false operation of protective relaying equipment.
- Eliminates coupled transients in protection and control cables in substations.
- Provides a vast improvement to the quality of power supply to customers [13].

The cost of a CSD is typically 5 % of the CB installation [11].

Table 3.1: Benefits of Controlled Switching Per Application [17].

Application	Consequences on Power Quality	
	Without controlled Switching	**With Controlled Switching**
Energising shunt capacitor and filter banks.	High magnitude inrush currents, severe voltage dip followed by high recovery voltage. Oscillatory transients transferred to other parts of the system including customers.	Virtually eliminates heavy inrush current currents and voltage dips. Prevents subsequent transients being transferred.
Shunt reactor switching.	Asymmetrical inrush current which causing transformer saturation during energisation. Current chopping during de-energisation, resulting in high transient over-voltage which may cause re-ignitions across the opening CB.	Eliminates asymmetrical current and prevents premature current chopping which can result in re-ignitions.
Energisation of unloaded power transformer energisation	Prevents heavy asymmetrical inrush current and resultant voltage dip at station bus.	Virtually eliminates the voltage dip and limits current to an almost steady state value.
Transmission line auto-reclosing.	Switching over voltages and possible unsuccessful auto reclose operation caused by breakdown of line insulation.	Limits switching over voltages and reduces the probability the auto reclose cycle failure.

3.5 Circuit Breakers Performance in Conjunction with Controlled Switching

The performance of a CS scheme depends greatly on the consistency of the controlled CB mechanical characteristics and dielectric strength. Also, the ability of the CSD to accurately predict the behaviour of the CB based on external factors which can influence its operating speed and for the deviation on the CBs performance due to aging. Desirable characteristics of a CB for use in controlled switching applications include:

- Consistent and repeatable operating (Open/Close) time.
- Excellent dielectric properties, i.e. a steep RDDS/RRDS slope.

3.5.1 Mechanical Repeatability of CB Operating Mechanism

Consistent repeatable performance of the CB in relation to open/close times is of the upmost importance when used in conjunction with a CSD. CB operational times will not always be the same, as there are a number of external influencing factors such as ambient temperature, control voltage level, idle time of the circuit breaker mechanism as well as the operating mechanism technology that can affect repeatable performance. By industry standards an acceptable deviation scatter between operational open/close times for a modern spring operated SF_6 circuit breaker is typically around +/- 1 ms. A delay in 1 ms can shift the switching point by 18 electrical degrees on a 50 Hz system, so it is important to consider how external factors can impact on the CBs performance and compensate for these deviations as much as possible. To ensure that the CB has a consistent and repeatable performance, manufacturers usually carry out mechanical endurance tests according to IEC 62271-100 to ensure the deviation of operating times are within the specified range. A number of CB repeatability tests should also be considered during the site commissioning stage.

3.5.2 Idle Time between CB Operations

This is the time the circuit breaker has been left idle between operations. The impact of idle time can differ significantly between CB operating mechanisms. Spring mechanisms have a more consistent operating time typically +/- 1 ms while hydraulic mechanisms can deviate above 2 ms depending on the length of time left idle. While it doesn't tend to be an issue for modern spring operated SF_6 CBs, it may be problematic for older mechanisms. In Figure 3.7 it can be seen following an idle time of 8 hours, that the average operating time variation can exceed the 1 ms window for the CB with the hydraulic mechanism, while the spring mechanism remains more repeatable. Each CB mechanism type and manufacturer may have a different performance, these values can only be obtained through manufacturers or from the utility's own experience. Many modern CSDs are programmable and can apply a compensation time based on the time elapsed between operations.

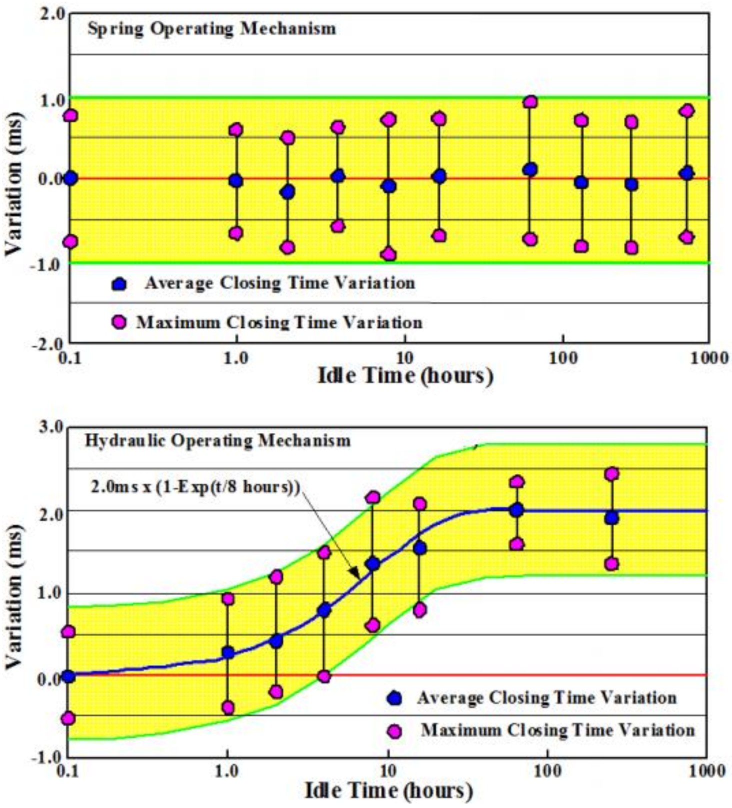


Figure 3.7: Influence of Idle Time on Closing Time by CB Mechanism Type [18].

3.5.3 External Influencing Factors

There are a number of external factors which can differ between locations which influence the predictable performance of the CB. These include, the temperature of the CB mechanism and the substation control voltage for the CB operating coils. Again, these factors are different between CB types and manufacturers, and typical performance data can only be obtained through the CB manufacturer or users' experience.

3.5.3.1 Ambient Temperature

The ambient temperature of the CB mechanism can influence the open/close coil resistance and this can affect the CB operate time. Also, temperature can affect the viscosity of lubricants on the mechanism and interrupter drive arms, causing an increase in friction between sliding or moving parts. Heaters are normally installed in the mechanisms to maintain a typical temperature of 21 ºC. However, if the heater is not working, a faulty temperature controller or during weather extremes, temperature may become an issue for operating times. Also, there is normally no system implemented for cooling the CB mechanism.

The temperature characteristic for a Siemens 3AP1F1 245 kV CB is shown in Figure 3.8. The manufacturer specifies that the CB operates 3% slower at -30°C and 4% slower at 55°C, best performance is at the nominal operating temperature 20°C. The actual temperature is measured via temperature sensor within the central CB mechanism box and is fed back to the CSD for compensation of operating times.

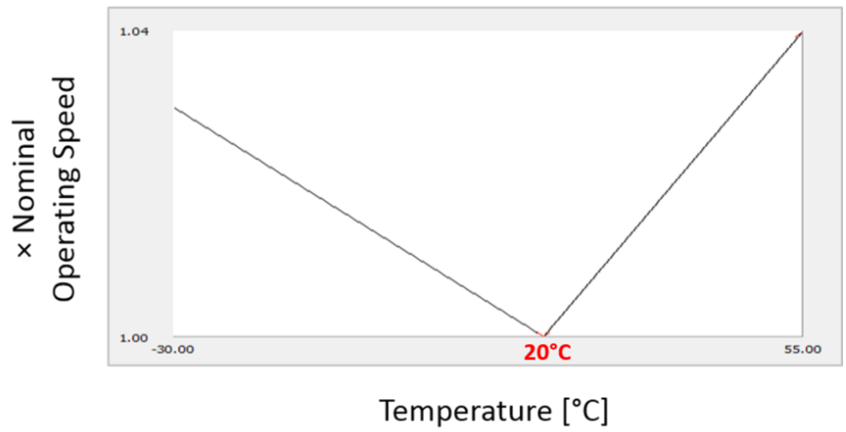


Figure 3.8: Temperature Variation Times on CB for a Siemens 3AP1FI 245 kV Operating Mechanism.

3.5.3.2 Operating Control Voltage Compensation

The magnitude of the DC control voltage operating the CB open/close coil influences the operating speed of the plunger which releases the spring mechanism. Increasing the control voltage increases the operating speed of the plunger, while reducing the control voltage slows it down. The nominal control voltage for the Siemens 3AP1F1 245 kV CB open/close coils is 220 V D.C. The manufacturer specifies that for every 1 V deviation from the nominal operating voltage, results in a 0.1 ms change in operating speed of the opening coil. Figure 3.9 shows commissioning results for CB trip coil under voltage tests. It can be seen that as the applied coil operating voltage for each test is reduced from 1.25 × U_n to 0.58 × U_n, the operating speed of the CB is reduced by 23 ms between extremes.

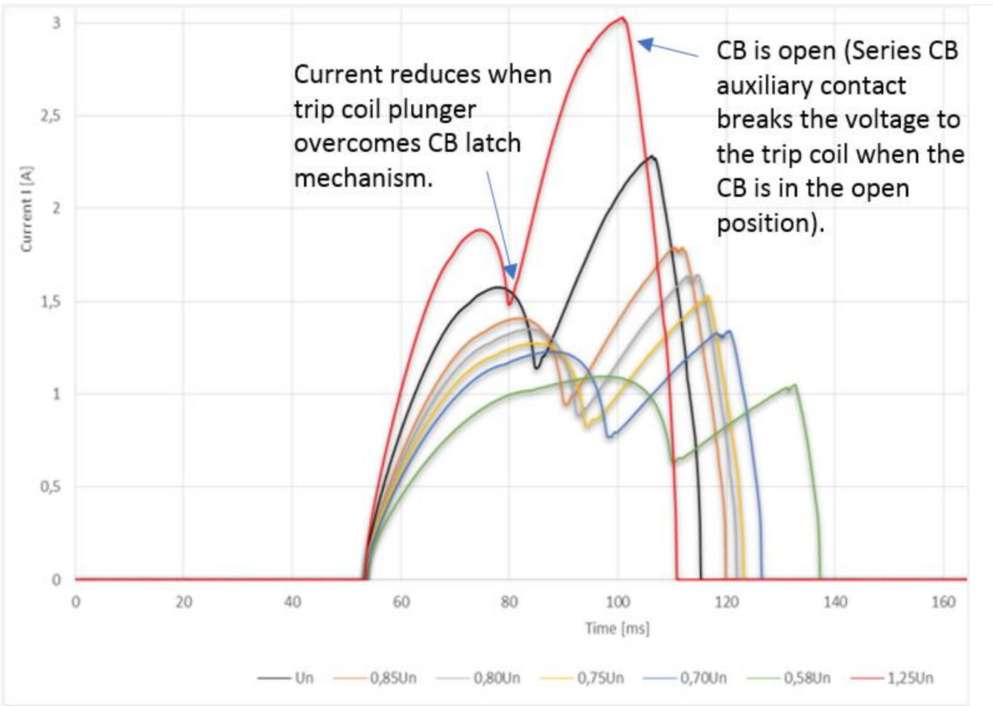


Figure 3.9: Site Commissioning Results for an Under-voltage Test on a CB Trip Coil from 1.25×$U_{n.}$ to 0.58×$U_{n.}$ using an Omicron CIBANO 500 Circuit Breaker Tester.

3.5.4 Rate of Decrease of Dielectric Strength

When closing a CB, electrical conduction does not necessarily occur when the primary contacts touch but rather when an arc is established between them. As the CB contacts approach each other, the voltage across them may exceed the dielectric strength of the insulating medium resulting in dielectric breakdown. This causes a pre-strike arc to occur until the contacts mechanically touch.

The rate at which the dielectric strength decreases when the circuit breaker contacts are moving is known as the rate of decrease of dielectric strength (RDDS). It is normally defined in kV/ms.

If RDDS of the circuit breaker is less than the system voltage, breakdown will occur before mechanical contact touch. Consequently, it is possible to close the circuit breaker at any point on the voltage waveform without any dielectric breakdown if the RDDS of the circuit breaker is greater than the system voltage. In Figure 3.10, it can be seen that if the RDDS slope of the CB is less than the system voltage, breakdown across the CB contacts can occur at non-optimal points on the voltage waveform and current conduction can start before the target zero voltage crossing. In this situation it is better to move the expected target.

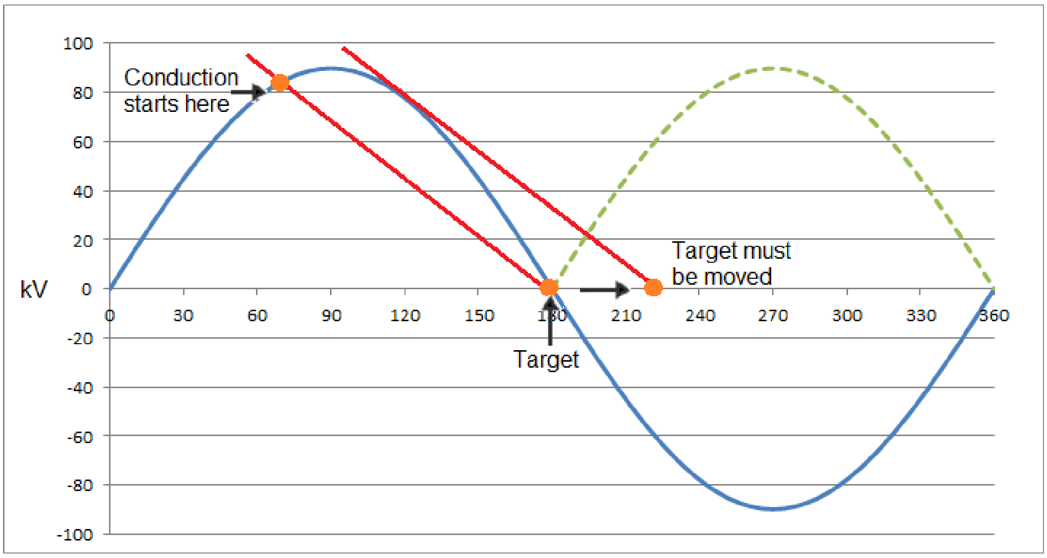


Figure 3.10: RDDS < 1. When the RDDS of the CB is less than the System Voltage, The Target Point on Wave Must be Moved as Dielectric Strength of CB must be greater than System Voltage.

Calculation of the system voltage slope:

$$Slope(kV/ms) = V_{ph-ph} \cdot \frac{\sqrt{2}}{\sqrt{3}} \cdot \frac{2\pi f}{1000}. \quad (3.1)$$

Calculation of system voltage to circuit breaker RDDS ratio:

$$RDDS\ ratio = \frac{RDDS_{CB}(kV/ms)}{Slope\ (kV/ms)}. \quad (3.2)$$

Typical RDDS ratio values are in the region of 0.5 - 1. If the RDDS of the CB exceeds the maximum system voltage, it is said that it’s possible to close the CB on any point of the wave without pre-strike occurring [19].

3.5.5 Rate of Rise of Dielectric Strength

During load interruption, the rate at which the withstand voltage between the CB contacts rises, as the contact gap increases is known as the rate of rise of dielectric strength (RRDS). This is an important characteristic for circuit CBs when used in controlled opening applications. CBs with high RRDS values can interrupt inductive loads without re-ignition as the CBs dielectric withstand exceeds the transient recovery voltage across its terminals. Where the RRDS of the CB is less than the transient recovery voltage, breakdown will occur during CB contact separation.

3.6 The Controlled Switching Device

Modern CSDs are classified as intelligent electronic devices (IED’s) and are in the same league as protective relays. They are completely programmable devices, in that user defined functions can be applied for applications such as:

- Controlling multiple CBs for breaker and half busbar schemes.
- User defined adaptive control and compensation measures.

All binary inputs and outputs can be user defined for the following:

- Control.
- Interlocking.
- Indication.
- Alarms.

They provide useful event logging and waveform recoding and are capable of being integrated into substation control systems via IEC103 and IEC61850 communications protocols.

3.6.1 Adaptive Control

In addition to compensation of external factors, an adaptive control function is used in most controlled switching devices to continually compensate for drifts in operating times due to CB aging and wear. The previous performance of the CB operation is measured and is then used to optimise the next switching action to meet its target.

Circuit breakers have a number of sliding and moving parts and operating characteristics are affected by the change of friction or sticking force on the surfaces of these parts due to long-term aging and wear [20]. As any changes usually progress slowly over time, an adaptive control can effectively compensate for the drifts in operating time caused by the consecutive operations and can ensure optimum performance of the scheme.

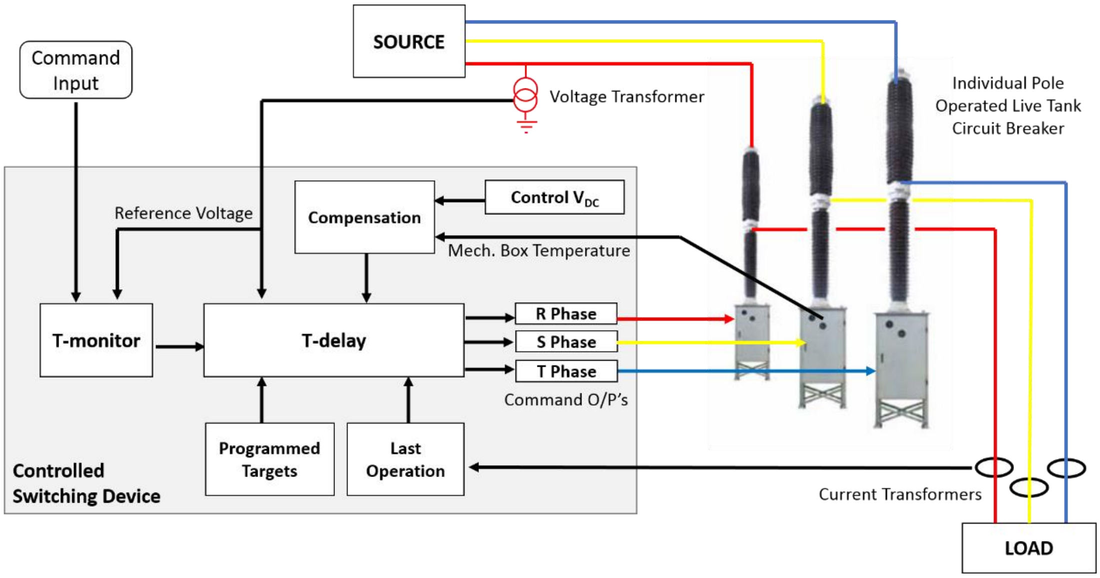


Figure 3.11: Controlled Switching Scheme Overview.

3.6.2 CSD Operation

To accurately predict the optimum controlled open/close operation time. All external compensating factors, idle time compensation and influence from the adaptive function should be added to the standard operating time delay to achieve the desired switching target on the waveform. Figure 3.11 shows the complete CS scheme overview with all the pertinent interfaces with the CB and field. The following is the main sequence of operation upon receipt of a command input to the CSD:

1. There is a monitoring period $T_{monitor}$ where upon receipt of the command, the CSD looks at a predefined number of cycles in the reference waveform to ensure a stable measurement;
2. The time delay T_{delay} for each of the commands to the CB poles is computed. This is based on:
    a. The programmed targets and duty (application dependent).
    b. Reference voltage.
    c. Compensation adjustment for the measured DC command control voltage magnitude, mechanism temperature measurement and if relevant the operating pressure for the CBs air or hydraulic mechanisms.
    d. Adjustment of targets from previous operations if necessary. This is normally achieved by measuring the current onset for energising targets

and current drop off for de-energising targets of the load and comparing it with the set targets.

3. Following computation of T_{delay} the commands to the circuit breaker poles are released from the CSD.

3.6.3 Controlled Energisation Target

When energising a capacitive load, the optimum energisation point on the voltage waveform is the zero crossing. Figure 3.12 shows how this target is typically achieved:

1. On receipt of the close command, there is monitoring period ($T_{monitor}$) of 3 half cycles of the reference voltage waveform.
2. The number of half cycles to the zero crossing where the load is to be energised at, is computed. This time is known as NT_{zero}.
3. The time delay (T_{delay}) before the CB close command is released, so that the target point on the voltage waveform can be accurately achieved. This time should take into account:
    a. The external compensation time (ΔT_{comp}).
    b. Adaptive control adjustment from previous operation (ΔT_{adap}).
    c. The CB operate time ($T_{operate}$), which is the time from when a close command output is issued by the CSD, to the CB in the fully closed position. This includes all intermediate components (relays and contactors), the CB travel time which includes the pre-arcing time ($T_{prearcing}$).
    d. The making time (T_{making}), which is the time difference from when the CSD command output is issued, to when current is predicted to flow. This can take place in the form of pre-arcing, if RDDS of the CB is less than system voltage, or when the moving contact touches the CB arcing contact.

$$T_{delay} = NT_{zero} + \Delta T_{comp.} + \Delta T_{adap.} - T_{making} \tag{3.3}$$

Therefore, the point at which current starts to flow, either during pre-arcing or when the moving contact touches the arcing contact, should be the target point on the zero crossing of the reference voltage waveform.

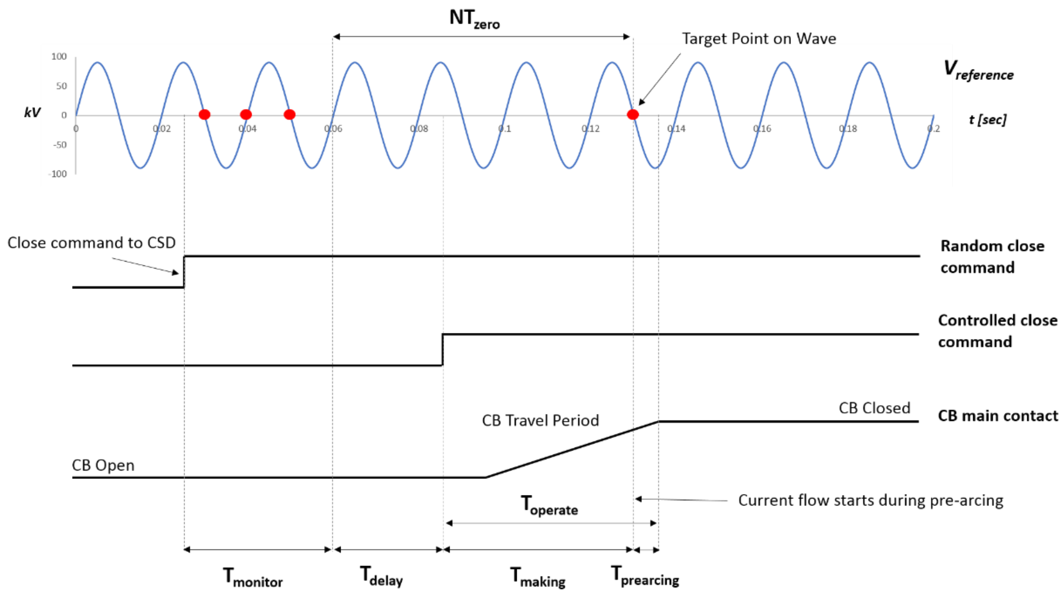


Figure 3.12: Controlled Energisation Operation for Capacitive Load using Equation 3.3 to Calculate T_{delay}.

3.6.4 Controlled De-energisation Target

When switching an inductive load, the optimum de-energisation point is the peak of reference voltage waveform or the zero crossing of the load current waveform. Figure 3.13 shows how this target can be achieved:

1. On receipt of the open command, there is monitoring period ($T_{monitor}$) of 3 half cycles of the load current waveform.
2. The number of half cycles to the zero-current crossing to where the load is to be de-energised at is then computed, this time is known as NT_{zero}.
3. The CB operate time ($T_{operate}$), which is the time from when an open command output is issued by the CSD, to the CB in the fully open position. This includes all intermediate components (relays and contactors), the CB travel time which includes the arcing time (T_{arcing}).

4. The time delay (T_{delay}) before the CSD open command is released, so that NT_{zero} point can be achieved, needs to be computed. This time should also take into account:
   a. The external compensation time (ΔT_{comp}).
   b. Adaptive control adjustment from previous operation (ΔT_{adap}).
   c. The breaking time ($T_{breaking}$), which is the time from when an open command is issued from the CSD, including all intermediate components (relays and contactors), to the start of CB mechanical separation.
   d. The minimum arcing time (T_{arcing}) for the load, from which time the arc produced after mechanical separation of CB contacts to the next current zero when the arc is extinguished.

$$T_{delay} = NT_{zero} + \Delta T_{comp.} + \Delta T_{adap.} - T_{breaking} - T_{arcing} \qquad (3.4)$$

Therefore, the target separation point is when the arcing current produced following mechanical separation, reaches its natural zero crossing.

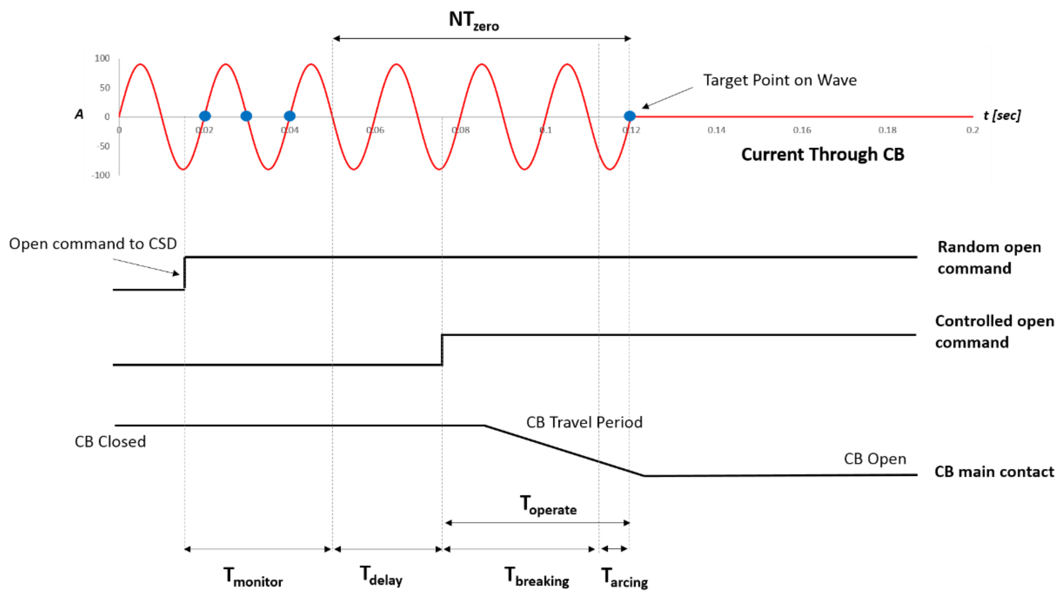


Figure 3.13: Controlled De-energisation Target for an Inductive Load using Equation 3.4 to Calculate T_{delay}.

3.7 Application of Controlled Switching on the Irish Transmission System

This research has found that CS for the energisation of shunt capacitor banks and filters has been applied in Ireland for 25 years now. As per industry standard, shunt capacitor banks are typically energised at or near the zero crossing of the energising voltage waveform. Controlled opening is generally not used for shunt capacitor banks in Ireland. CS is applied to all shunt capacitor banks ranging in size from 5 MVAr to 50 MVAr at 110 kV and C type filter plant at 110 kV. It is also proposed for future filter plant to be installed on the 220 kV transmission system.

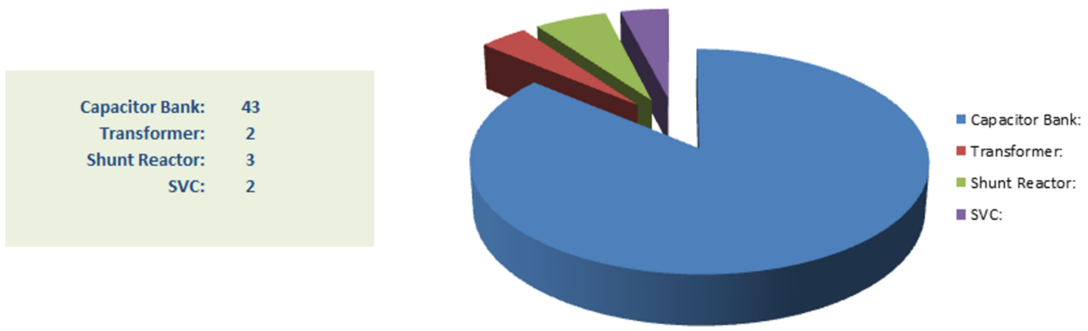


Figure 3.14: Number of Controlled Switching Installations in Ireland by Application.

Other applications where CS has been recently applied include:

- Shunt reactors for voltage limiting in large urban centres where there are heavily meshed cable networks. CS is mainly used for the controlled opening only. The switching point is controlled so that the arcing current is broken at that natural zero crossing to prevent any premature current chopping.
- CS is also being considered for the controlled energisation of shunt reactors. This is due to the potential impacts of DC offsets observed in the energisation current waveforms, which could potentially result in the false operation of protection relays due to CT saturation.
- In 2017, CS has been applied to the energisation of two power transformers, the first being for controlled energisation of a 220 kV/21 kV, 500 MVA unloaded power transformer at an IPP interface.

Controlled switching applications for transformers is likely to grow in Ireland over the next few years, particularly for the energisation of large transformers at windfarm interfaces. These transformers are normally located in remote areas, therefore at weaker parts of the system. The motivation for using CS here is to eliminate any dip in the localised system voltage that occurs during energisation.

However, at the moment the author has found that there is no consideration of the transformer residual flux during energisation. A static switching strategy used where the first phase is switched at its voltage peak, thus magnetising the transformer. Then the remaining phases are switched 90 electrical degrees later. This strategy is used as these transformers are star/wye connected with the neutral solidly grounded.

There are also a number of ‘special applications’ where CS has been employed. These include the energisation of: Static VAr Compensation (SVC) plant in two remotely located substations, and the use of pre-insertion resistors for the energisation of a 500 MW HVDC interconnector converter station on the 400 kV system. As these applications are special, independent switching studies are necessary to work out the optimum switching strategies to be used.

Figure 3.15: CB with Pre-insertion Resistor at 500 MW HVDC Converter Station.

During the course of this research, it has been found that for CS schemes in Ireland, the CS manufacturer tends to be always the same as the CB. Even if CS is being retrofitted, the CS device suggested by the manufacturer will always be used. The level of compensation applied is completely dependent on recommendations from the manufacturer. Predominantly there tends to be CSDs from 3 main manufacturers in use. It has been found that one manufacturer recommends compensation measures only, with no adaptive control. This particular manufacturer suggests any drift is most likely as result of degradation of the CB contacts and requires action. Internal monitoring functions within the CSD are used to trigger alarms if operational levels are outside predefined operating limits. The manufacturer in question suggests that the adaptive function should only be used when switching a circuit breaker from a different vendor.

Conversely, another manufacturer applies the adaptive function only. Their CSDs have the ability to compensate for temperature and control voltage, but in practice ‘additional compensation’ is rarely used.

The internal monitoring functions of the CSD are normally used as a key indicator of any abnormal switching performance. In addition to this, phasor measuring units (PMUs) are also present in many substations where CS is in use and provide a constant source of valuable information for the performance of the CS scheme.

Additionally, all CSD equipment is fitted with a bypass switch, which is locally operated. So, in the event of failure or uncertainty of the CSD, the load can still be operated in an uncontrolled manner.

4. Simulation Tools

In practice calculation and analysis of transients that occur during switching is a complex task and is something which cannot be practically performed manually. Therefore, software tools are crucial for realistic power system transient simulation. In Ireland the author has found that the main software utilised for transient switching studies is EMTP-ATP (Electro Magnetic Transients Program – Alternative Transients Program).

4.1 EMTP-ATP

EMTP-ATP was first developed for the digital simulation of power system electromagnetic transients by Bonneville Power Administration (BPA) Oregon, USA [21]. EMTP-ATP is a powerful transient system analysis tool and for can perform both time and frequency domain computations. Circuits are represented by a nodal admittance equation which is formulated by using the trapezoidal rule of integration, where a simultaneous differential equation is transformed to a simultaneous equation with real number coefficients [9].

EMTP-ATP is an ideal tool for efficiently performing:

- Time domain simulations;
    - Switching transients and over-voltages.
    - Circuit breaker transient recovery voltage.
    - Lightning transients and over-voltages.
    - Fault simulation and protection analysis.
- Frequency domain simulations;
    - Sub-synchronous resonance (SSR).
    - Harmonic resonance.

4.2 Structure

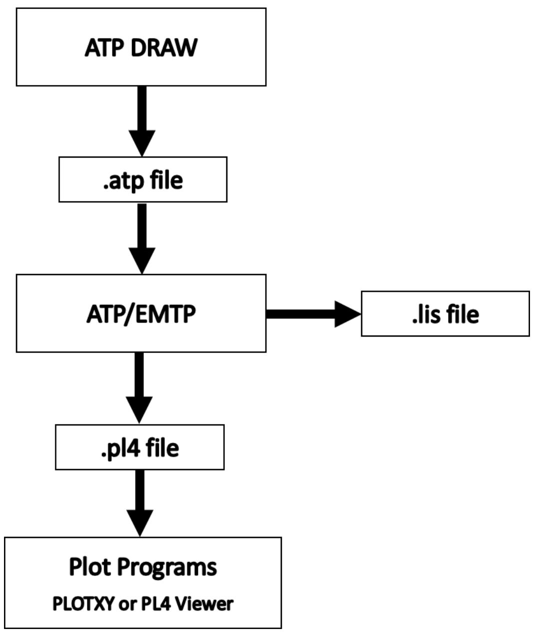


Figure 4.1: EMTP-ATP Process Structure.

The main process stages within EMTP-ATP are:

- ATP Draw

  Using an extensive library of pre-defined components. It allows the user to create a graphical model of the electrical network to be simulated. The pre-processor then automatically creates the corresponding ATP input file in the appropriate format, so it can be processed by the EMTP-ATP solver.

- EMTP-ATP Solver

  Processes the ATP output file from ATP Draw and produces the solved output file known as the LIS file. This file contains the steady state phasor and transient solution for switch currents, node voltages and power flows, with switching times, min/max values and any error messages. It also produces a PL4 file which provides information for plotting programs.

- Plot Programs

  Using the PL4 output file from EMTP-ATP solver, plot programs such as PLOTXY, PL4 Viewer and GTPPLOT can be used to analyse results.

4.3 Control Systems

ATP-EMTP supports two different control system formats TACS and MODELS. TACS is a block programming language and MODELS is language statement.

4.3.1 TACS

TACS or Transient Analysis of Control System Systems was developed in 1977 initially for the purpose of simulating HVDC controls [8]. TACS is a block programming language which can be used to simulate devices or phenomena which can't be directly modelled such as:

- Converter controls in power electronics, such as STATCOM's and SVC's.
- Switching arc and pre-strikes.
- Excitation systems for synchronous machines.

TACS are solved separately to the main model and use input network quantities such as current, voltage and switch status inputs from the network simulation. These quantities are then processed using logical and mathematical expressions to generate output quantities for controlling switches and variable resistances.

4.3.2 MODELS

MODELS is a programming language which is similar to Pascal. It was developed in 1992 to enable users to develop their own components and controls, which could not be easily developed using TACS or existing components. MODELS affords the flexibility to the user of a full component programming language without have to interface at the EMTP programming level [8].

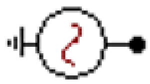
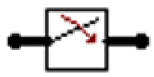
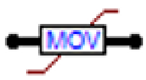
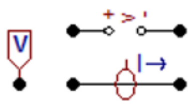
The interface is completely designated by the user, and it provides a system for black box modelling of components, which can be used multiple times in the same simulation with different parameters. It is capable of performing:

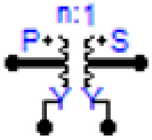
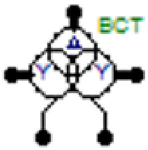
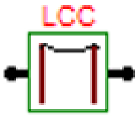
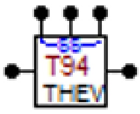
- Mathematical operations including Laplace transfer functions and differential equations.
- Logical Boolean expressions.
- Conditional statements such as: if, for and while.
- Models can also be interfaced directly with circuit diagram components using the type 94 user defined component.

4.4 Components

4.4.1 Standard Circuit Components

Table 4.1: Standard ATPDraw Components.

Component	Symbol	Function
AC Source (1&3)		AC voltage source, single/three phase grounded or ungrounded.
Time Controlled Switch		User defined, single/ three phase time and current controlled switch. Circuit breaker or disconnector.
Resistor, Inductor, Capacitor		Individual component definition or lumped series RLC component, single/ three phase, delta star connected.
Metal Oxide Varistor		User defined, non-linear resistor, single/ three phase.
Measurement		Node voltage, branch voltage, line current measurement.

Ideal Transformer		Lossless transformer, single/ three phase.
BCTRAN Transformer Model		Configurable winding connections, estimates core and winding characteristics based on factory results.
Line Constants or Cable Constants Model		Line/ cable model, configurable geometric conductor spacing and physical conductor model, constant or frequency dependent.
MODULES User defined component		Type 94 user defined MODULES component that can interface directly with main circuit.

4.4.2 Time Controlled Switch

The time-controlled switch component is an "ideal" switch and is mainly used for switching studies. Ideal meaning, it has no resistance in a closed position and infinite resistance when in the open position. The switch can be configured as single or three phase and can measure current and recovery voltage directly.

Both the open or close action time can be individually set to operate the specified simulation time. There is also a drop off current threshold, which is useful for modelling current chopping phenomena in circuit loads.

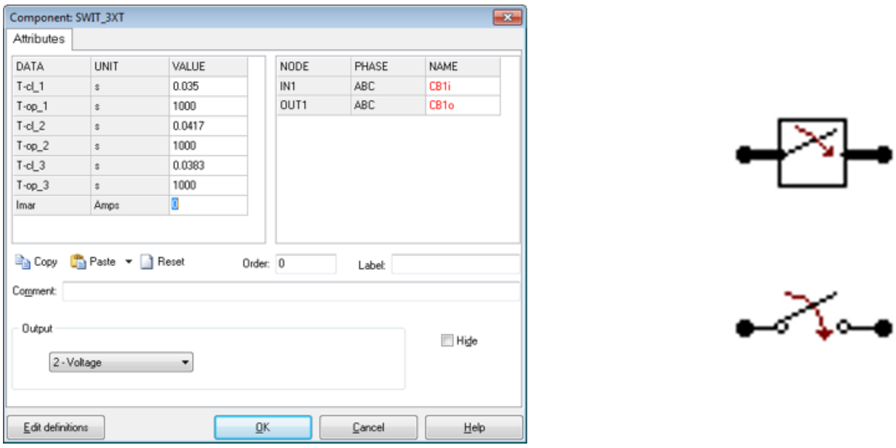


Figure 4.2: Time Controlled Switch.

4.5 Transmission Line Model

EMTP/ATP has a number of different components for modelling overhead transmission lines and cables. These components can be modelled using simple line models such as the PI model, which uses the relative resistance and inductive reactance per unit length of conductor. The capacitance between the individual conductors and to ground must be also configured in per unit length of the line. However, the most efficient integrated component was found to be the line cable constant (LCC) model. The LCC model has the advantage of being able to model the overhead line or cable based on the:

- Geometric data of the feeder (distance between conductors/ground or sheets).
- Line/cable length.
- Electrical properties of the conductor(s) and soil resistivity.

The LCC model also has a number approaches for accurately modelling line parameters depending on the application, these are:

- Constant frequency models such as the Bergeron and PI. These models are more suitable for steady state frequency applications such as power flow analysis.
- Frequency dependent models such as JMarti, Semlyn and Noda, which are more suitable for transient studies as line parameters are modelled over a wide frequency range. For transient simulations in this research, the JMarti model was used for transmission line modelling.

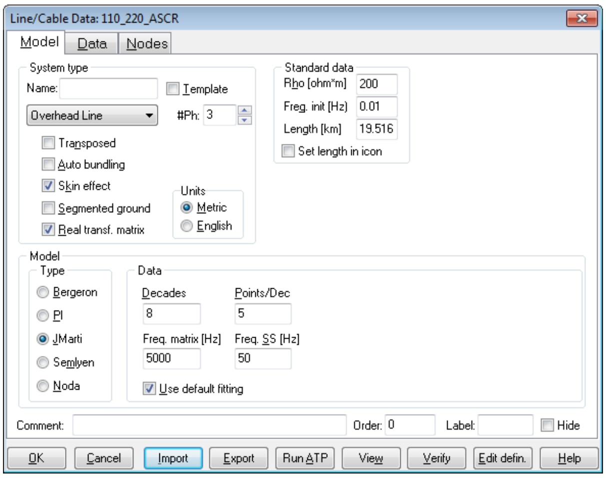


Figure 4.3: LCC Component Dialogue.

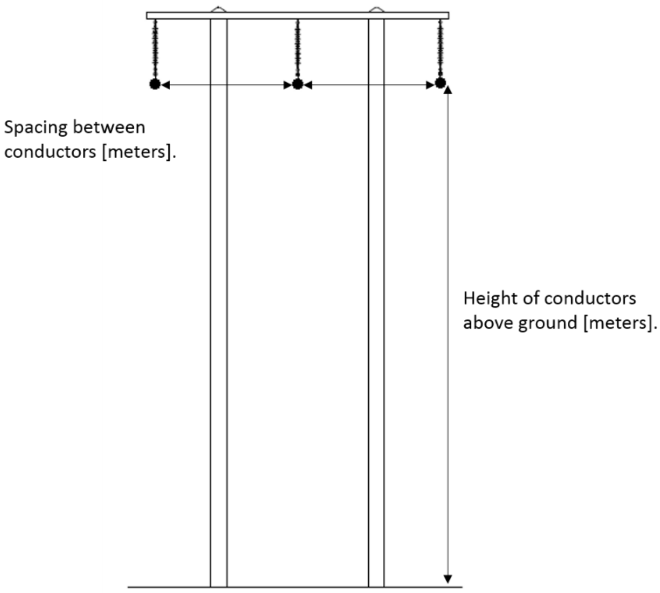
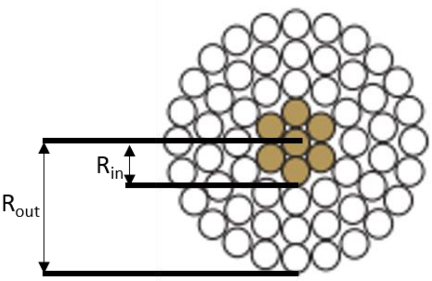


Figure 4.4: 110 kV Transmission Line Wood Pole Structure.



	Ph.no.	Rin	Rout	Resis	Horiz	Vtower	Vmid
#		[cm]	[cm]	[ohm/km DC]	[m]	[m]	[m]
1	1	0.03	0.085	0.1433	-4.5	22	16
2	2	0.03	0.085	0.1433	0	22	16
3	3	0.03	0.085	0.1433	4.5	22	16

Conductor construction and DC resistance per km

Physical spacing of conductors

Figure 4.5: 220mm² Aluminium Conductor Steel Reinforced (ACSR).

4.6 Transformer Models

There are a number of standard components that can be used to model transformers, these include the ideal transformer, which is a lossless transformer that applies a ratio factor to step up or down simulated voltage. Also, there is a saturable model which requires specific information on the core magnetisation characteristic. However, the most practical and efficient models were found to be the BCTRAN model and the XFRM hybrid transformer model. These models can use information directly obtained from the factory test data such as open and short circuit tests to automatically calculate important transformer characteristics for modelling.

4.6.1 BCTRAN Transformer Model

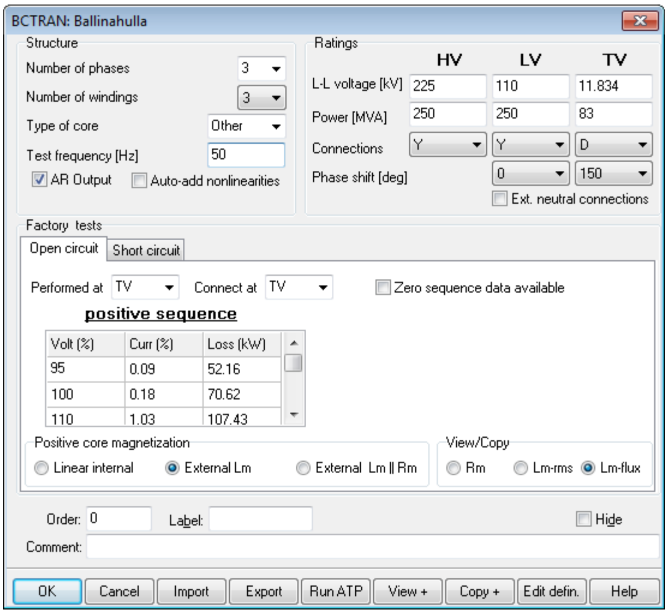


Figure 4.6: BCTRAN Component Dialogue.

The BCTRAN model allows the user to input data directly from the transformer name plate which includes voltage ratios, vector groups and power ratings. It uses data directly from the factory acceptance tests, such as short circuit tests for the percentage impedance measurement and open circuit tests for the core saturation characteristic. During this research, it was found that this component presents some difficulty for directly modelling transformer switching applications, in that the remnant flux cannot be directly initialised in the model. If remnant flux is to be considered, external non-linear inductors have to be used. However, the saturation characteristic can be copied directly from the BCTRAN model into the external non-linear inductor components.

4.6.2 XFRM Transformer Model

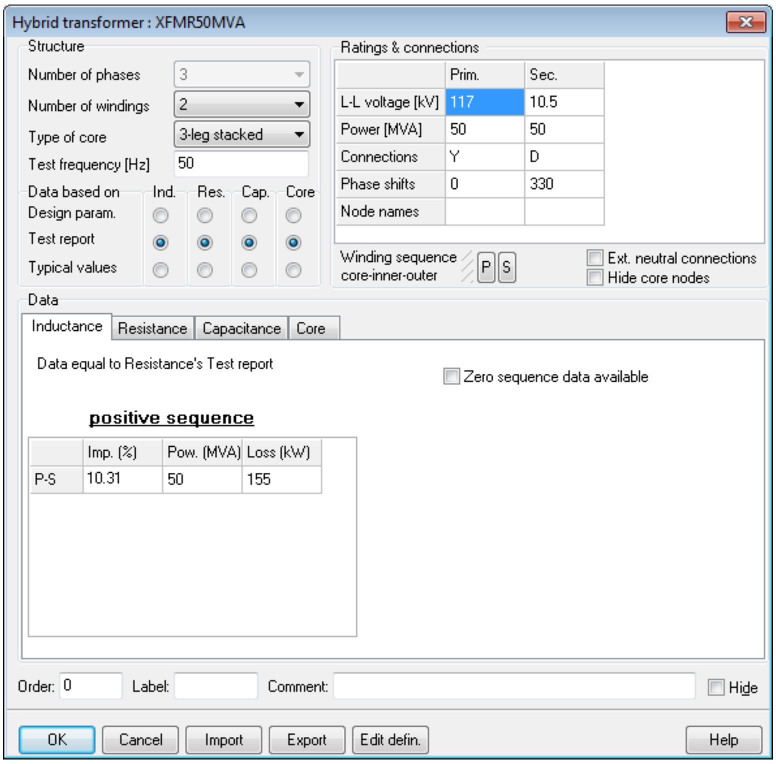


Figure 4.7: XFRM Transformer Component Dialogue.

The XFRM hybrid transformer is a powerful component for modelling transformers using design data and information from factory test results. It can also provide typical values for unknown parameters. Like the BCTRAN model, similar nameplate data can be used along with short and open circuit tests. This model also has the added advantage of modelling some of the physical parameters such as the winding sequence, capacitive measurements, core construction and geometric data. For modelling of transformer switching operations, the core non-linearity can be configured as a type 96 inductor which retains remnant flux memory. This model was considered to be the most suitable component for modelling transformer switching in this research.

4.7 Surge Arrester Models

4.7.1 MOV – Metal Oxide Varistor

The MOV component is a non-linear resistance model in which the user defines the resistance characteristic based on the permissible current flow for the applied voltage. The MOV can be used to simulate a surge arrestors behaviour for fundamental, 50 Hz circuit analysis and the circuit reaction for low frequency and slow front transients. The V-I characteristic is based on data from the surge arrestors manufacturer. However, during this research it was found that most manufacturer's only provide data for currents in the range of 1-40 kA and current leakage below this is usually not offered [8]. Curve fitting tools available from manufacturer's can be used to generate this information [22].

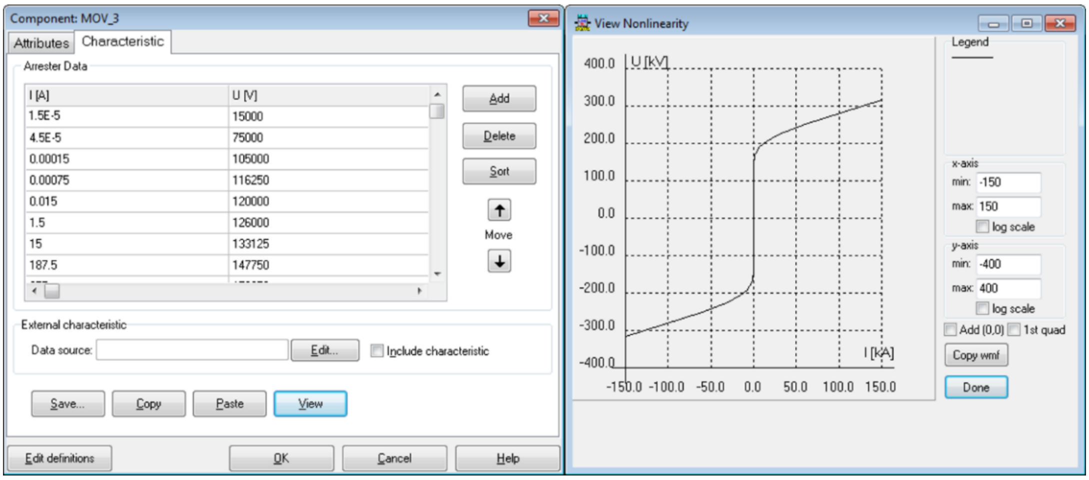


Figure 4.8: MOV Component V-I Characteristic.

When considering higher frequency transients in the order of microseconds, frequency dependent models must be used. Two of the main frequency dependent models are the:

- IEEE frequency dependent model proposed by IEEE working group 3.4.11. This model is based on the physical characteristics of the arrestor.
- Pinceti – Gianettoni model which is a variant of the IEEE model and is based on the electrical characteristics from the manufacturer.

4.7.2 IEEE Frequency Dependent Model

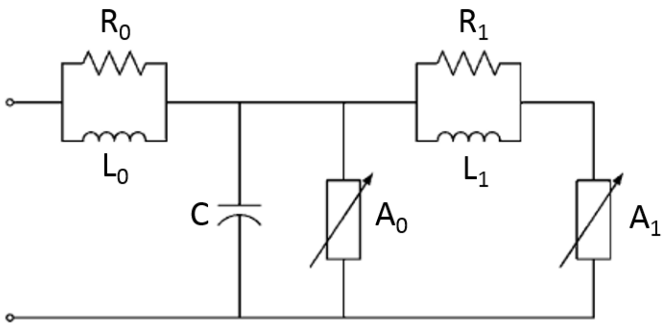


Figure 4.9: IEEE Frequency Dependent Surge Arrester Model.

In this method of modelling the surge arrester, the circuit is divided into two sections with two independent MOVs designated as A_0 and A_1. The MOVs are separated by a lowpass R- L filter (R_1 and L_1). For slow front surges, the lowpass filter has a low impedance and both MOVs A_0 and A_1 are in parallel. For faster front surges, the impedance of the lowpass filter becomes more significant resulting in more current through A_0 [23]. The V-I characteristic of A_1 is slightly less than surge arresters lightning current impulse wave (8/20 µs 10 kA), while A_0 is 20% to 30% higher [24].

A series inductance of about 1 µH per meter should also be considered in the model for earth lead conductors from the base of the surge arrestor to the station earth grid.

To define the values of the components in Figure 4.9, the following equations can be used:

$$L_0 = 0.2\frac{d}{n} \quad (\mu H). \qquad R_0 = 100\frac{d}{n} \quad (\Omega). \tag{4.1}$$

$$L_1 = 15\frac{d}{n} \quad (\mu H). \qquad R_1 = 65\frac{d}{n} \quad (\Omega). \tag{4.2}$$

$$C = 100\frac{n}{d} \quad (pF). \tag{4.3}$$

Where:

- d = The height of the surge arrester in meters.
- n = The number of parallel metal oxide columns.

Values for A_0 and A_1 MOV V-I characteristic can be determined from Table 4.2. based on per unit values of $V_{r\,(8/20)}$ which is specified by the manufacturer.

Table 4.2: IEEE Recommended Values for A_0 and A_1.

Current [kA]	per unit Voltage of $V_{r\,(8/20)}$	
	A_0	A_1
0.01	0.875	0.623
1	1.056	0.788
5	1.131	
10	1.188	
15	1.244	
20	1.313	1

4.7.3 Pinceti - Gianettoni Model

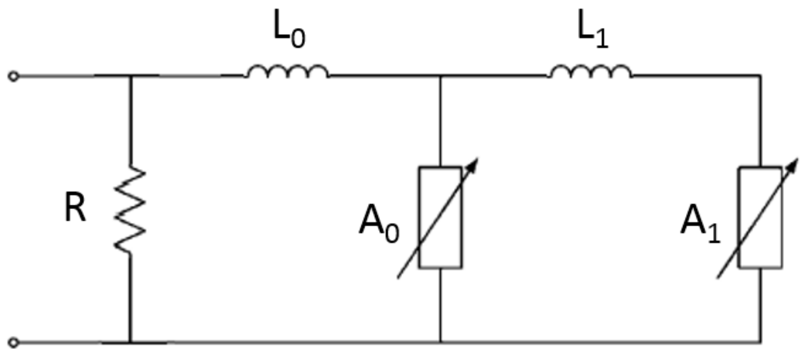


Figure 4.10: Pinceti – Gianettoni Surge Arrester Model.

This model is a simplified version of the IEEE frequency model but relies on the arrester's electrical characteristics rather than its physical construction. In this model, the parallel capacitance is eliminated because of its negligible effects on the behaviour of the circuit, and the resistors in parallel with the inductors are replaced by a single 1

MΩ resistance at input terminals [10]. To define the values of L_0 and L_1, the following equations can be used:

$$L_0 = \frac{1}{12} \cdot \frac{V_{r\frac{1}{T_2}} - V_{r\frac{8}{20}}}{V_{r\frac{8}{20}}} . V_n \quad (\mu H). \tag{4.4}$$

$$L_1 = \frac{1}{4} \cdot \frac{V_{r\frac{1}{T_2}} - V_{r\frac{8}{20}}}{V_{r\frac{8}{20}}} . V_n \quad (\mu H). \tag{4.5}$$

Where:

- Vn = Is the rated voltage of the arrester.
- $V_{r\,(1/T2)}$ = The arrester discharge voltage at 10 kA fast front current surge.
- $V_{r\,(8/20)}$ = The discharge voltage at 10 kA, with 8/20 µs current shape.
- R = 1 MΩ (this resistance replaces R_0 and R_1 in the IEEE model [10]).

Values can be A_0 and A_1 for the V-I characteristic can be determined from Table 4.3. based on per unit values of $V_{r\,(8/20)}$ which is specified by the manufacturer.

Table 4.3: Values for A_0 and A_1 for Pinceti – Gianettoni Arrester Model.

Current [kA]	per unit Voltage of $V_{r\,(8/20)}$	
	A_0	A_1
0.000002	0.81	0.623
0.1	0.974	0.788
1	1.052	0.866
3	1.108	0.922
10	1.195	1.009
20	1.277	1.091

4.8 Black Box Arc Model

Black-box modelling is a method of apply a mathematical function using either TACS or MODELS, to simulate the arcing behaviour of a circuit breaker during switching operations. The model usually manipulates a derived non-linear resistance in parallel with the opening CB to simulate arcing resistance. The most commonly used equations used in black box arc modelling are the:

- Mayr arc model which is more suitable for simulating lower switching current levels such as inductive loads.
- The Cassie arc model is more suitable for higher current arcing that may occur during short circuits (in the region of kA).

4.8.1 Mayr Arc Model

Mayr's arc model assumes that the conductance is non-linear during contact separation, and that arc diameter and arc loss are constant. This model is suitable for simulation of arcing during small inductive current interruption such as shunt reactor switching. The Mayr arc model can be described by the following equation [9]:

$$\frac{dG}{dt} = \frac{G}{\tau}\left(\frac{vi}{N_0} - 1\right). \qquad (4.6)$$

By replacing the arc conductance *G* with *i/v*, the equation can be written as follows:

$$\frac{dG}{dt} = \frac{1}{\tau}\left(\frac{i^2}{N_0} - G\right). \qquad (4.7)$$

Where:

- G = arc conductance.
- τ = arc time constant.
- v = arc voltage.
- i = arc current.
- N_0 = constant arc power loss

This equation can be directly applied to the circuit model using TACS program within EMTP-ATP for thermodynamic control of the arc. However, in practice the author has found that it is difficult to determine the parameters for the Mayr arc model. The pertinent data are normally obtained during factory type tests of the circuit breaker by the manufacturer. The main parameters required to derive the necessary values are:

- The arc power loss N_0.
- The circuit breaker chopping number λ.
- The arc time constant τ.

The range for the arc time constant τ for SF_6 circuit breakers is typically in the region of 0.05 - 0.5 µs. The chopping number for SF_6 circuit breakers, is typically in the range of 4 - 17 $\times 10^{-4}$ and can be calculated using the following equation [25]:

$$\lambda = \frac{i_{ch}}{\sqrt{C_t}} = \sqrt{\frac{N_0}{\tau}} \tag{4.8}$$

Where:

- i_{ch} is the chopping current.
- C_t is the equivalent capacitance between the CB contacts.

4.8.2 Thevenin Type 94 Arc Model

Another approach to simulating the arcing is by using Thevenin type 94 model using MODELS. This is a two-pole component which takes the system Thevenin equivalent voltage V_{th} and resistance R_{th} and calculates the value for arcing current I_{arc} for each time step. The following equations are solved simultaneously using an iterative method available in MODELS [8]:

The Stationary arc conductance:

$$G = \frac{i^2}{p_0 + u_0 \cdot |i_{arc}|} \tag{4.9}$$

I_{arc} calculation:

$$i_{arc} = \frac{g \cdot v_{th}}{1 + g \cdot r_{th}} \qquad (4.10)$$

The arc equation is solved using the MODELS Laplace function:

$$g(s) = \frac{1}{1 + \tau \cdot s} \cdot G(s) \qquad (4.11)$$

4.9 Considerations when Modelling Shunt Capacitor Bank Switching

The main goal of modelling shunt capacitor bank switching is to analyse the transient inrush current and magnitude of local and remote system voltage. The main components that were used in this research for modelling capacitive load switching included:

- Voltage source and source impedance.
- Circuit breaker (time-controlled switch).
- Inductive reactance of the busbars and substation conductors.
- Shunt capacitance including configuration (Y or D) and grounding arrangement.
- Current limiting reactors.

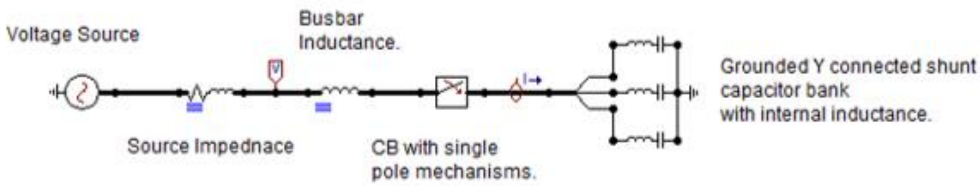


Figure 4.11: Simplified Shunt Capacitor Bank Model.

Experience of conducting simulations during the course of this research has found that statistical variation around the CB mechanical scatter time is an important factor to be considered when modelling. This ensures that the worst cases can be observed around the maximum deviations of the CB. Also, it was found that, accurate values of inductance for the busbar conductors and internal capacitor bank is important, as the inductance is the main factor that limits inrush current.

4.10 Shunt Reactor Switching Model

The main focus of the shunt reactor switching model is to analyse the voltage across the shunt reactor and the transient recovery voltage across the CB, and to observe these voltages during re-ignition.

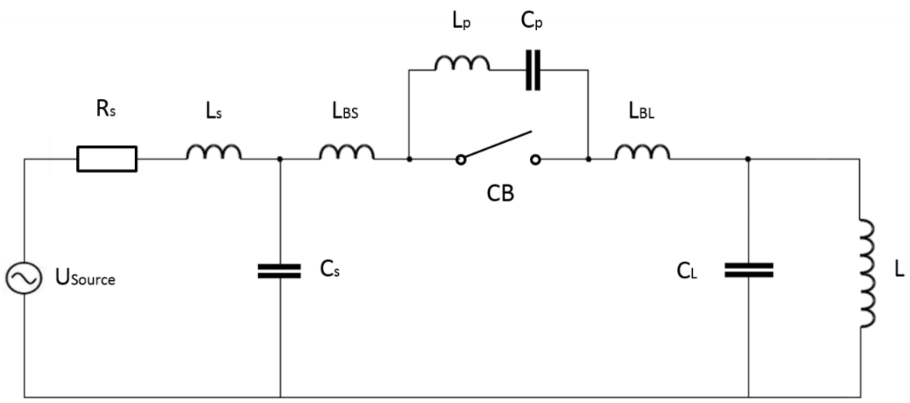


Figure 4.12: Single Phase Equivalent Shunt Reactor Circuit.

The basic components required to model the switching performance of shunt reactors in this research include:

- Source voltage and impedance.
- Circuit breaker (Time controlled switch).
- Internal capacitance and inductance of the circuit breaker.
- Inductive reactance of the busbars and substation conductors (both source and load side).
- Source parallel and load capacitance.
- Shunt reactor.

To simulate re-ignition following current interruption, the author has found that the most efficient method is to use an additional time-controlled switch parallel with the main CB and configure it to close at a non-optimum point on the recovery voltage waveform. While not the most accurate method, it simulates worst case impacts. Black box arc models are usually not implemented in general transient switching studies, as accurate information is difficult to obtain.

4.11 Unloaded Power Transformer Energisation Modelling

In this application, the important factors to be observed are the transient inrush current and the quality and magnitude of the local busbar voltages. It is important to consider the impacts of dynamic and remnant flux in the transformer core before and during energisation.

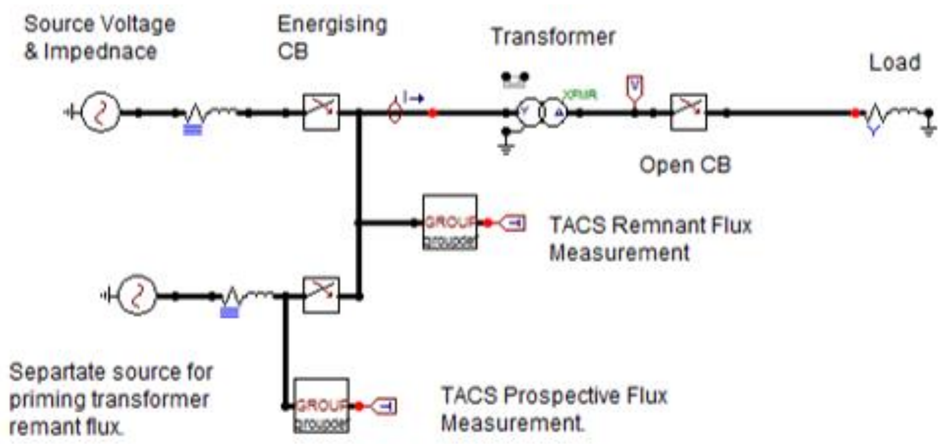


Figure 4.13: Simplified Power Transformer Energisation Model.

The basic components used to model the switching performance of unloaded power transformers in this research included:

- Voltage source and source impedance.
- Circuit breaker (Time controlled switch).
- Inductive reactance of the busbars and substation conductors.
- XFRM transformer model, with transformer nameplate and factory test results data from open circuit, short circuit and capacitance tests. To model the remnant

flux in this research, the XFRM core was configured as a type 96 non-linear inductor and initialised to a known value of remnant flux using a separate voltage source.

- To monitor the core remnant flux, the author used TACS to perform a conversion calculation on the measured voltage.

5. Shunt Capacitor Switching

5.1 Shunt Capacitor Banks

Shunt capacitor banks are vital components on the Irish transmission systems for supplying an economical source of reactive power to support system voltage. They provide localised voltage support to weaker parts of network where there are little or no generation sources available and are normally switched manually by system operators, but in some locations can be automatically regulated by the substation control systems depending on system voltage requirements. Typically, capacitor banks can be switched multiple times per day. Therefore, during the course of this research it has been found that capacitor bank circuit breakers could be operated hundreds of times per year. To analyse the performance of CS as applied to shunt capacitor bank installations on the Irish transmission system, the author considered the following aspects and methods:

- Issues that arise during shunt capacitor switching.
- The theory surrounding the inrush transients that occur during switching.
- Optimum controlled switching strategies and mitigation measures.
- EMTP-ATP simulations on the impacts of switching a 30 MVAr shunt capacitor bank at a 110 kV transmission substation in the west of Ireland.
- Practical overview surrounded the commissioning of a CSD on a 30 MVAr shunt capacitor bank installation.

Figure 5.1:Shown is a 110 kV, 15 MVAr Shunt Capacitor Bank.

5.2 De-energisation of Shunt Capacitor Banks

Unlike shunt reactors, it was found that the de-energisation of shunt capacitor banks does not present much difficulty for the CB to handle. The current to be interrupted is usually small and the slope of the recovery voltage is very low [13]. The residual charge in the capacitor bank could at worst be at the peak of the system voltage when interrupted, this would result in recovery voltage across the breaker being at twice the rated voltage, 10 ms later at the next opposing cycle in the system voltage waveform. Additionally, CBs for the purpose of switching shunt capacitor banks are normally specified as C2 class under IEC62271-100. C2 class specified CBs have a very low probability of restrike following current interruption.

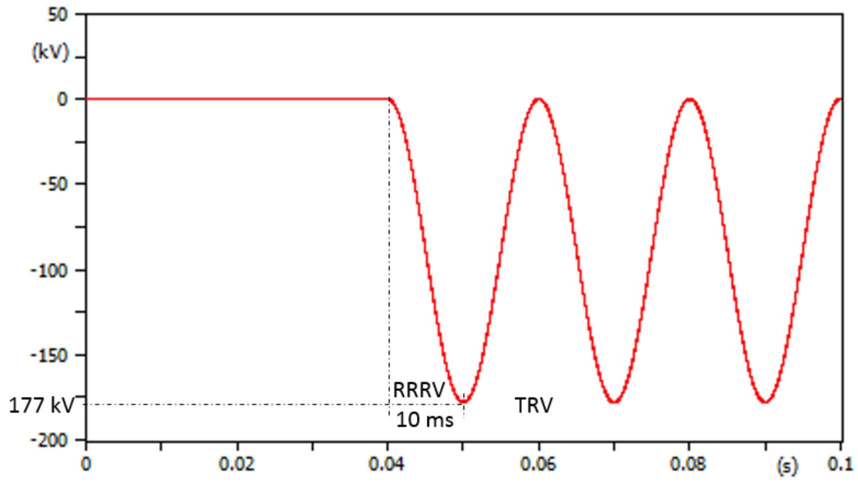


Figure 5.2:Rate of Rise of Recovery Voltage During a 110 kV Shunt Capacitor Bank De-energisation.

5.3 Energisation Shunt Capacitor Banks without any Mitigation Technique

Since capacitor banks have a small surge impedance, typically only a few ohms and at higher voltage levels, there is less system damping due to higher X/R ratios [20]. This results in a large inrush current when a shunt capacitor bank is energised. This current is inversely proportional to the surge impedance of the load circuit. A large inrush current is drawn because there is a sudden change in applied voltage to the capacitor bank from zero to thousands of volts [5]. Depending on the network topology, current in the region of 2 to 5 times rated current at frequencies of 200 – 600 Hz can occur during the energisation of a single capacitor on a bus. When there is a previously energised bank in service or a cable feeder connected to the bus, this inrush current could be over 40 times the rated current at frequencies in the order of kHz [26].

Besides inrush currents, transient over voltages of up to 2 times the rated voltage may occur at the local bus and may be magnified up to 4 times the rated voltage at remote locations on the network, particularly at the remote ends of radial fed lines [27]. These transient over voltages can result in damage to transformer windings, HV equipment insulation and electronic equipment in substations. Transient over voltages may also be transferred to customer's loads and can be further compounded by the distorted harmonic waveforms generated by the customers' non-linear loads and amplified, causing low voltage power electronics to fail or variable speed drives to trip out [28]. The magnitude of this over-voltage greatly depends on system damping from the source impedance.

Besides the negative effects for the system, switching of shunt capacitor banks can be quite an onerous duty for the switching device to handle. The inrush current starts to flow the moment of prestrike before the circuit breaker contacts touch. Depending on the frequency of the inrush current and duration of the pre-arcing period, a very high current can flow through the pre-arc [5] and this can lead to major stressing and damage to the circuit breaker contact system.

The high inrush current associated with uncontrolled energisation may also result in the false operation of shunt capacitor bank protection relays. The following fault recording is a real-life example the author found during his research of false operation of a 15 MVAr capacitor bank protection system. This mis-operation resulted in a key item of voltage support plant being unavailable in a particularly weak location on the 110 kV network. The shunt capacitor bank was energised near the peak of T voltage waveform. This resulted in a peak current of 520 A and caused the capacitor unbalance protection relay to operate.

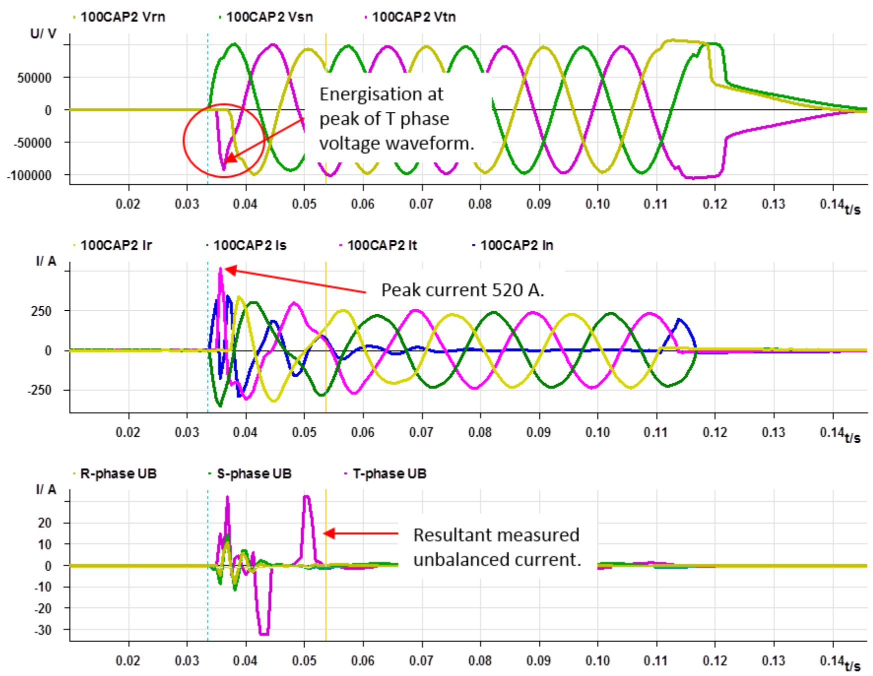


Figure 5.3 Fault Recordings from Unbalanced Protection.

Therefore, without any mitigation technique, a randomly energised capacitor bank could potentially generate an inrush current several times the nominal value at high frequency in the order of kHz, which is harmful for equipment in the energisation current path and can also result in significant temporary surges to the network voltage and lead to false operation of protection relays as it did in the case of Figure 5.3.

5.4 Considerations when Energising Shunt Capacitor Banks

When energising a shunt capacitor bank, it is important to consider the magnitude and frequency of the transient inrush current in order to ensure that the equipment is appropriately rated and to select the most appropriate mitigation method. The following are the main factors which must be considered:

5.4.1 Voltage

The magnitude of the inrush current is dependent on the difference between system voltage and the trapped voltage charge within the capacitor bank at the instant of energisation. The optimum instant for the energisation is when the system voltage is at its zero crossing, provided the capacitor bank has been completely discharged. It is always assumed that prior to energisation, that a capacitor bank is completely discharged. Each capacitor can is usually fitted with a discharge resistor across its main terminals, see Figure 5.4. The discharge resistor usually discharges the can within 5 minutes. Also, it is prudent to include a timed electrical interlock on the circuit breaker, to prevent the capacitor bank been re-energised again typically within 10 minutes of being de-energised to allow sufficient time for the can to discharge.

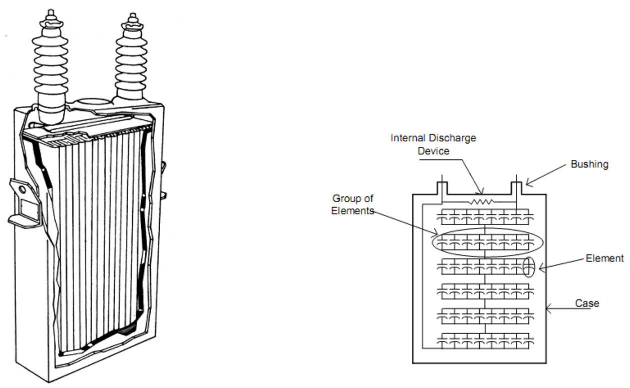


Figure 5.4:Typical HV Capacitor Can Construction.

5.4.2 Capacitance in the Circuit

The size of the capacitor bank being energised also influences the magnitude of the inrush current. This is especially so if there is a previously energised capacitive load in the vicinity of the capacitor bank being energised. This will result in a situation know as back to back capacitor bank switching, where the previously energised capacitive load provides the charging energy to the capacitor bank being energised. Back to back switching results in a large inrush current with a very high frequency.

5.4.3 Inductance in the Circuit

Inductance in the current path to the capacitor bank being energised will limit the magnitude of the inrush current. This inductance consists of:

- Source inductance.
- Inductance of the busbars.
- Inductance of the conductors between capacitor bank(s).
- Internal inductance of the capacitor bank.

5.4.4 System Damping

Source resistance and the application of any pre-insertion resistors in the energisation current path will have a damping effect on the oscillatory response of the transient inrush current. Most systems have an underdamped oscillatory response. The greater the resistance in the energising current path, the greater the damping effect will be. However, with the introduction of pre-insertion resistances, this may provide an overdamped response.

5.5 Energising Single Capacitor bank

Considering the factors mentioned in 5.4, the following simplified circuit can be used to calculate the transient inrush current peak magnitude and oscillating frequency.

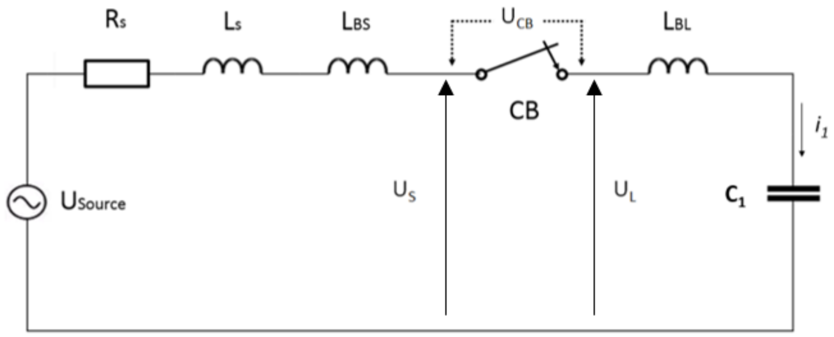


Figure 5.5: Simplified Circuit for Energising Single Capacitor Bank.

Where:

- U_{source} = RMS Source voltage (Ph – E).
- U_s = Source side of CB voltage (Ph – E).
- U_L = Load side of CB voltage (Ph – E).
- U_{CB} = Voltage across the CB.
- R_s = Source resistance.
- L_s = Source reactance.
- L_{BS} = Inductance of source side busbar.
- L_{BL} = Inductance of load side busbar.
- C_1 = Load Capacitance.
- i_1 = Energising current.

Taking the circuit shown in Figure 5.5, and by applying the circuit inductance into a single inductance L_{eq}, the result can be considered as a series RLC circuit. Applying a voltage U_{source} the following general equation can be used to calculate the current [6].

$$U_{Source} = R_S i_1 + L_{eq}\frac{di_1}{dt} + \frac{1}{C_1}\int i_1 . dt \tag{5.1}$$

By differentiating equation (5.1) and applying U_{source} as the peak step voltage:

$$\frac{d^2 i_1}{dt^2} + \frac{R_S}{L_{eq}} . \frac{di_1}{dt} + \frac{1}{L_{eq} C_1} i_1 = 0 \tag{5.2}$$

The 2nd order differential equation shown in (5.2), can be solved into 3 separate equations to calculate the current depending on the degree of damping in the circuit, where the system damping α and circuit frequency ω_i can be calculated as:

$$\alpha = \frac{R_S}{2L_{eq}}. \qquad \omega_i = \frac{1}{\sqrt{L_{eq}C_1}} \tag{5.3}$$

a) Critically damped circuit where $\alpha^2 = \omega_i^2$

$$i_1(t) = \frac{U_{source}}{L_{eq}}\, te^{-\alpha t} \tag{5.4}$$

b) Under damped circuit where $\alpha^2 > \omega_i^2$

$$i_1(t) = \frac{U_{source}}{L_{eq}\sqrt{\omega_i^2 - \alpha^2}}\, e^{-\alpha t} \sin\left(\sqrt{\omega_i^2 - \alpha^2}\right)t \tag{5.5}$$

c) Over damped circuit where $\alpha^2 < \omega_i^2$

$$i_1(t) = \frac{U_{source}}{L_{eq}\sqrt{\alpha^2 - \omega_i^2}}\, e^{-\alpha t} \sinh\left(\sqrt{\omega_i^2 - \alpha^2}\right)t \tag{5.6}$$

Considering that in most situations, the system will be under damped, therefore equation (5.5) can be simplified as follows:

$$i_1 = \frac{\hat{U}}{Z}\, e^{-\alpha t} \sin\omega_i t \tag{5.7}$$

Where:

$$Z = \sqrt{\frac{L_{eq}}{C_1}} \tag{5.8}$$

- i_1 = Inrush current magnitude.
- $\widehat{U}$ = source voltage peak.
- $\omega_i = 2\pi f_i$ inrush current frequency (rads/s).

The only two quantities of interest are the peak inrush current i_{1peak} and its frequency f_1, therefore:

$$i_{ipeak} = \frac{\widehat{U}}{Z} = \frac{U\sqrt{2}}{Z}. \qquad f_i = \frac{1}{2\pi\sqrt{L_S C_1}} \tag{5.9}$$

Where:

$$Z = \sqrt{\frac{L_S}{C_1}} \tag{5.10}$$

The peak inrush current i_{1peak} can be simplified further:

$$i_{ipeak} = \sqrt{2}\sqrt{I_{S/C} i_1}\,. \qquad f_1 = f_s \frac{I_{S/C}}{i_1} \tag{5.11}$$

Where:

$$I_{S/C} = \frac{U}{\omega_s L_s}. \qquad i_1 = \omega_s U C_1 \tag{5.12}$$

- $I_{S/C}$ = Short circuit current from source.
- f_S = Power frequency.

5.6 Back to Back Energisation

Due to the increased use of shunt capacitor banks for reactive compensation on the Irish transmission system, it is common to have more than one capacitor bank connected to the same bus. This poses difficulties when switching one of the banks where there is one or more of the capacitive loads connected. When switching, there is a high frequency current discharge from the previously connected load into the bank being energised, the discharge is typically more severe than with standalone energisation and normally flows during pre-arcing phase in the closing operation of the CB [5]. The only factor limiting the discharge current, is the inductance of the conductors between the capacitor banks. This transient phenomenon is known as back to back switching. Most banks have to be supplemented with current limiting reactors to reduce the magnitude of the high frequency transient current [29].

The perturbation associated with back to back capacitor bank switching can be characterised by two separate oscillatory stages [30]:

1. The first, is the high frequency current discharge from the previously connected bank into the energising load. This load can be analysed as a *LC* series circuit.
2. In the second stage, due to circuit losses the voltage across the two banks will settle to a common value lower than the system voltage. This must be brought in line with system voltage and there is a resultant lower frequency current transient during this process.

5.6.1 Analysis of Peak Inrush Current and Oscillatory Frequency During Back to Back Switching

As shown in Figure 5.6. When energising C_1 capacitor bank with C_2 previously energised, C_2 will supply the inrush current which is limited only by the inductance in the energisation current path. Therefore, as the previously energised capacitor C_2 will provide the majority of the inrush current, the circuit can be simplified as shown in Figure 5.6, neglecting the voltage source and source inductance.

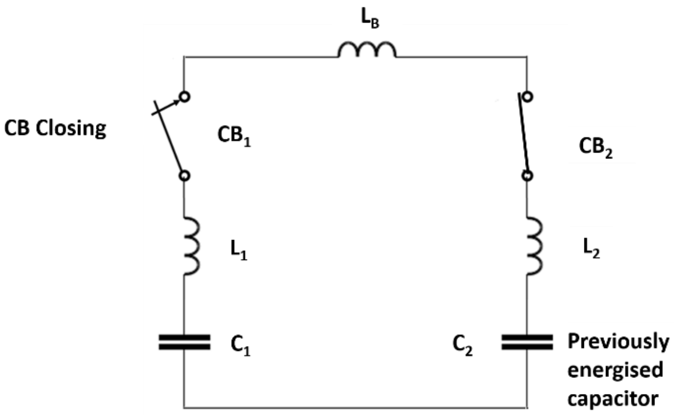


Figure 5.6:Simplified Circuit for Analysing Back to Back Switching of Shunt Capacitor Banks.

Where:

- L_1 ,L_2 = Respective load side inductance.
- C_1 ,C_2 = Respective load side capacitance.
- L_B = Inductance in busbars between capacitor banks.

The peak inrush current i_{peak} and frequency f_1 can be calculated using the following equations, expanded from equations derived in section 5.5:

$$i_{ipeak} = U\sqrt{2}\sqrt{\frac{C_t}{L_t}}. \qquad f_1 = \frac{1}{2\pi\sqrt{L_t C_t}} \tag{5.13}$$

Where:

$$C_t = \frac{C_1 C_2}{C_1 + C_2}. \qquad L_t = L_1 + L_2 + L_B \tag{5.14}$$

5.7 Mitigation Measures

To reduce transient over voltages and inrush currents that occur during switching of shunt capacitor banks, there are a number of methods which can be employed. The three main methods are:

1. Pre-insertion resistors which add additional damping for a short period to limit the inrush current which in turn prevents the occurrence of remote over voltages. This is a straight forward solution however; the cost and additional maintenance requirements of the specialised CB make it prohibitive. Pre-insertion resistors are not normally used in Ireland.
2. Current limiting reactors can be fixed in series with the capacitor bank and is a good method of reducing the high frequency transient inrush current that occur during switching. It was found that they are nearly always used in back to back situations in Ireland when there's an adjacent capacitive load present or when switching large capacitor banks. They are a fairly cost effective and maintenance free solution however they do not limit the occurrence of remote transient over voltages [6].
3. Controlled switching is a more commonly implemented solution in Ireland, CSDs control the point on the voltage waveform at which the CB energises the load, so that the residual voltage magnitude of the load is the same as the source voltage. This is normally the zero crossing of the supply voltage as the load is completely de-energised.

5.8 Controlled Switching Strategies

Depending on the configuration, grounded-star, delta, or star configuration in an isolated system, the switching strategy will differ. Current cannot flow until a complete circuit path is made, either via phase to ground path in a grounded star point system or phase to phase path in configuration isolated from an earth path.

5.8.1 Energising grounded Star (Wye) connected capacitor bank

The optimum point for switching a grounded star connected shunt capacitor bank, is at the zero crossing of the voltage sine wave of each phase, provided that the capacitor bank is completely de-energised. The time delay for each of the CB pole operations is also dependent on the reference quantity used by the CSD and the system frequency. Table 5.1 shows the typical CSD operating times for each CB pole based on the reference quantity used for a 50 Hz system.

Table 5.1: CSD Close Command Time Delays for Reference Voltage Based on 50 Hz System for Grounded Capacitor Bank

Reference Voltage to CSD	R Pole	S Pole	T Pole
R - E	0.0 ms	6.7 ms	3.3 ms
S - E	3.3 ms	10.0 ms	6.7 ms
T - E	6.7 ms	13.3 ms	10.0 ms
R - S	1.7 ms	8.3 ms	5.0 ms
S - T	5.0 ms	11.7 ms	8.3 ms
T - R	8.3 ms	15.0 ms	11.7 ms

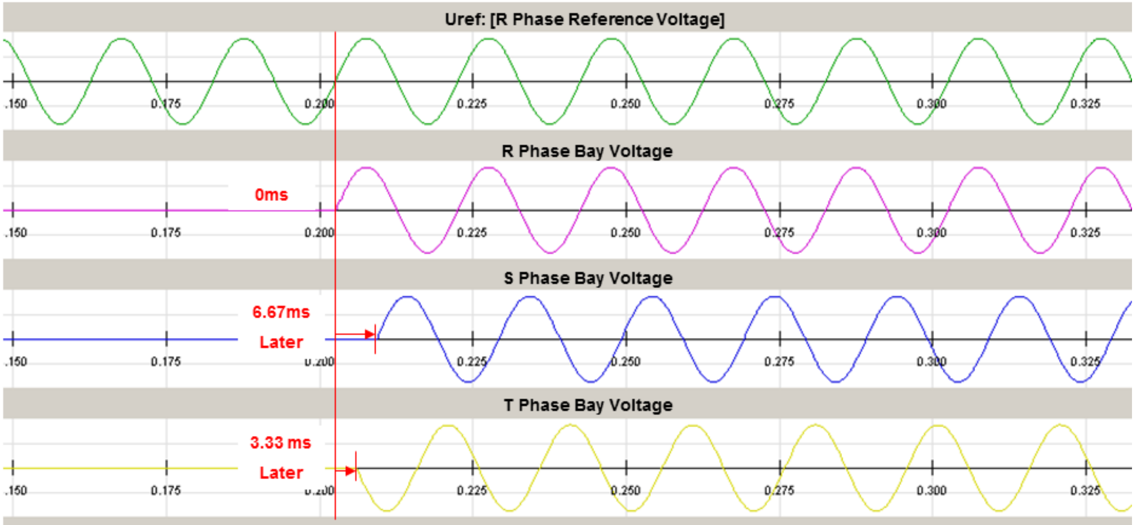


Figure 5.7: Voltage Waveforms for Switching of Grounded Capacitor Bank using R-E Phase Reference Voltage.

5.8.2 Energising Un-Grounded Star (Wye) or Delta Connected Capacitor Bank

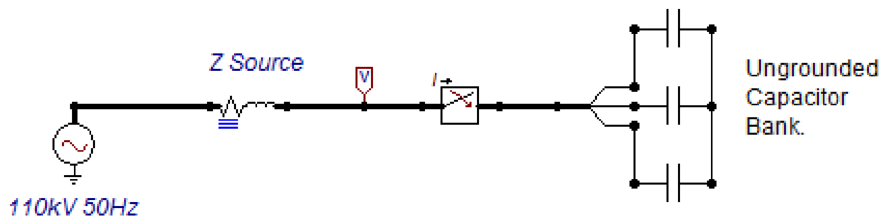


Figure 5.8: Simplified Circuit Model of Capacitor Bank with Floating Neutral.

The optimum switching strategy used for energising shunt capacitor banks with these configuration types, is to switch two poles simultaneously when they are at the same voltage magnitudes. This ensures that there is no voltage difference across the two closing CB contacts, then the final pole is switched at its zero-voltage crossing. The strategy is effective provided that there is no residual charge in the capacitor bank. The typical closing sequence for the circuit breaker is, R and T poles simultaneously followed by S pole. Table 5.2 below shows typical CSD operate time for each CB pole based on this closing sequence.

Table 5.2: Capacitor Bank Floating Neutral Close Delays based on R and T Pole followed by S Pole Closing Sequence

Reference Voltage to CSD	R Pole	S Pole	T Pole
R - E	1.7 ms	6.7 ms	1.7 ms
S - E	5.0 ms	10.0 ms	5.0 ms
T - E	8.3 ms	13.3 ms	8.3 ms
R - S	3.3 ms	8.3 ms	3.3 ms
S - T	6.7 ms	11.7 ms	6.7 ms
T - R	0.0 ms	15.0 ms	0.0 ms

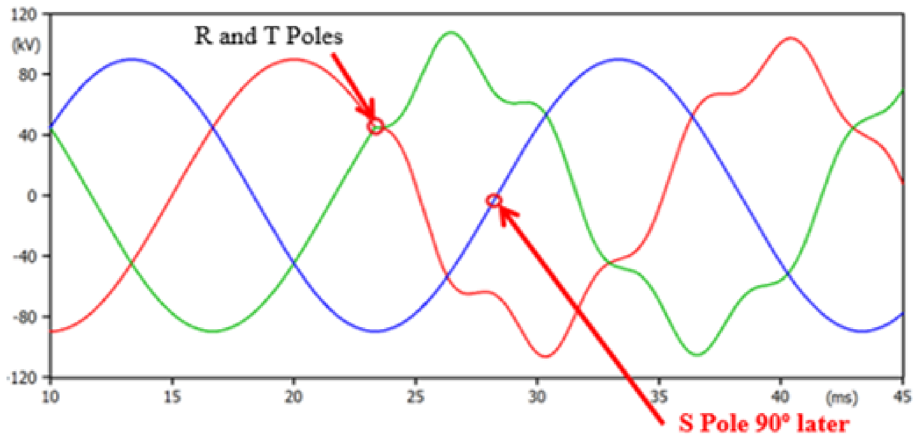


Figure 5.9: Source Voltage Waveform for Closing Strategy for Floating Neutral.

5.8.3 Fast Switching of Shunt Capacitor banks

Where shunt capacitor banks are used in specialised applications such as, static var compensators (SVC) or synchronous static compensators (STATCOMs), extremely fast switching sequences are required to energise capacitors in these situations, as there may be periods where it is not permissible to allow an appropriate discharge time of the capacitor residual charge between switching operations. In these applications, the CSD must account for the capacitor residual charge and the self-discharge characteristics of the capacitor bank to determine the optimum switching point [19]. Depending on the residual charge present, the CSD must provide synchronised closing for each CB pole to ensure that energisation takes place when the instantaneous system voltage is the same as the residual charge of the capacitor bank, i.e. when there is no voltage difference across the closing CB contacts.

5.9 EMTP-ATP Modelling of Shunt Capacitor Bank Switching Operations

In most situations, the potential problems that arise as a result of shunt capacitors switching can be best analysed using simulation software. The potential mitigation measures can also be investigated to ensure their effectiveness before being practically implemented.

5.9.1 Model Overview

The model shown in Figure 5.10, represents two 110 kV substations located in the West of Ireland.

- The first or primary substation, has two separately switched 30 MVAr shunt capacitor banks connected to the 110 kV busbar.
- The second is a radially fed 110 kV station, supplied from the primary substation via 37 km of overhead line, and is feeding customer loads.

The purpose of this model is to analyse the potential impacts that result from switching of capacitor bank 1 in the primary substation. The impacts are analysed in terms of:

1. Transient inrush current to capacitor bank 1 when switched individually and when capacitor bank 2 is previously energised.
2. Impacts to system voltage and voltage quality at the customers interface during switching.

The most practical mitigation measures discussed in section 5.7 are applied to the model to analyse the solution performance.

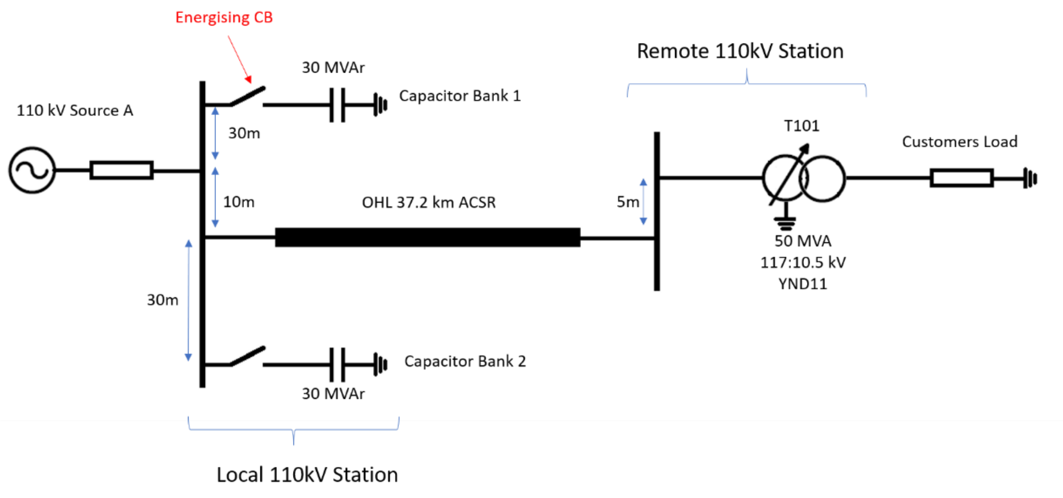


Figure 5.10: EMTP/ATP Model of 110 kV Network under Investigation.

5.9.1.1 Model Data

- Source line to line voltage: *110 kV.*
- Thevenin equivalent source impedance: $R = 5.712\ \Omega$, $X_L = 17.243\ \Omega$.
- Busbar inductance: *0.856 µH/m.* [6]
- *30 MVAr* capacitor bank inductance: *10 µH.* [6]
- *30 MVAr* capacitor bank capacitance: *7.89 µF/phase.*
- Overhead line data (4 sections):
  - *1 × 15.6 km* and *1 ×1.267 km* of $200\ mm^2$ ACSR OHL conductor with $R_{DC} = 0.1693\ \Omega / km$ @ 20 ºC, $r_{in} = 0.025\ cm$ and $r_{out} = 0.08\ cm$.
  - *1 × 19.52 km* and *1 ×0.85 km* of $220\ mm^2$ ACSR OHL conductor with $R_{DC} = 0.1433\ \Omega / km$ @ 20 ºC, $r_{in} = 0.03\ cm$ and $r_{out} = 0.085\ cm$.
  - Tower geometry (wood pole, horizontal conductors, no guard wire):
    - Distance between conductors: *4.5 m.*
    - Average conductor height at tower: *22 m.*
    - Average conductor height at mid span: *16 m.*
  - Soil resistivity R_{ho} taken as: *200 Ω meters*.
- Customer transformer: *50 MVA, 117kV/10.5 kV, YNd11, 14.29 %.*
- Customer load: *10.6 MW @ 0.95 PF.*

5.10 Simulation Results

5.10.1 Energisation of Single Shunt Capacitor Bank

Shunt capacitor 1 is energised without capacitor bank 2 connected to the primary bus.

5.10.1.1 Simulation 1: Worst Case

Shunt capacitor bank 1 circuit breaker is set up as a single mechanism operating the 3 circuit breaker poles at the same time. Energisation takes place at the peak of the R phase system voltage waveform.

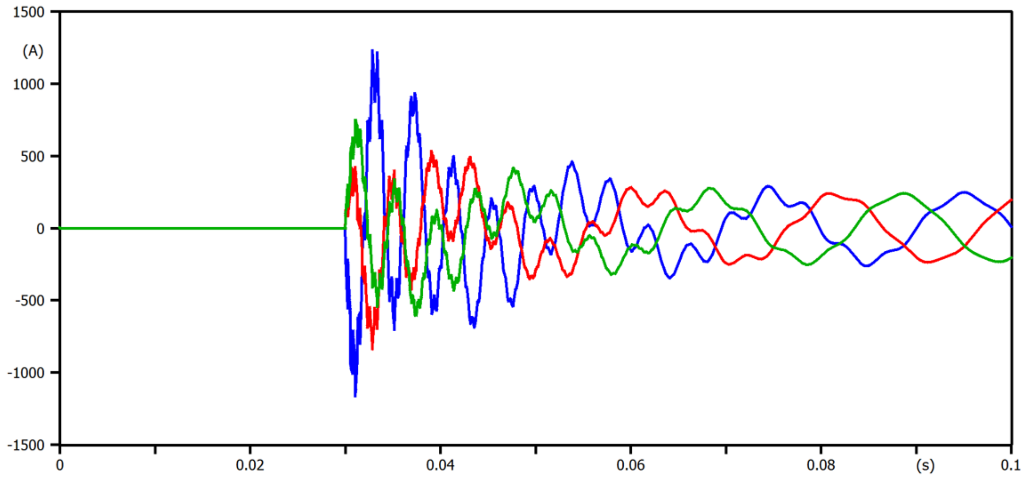


Figure 5.11: Transient Inrush Current.

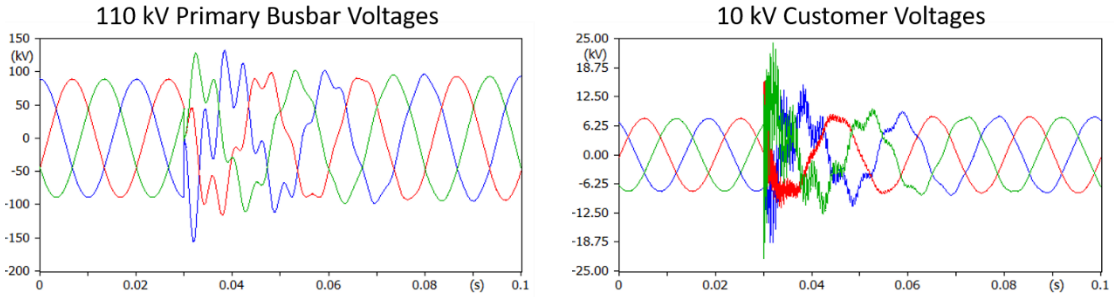


Figure 5.12: Voltages at Primary Substation and Customer Interface.

It can be seen from this scenario that:

- There is a high frequency inrush current with a peak of 1251 A. This can be observed in Figure 5.11.
- In Figure 5.12 it can be seen that the voltage at the primary substation 110 kV bus collapses at the instant of energisation and recovers to a peak of 155 kV.
- A severe oscillatory transient can be seen at the customers interface in Figure 5.12. The peak transient voltage is over 3 times the rated rms voltage.

5.10.1.2 Simulation 2: Worst case with Surge Arresters

The simulation is the same as the previous however, this time surge arrestors are fitted to the remote end of the transmission line. The surge arrestors used in this model are a class 3 polymer with a maximum continuous over-voltage (MCOV) rating of 75 kV.

The model proposed by Pinceti – Gianettoni [10] was used by the author to simulate the surge arrester's behaviour.

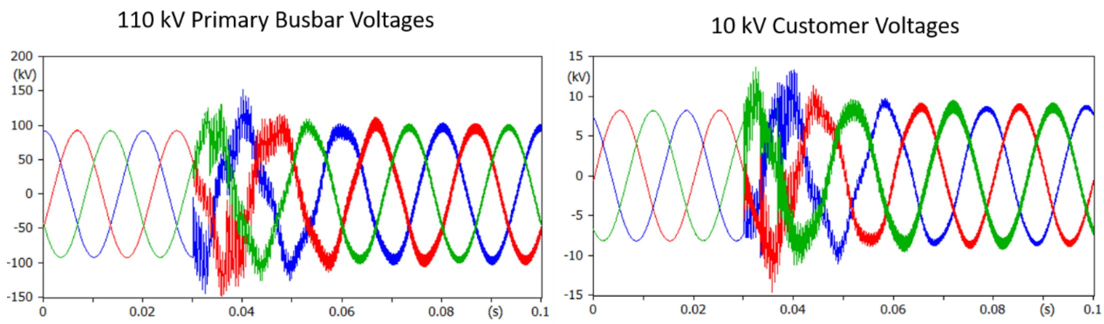


Figure 5.13: Voltages at 110 kV Remote Substation and Customer Interface.

It can be seen that the voltage at the remote stations is slightly reduced however, it was found difficult to model the surge arrestors actual characteristic at the lower ranges of over voltages for transient switching simulations. The minimum point at the V-I characteristic for this model was 145.782 kV with a leakage current of 0.02 A. So, this method is not considered adequate for modelling lower magnitude switching over voltages. The IEEE model's minimum leakage current in their tables is even higher at magnitude of 10 A.

5.10.1.3 Simulation 3: Controlled Switching

Controlled switching is applied to the circuit breaker of capacitor bank 1, this time a CB with an individual mechanism for each pole was used. The CB is assumed to have a high RDDS slope, so pre-arcing was not taken into account. However, the mechanical scatter must be considered, so the simulation is performed at 3 standard deviations (σ) considering a maximum mechanical scatter of ± 1 ms. No surge arrestors were used in this simulation.

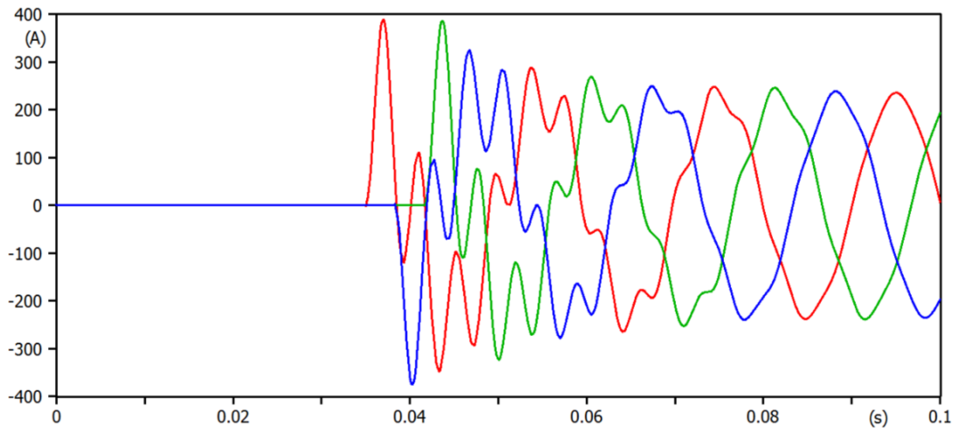


Figure 5.14: Capacitor Bank 1 Inrush Current with CS at Optimum Point.

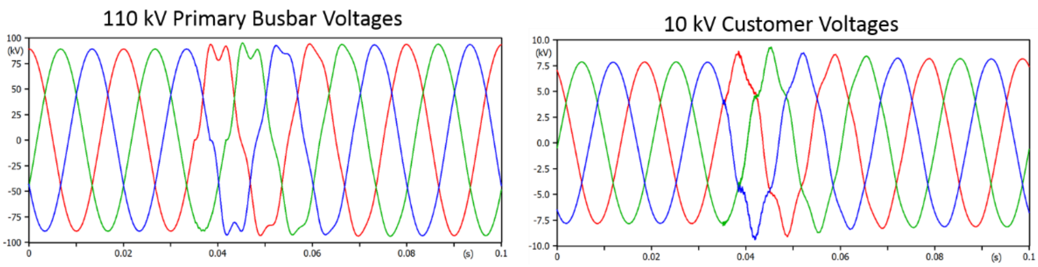


Figure 5.15: Voltages at Primary Substation and Customer Interface with CS at Optimum Point.

By applying controlled switching, it can be seen that the energisation inrush current is greatly reduced and the impacts to the voltage quality are minimised. The following peak values were recorded in Table 5.3 by the author, taking into account mechanical scatter of the CB.

Table 5.3: Peak Values Recorded Considering 1 ms Mechanical Scatter of CB

	Zero Voltage Crossing	σ = + 1 ms	σ = - 1 ms	Nominal Peak Values
Capacitor Bank 1 Current	387 A	556 A	547 A	223 A
Primary Busbar Voltage	92.4 kV	107 kV	106.9 kV	89.9 kV
Voltage at Customer Interface	9.2 kV	10.4 kV	10.3 kV	8.16 kV

5.10.2 Back to Back Switching

To consider the issues that arise during back to back switching, capacitor bank 2 is connected to the primary busbar when energising capacitor bank 1.

5.10.2.1 Simulation 4: Back to Back Worst Case

This is a very unrealistic situation, where a shunt capacitor bank would be switched near a previously energised capacitive load without the presence of a current limiting reactor. Shunt capacitor bank 1 CB is set up as a single mechanism operating all 3 CB poles simultaneously. Energisation takes place at the peak of the R phase system voltage wave form.

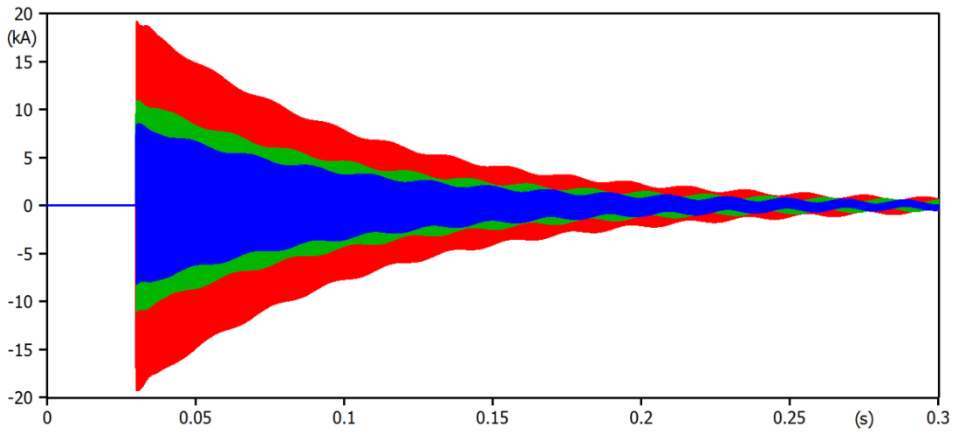


Figure 5.16: Back to Back Switching - Capacitor Bank 1 Inrush Current

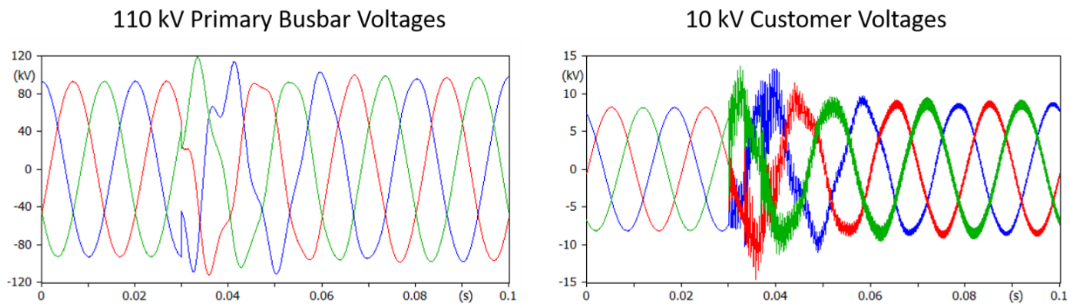


Figure 5.17: Voltages Waveforms at Primary Substation and Customer Interface.

It can be seen without any mitigation measures, that an extremely high frequency inrush current is produced in back to back switching situations.

- The inrush current in Figure 5.16, was in excess of 15 kA at a frequency of 8.6 kHz.
- The voltage at the primary substation 110 kV busbar experienced a collapse during the cycle at which capacitor bank 1 was energised followed by a recovery peak of almost 120 kV, this can be seen in Figure 5.17.
- An oscillatory transient over-voltage with a peak value of approximately 15 kV can be seen at the customer interface at the remote station in Figure 5.17.

5.10.2.2 Simulation 5: Back to Back Current Limiting Reactor

To create a more realistic scenario, a current limiting reactor was placed in series with capacitor bank 2. The reactor inductance is 321 mH. Again, shunt capacitor bank 1 CB is set up as a single mechanism operating all 3 CB poles simultaneously. Energisation takes place at the peak of the R phase system voltage wave form.

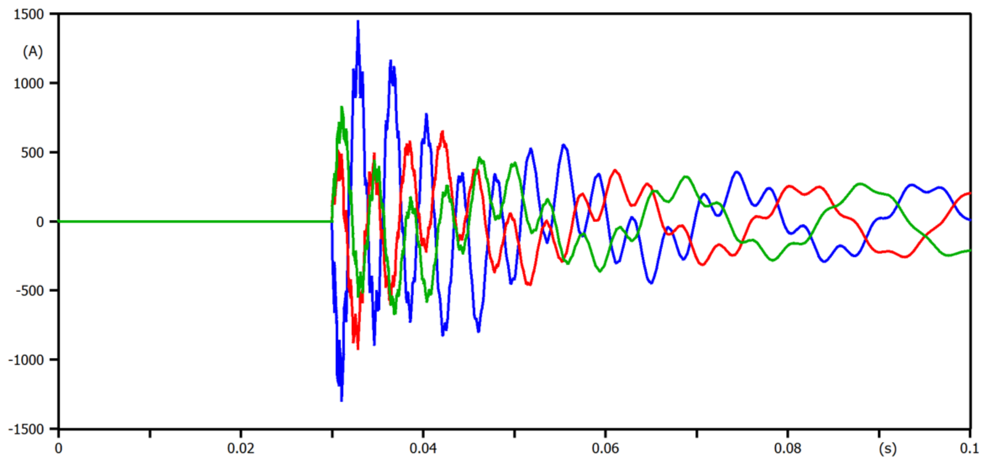


Figure 5.18: Back to Back Switching - Capacitor Bank 1 Inrush Current

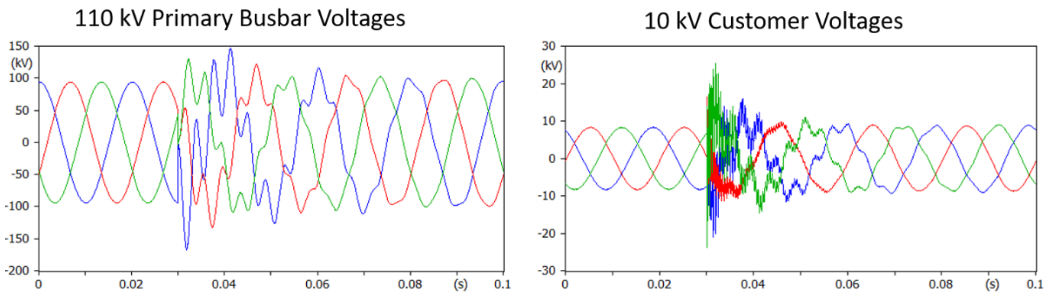


Figure 5.19: Voltages Waveforms at Primary Substation and Customer Interface.

With the current limiting reactor installed the transient inrush is greatly reduced to 1.05 kA peak (see Figure 5.18), however as the reactor limits the outrush from capacitor 2 during switching, the system picks up the slack. It can be seen that:

- The primary substation experience over voltage oscillations for the first few cycles with a voltage peak of 163 kV. This can be seen in Figure 5.19.
- While at the customer interface, a severe oscillatory transient is superimposed on the voltage waveform with a peak in excess of 24 kV (see Figure 5.19).

5.10.2.3 Simulation 6: Back to Back Controlled Switching

In this simulation, controlled switching was applied with a single pole CB (3 mechanisms) for energising capacitor bank 1. Again, as the CB is assumed to have a high RDDS slope, no pre-arcing was considered, and the simulation is performed at 3 standard deviations (σ) to take into account a maximum mechanical scatter of ± 1 ms. The current limiting reactor was left in situ.

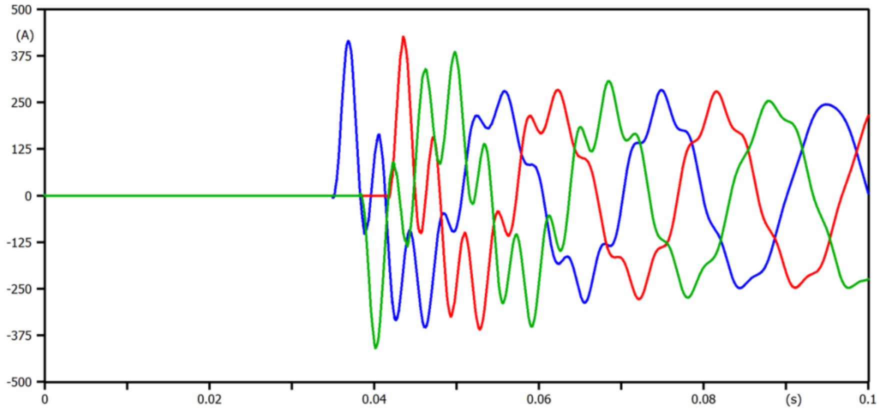


Figure 5.20: Back to Back Switching with CS - Capacitor Bank 1 Inrush Current

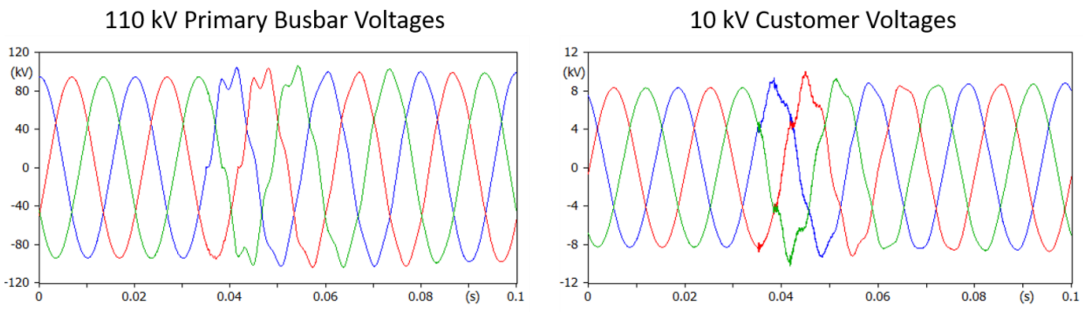


Figure 5.21: Voltages Waveforms at Primary Substation and Customer Interface.

With the application of controlled switching, it was found that the energisation inrush current is reduced even further, and the impacts to the voltage quality are also reduced. The following peak values were recorded by the author in Table 2.1, with CB mechanical scatter deviation of ± 1 ms.

Table 5.4: Peak Values Recorded Considering 1 ms Mechanical Scatter of CB.

	Zero Voltage Crossing	σ = + 1 ms	σ = - 1 ms	Nominal Peak Values
Capacitor Bank 1 Current	410 A	458 A	441 A	223 A
Primary Busbar Voltage	105 kV	109.7 kV	108.96 kV	89.9 kV
Voltage at Customer Interface	10.5 kV	14 kV	14 kV	8.16 kV

5.11 Commissioning of Controlled Switching Devices on Shunt Capacitor Banks on the Irish Transmission System

The process outlined is detailed through the author's own experience in commissioning CS projects during the course of this research.

5.11.1 Commissioning Process

In the author's experience the majority of CS schemes in Ireland are commissioned by the utility's internal commissioning personnel. However, depending on:

1. The manufactures equipment that is used.
2. How specialised the switching application is and service agreements.

The manufacturer's specialist commissioners can also be employed but will be witnessed by representatives from the utility. The following is the typical staged approach adopted for commissioning of these scheme types:

5.11.2 Stage 1: Design Review

This is the first stage in the commissioning process, the designated commissioner will take charge of the project from the construction stage. As part of the construction stage, there is also a pre-commissioning phase before handover is allowed. This is to ensure that the installation/construction has been completed in accordance with the intended design and all equipment is present. Once handover has taken place, the commissioner will normally:

1. Start a review of the design.
2. Compare it against standardised designs produced for the CSDs configuration.
3. Examine the equipment name plate details.
4. Examine equipment manuals and design drawings, firmware of equipment.
5. Ensure all the relevant information has been received including any CS device settings/configuration with a description of the CS strategy being implemented.

5.11.3 Stage 2: Primary Equipment Testing

This stage is normally performed next as it may be invasive. There may be a need to disconnect some wiring to prevent damage to secondary equipment during testing. So, taking the pertinent devices for the CS application, namely the instrument transformers and the circuit breaker operated by the CSD, the following primary commissioning tests are performed, independent of the load equipment:

- Circuit Breakers: Insulation, SF6 gas quality checks, Opening/Closing Timing Tests, static contact resistance, dynamic contact resistance, Motion/ reference contact travel tests.
- Circuit breaker timing tests are always performed on site. This is to ensure correct operation following assembly and to confirm that operating times are within the manufacture's specifications. It is also important to record the CBs characteristic at the time of installation. This can then be used as a benchmark for future maintenance tests performed on the equipment. Also, as a part of timing checks, a number of timing operations are also performed (typically 3 operations) to ensure the repeatability of the CB operating times. Normally it is confirmed that CB is within +/- 1 ms of repeated operation.
- Timing tests from the output command contacts of the CSD to the primary contacts of the circuit breaker are also performed at this stage, to take into account any delays added in from intermediate components such as auxiliary

relays, bay control units (BCU's) etc. This information will be applied to the CSD settings in stage 4.

- Instrument transformer testing: insulation, excitation curves of CT's, ratio, polarity, winding resistances etc.

5.11.4 Stage 3: Installation and Wiring Checks

This stage includes:

- Application of controlled switching device settings/ configuration (including other control and protective devices). As most modern electronic devices are completely configurable, correct device configuration for the intended installation ensures that everything operates as expected.
- Checking the segregation and polarity of individual DC control supplies.
- Point to point wiring check of the complete wiring installation. Binary inputs, command outputs, alarms etc.
- Secondary injection of instrument transformer, current and voltage circuits. Phasing and polarity is confirmed, comparison of correct ratios on all electronic equipment including CSDs. Burden checks are normally performed after injections have taken place, as all terminal links and connections are checked and proven correctly so more accurate information can be obtained. As a final check, primary current and voltage injections are performed. It ensures the integrity and correct ratios of the complete installation.
- Provision of a reference measuring voltage to the CSD. This may require outages on adjacent bays within the station. Busbar VT's are not normally used in Ireland. Therefore, a reference voltage selection scheme may have to be implemented in the station. This scheme uses an actual image of the station busbar disconnect and CB arrangement and a secondary reference voltage can be provided from a bay which the CS load is to be connected in parallel with. The complexity of these schemes depends on the substation size, arrangement and technology generation of the station. There can be considerable time taken in commissioning these schemes.

5.11.5 Stage 4: Functional Tests (Dead)

At this stage, the project specific settings can be applied based on information found during the circuit breaker timing tests. These are the:

- Actual CB operating times, from the CSD command contacts to the primary poles (considering intermediate components). Also, it is important to look at the temperature operating characteristic (if these details are known).
- Delay time between the reference or auxiliary contacts and the main contacts of the CB (if required).

A number of 'dead' operations are then performed. These tests are performed using the on-line monitoring tool within the CSD (depending on quality of information) or else external recording equipment, normally relay test equipment with analog measuring capabilities (typically 10 kHz resolution). The following are then confirmed:

- Correct opening/ closing commands are sent to the correct circuit breaker poles.
- Position indication of auxiliary or reference contacts for each circuit breaker pole are correctly measured by the CSD.
- Switching points are as per the applied settings. This is normally done by comparing the circuit breaker auxiliary contacts or in some cases primary contacts change in status, to the predicted times along the measured reference voltage.
- If DC control operating voltage compensation is used, on-line measurements are taken to ensure that correct voltage measurement is being obtained and compensation is being correctly applied to the expected operating times based on the manufacturer's operating curve.
- If temperature compensation is applied, ensure correct temperature measurement in CSD compared to temperature in operating mechanism.
- Typically, 3 operations are performed ensuring the repeatability of each of the above.

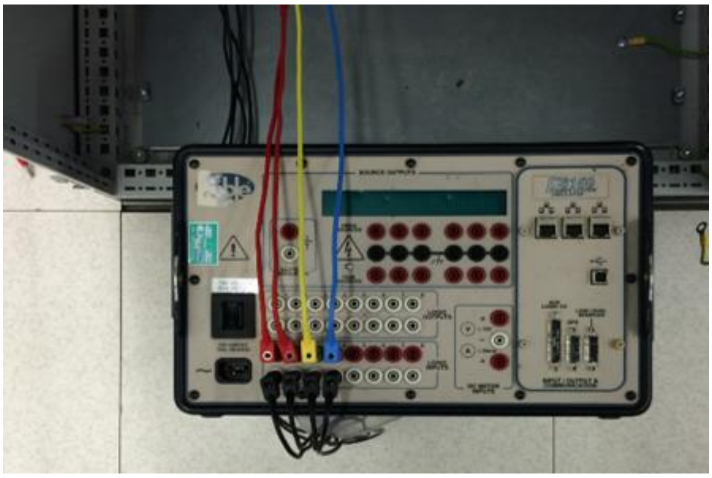


Figure 5.22: External Recording Equipment used: Doble F6150 with 10 kHz Analog Input Measurement Board.

5.11.6 Stage 5: Live Tests

Live testing is the final stage in the commissioning process and strict switching limitations are imposed by the system operator depending on type of the proximities of sensitive customers which will not tolerate any switching transients or voltage fluctuations. Therefore, live testing can only be performed at certain off-peak times dictated by the system operator. This poses greater challenges in commissioning.

Ideally, a number of similar consecutive live controlled switching operations of the load are required to declare the scheme fit for service, but depending on the location this can be difficult, especially where there is a risk to customers' power quality. To overcome this, an additional part of the commissioning stage may involve physically disconnecting the load and then operating the CB under tension using system voltage (without the capacitor bank connected). The voltage onset of each phase is compared with the expected operating point and adjusted if necessary. A minimum of three similar consecutive operations are required to move on to actual on load tests with the capacitor bank connected.

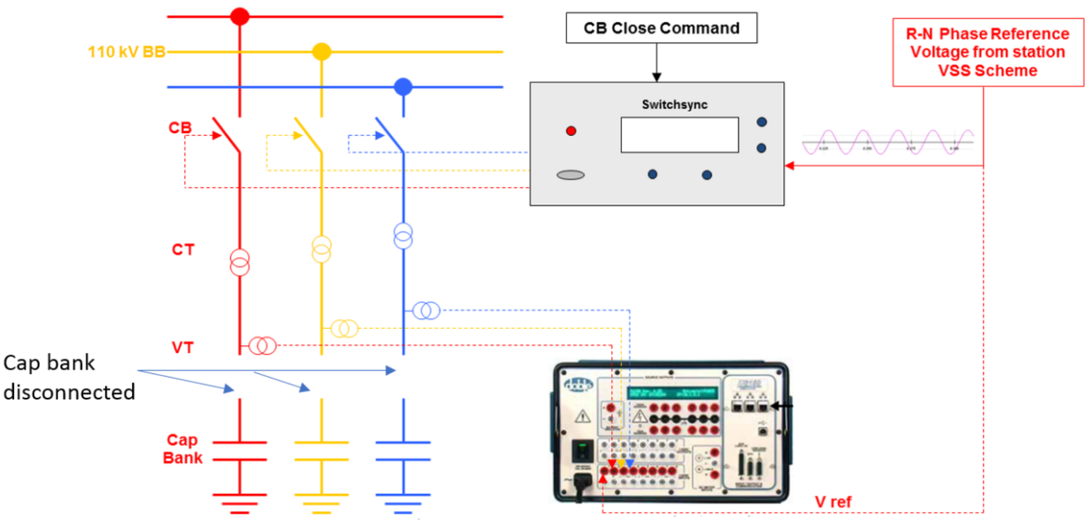


Figure 5.23: Physical Break Between 110 kV System and Capacitor Bank.

Ideally, commissioning should be done with the actual load and measuring load current, but experience has found that rarely adjustment is required afterwards. When the load is reconnected, one switching operation is normally allowed to ensure the correct operation. Subsequent in service switching operations performed are then closely monitored to ensure the correct performance is maintained. Figure 5.24 shows actual recordings of the current and voltage waveforms during CS commissioning tests performed by the author on a 15 MVAr shunt capacitor bank.

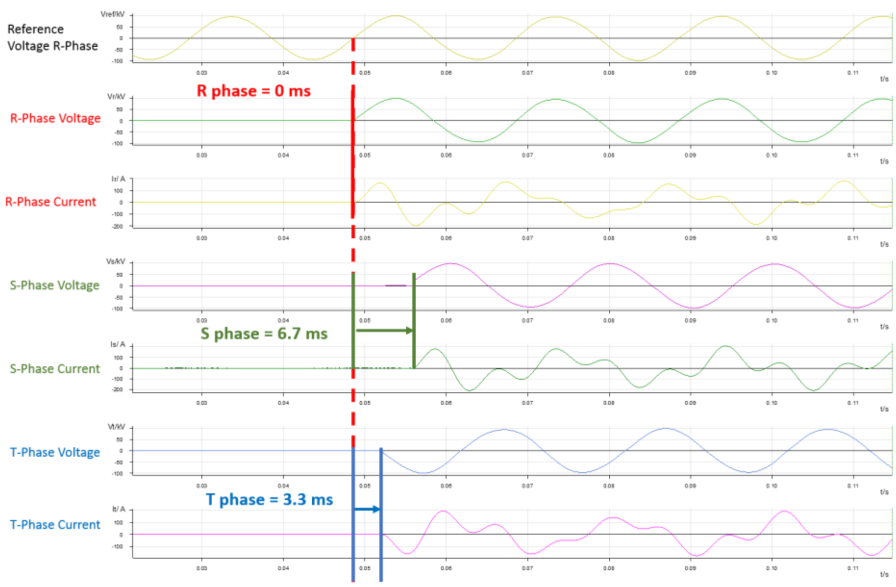


Figure 5.24: CS Commissioning Test Results on a 15 MVAr Shunt Capacitor Bank.

6. Shunt Reactor Switching

Dublin has a strongly meshed cable network with approximately 2 GW of connected generation. At off peak load times particularly at night, there is a considerable voltage rise due to the capacitive effect of lightly loaded cables. To limit the system voltage, the system operator has traditionally applied the following voltage control measures:

- Staggering of on load tap changers on transmission transformers.
- Dispatching leading/lagging reactive power from generators at key points on the network.
- Switching out of cables during low load periods.

In recent years however, economic growth has seen a demand for a more secure and reliable power quality supply from transmission customers. These customers are mainly, major data centre's which serve as a gateway between European and American data centres and specialists in the sensitive manufacturing processes such as microprocessors. These customers are highly susceptible to system voltage variations and switching transients and therefore, voltage quality must be managed to a high degree to service the customers' needs.

Table 6.1: Irish TSO Recommended Voltage Targets

System Nominal	Morning [kV]	Peak Load [kV]	Evening [kV]	Night [kV]
400 kV	404 - 407	405 - 408	399 - 405	395 - 399
220 kV	233 -235	234 - 236	223 - 234	229 - 231
110 kV	112 - 114	113 - 117	112 - 114	110 - 113

Traditionally, several strategic cables on the system were switched out at night in order to limit capacitive voltage rise during low load periods. They were then returned to service in the mornings when the system load increased. However, cable switching has a number of disadvantages:

- Cable switching is similar to switching a shunt capacitor bank. Voltage transients and heavy inrush currents are generated which can lead to damage of plant over time and may cause power quality problems for customers.
- Unavailability of key transmission infrastructure is potentially putting the greater system at risk in the event of losing additional assets as a result of fault.

In order to reduce switching transients and increase system reliability, the practice of switching cable feeders for system voltage control is no longer a practical solution. To ensure a more dependable approach in managing the system voltage, two 220 kV, 50 MVAr separately switched shunt reactors are to be installed at a central location. These shunt reactors are expected to eliminate the practice of cable switching for voltage control and prevent inefficient reactive power absorption from generation plant. It envisaged that the shunt reactors will remove the need for at least one base load generation plant during low load periods.

Figure 6.1: The 220 kV - 50 MVAr Air Core Shunt Reactors.

6.1 Shunt Reactors

Shunt reactors are key components on transmission systems for control of localised system voltage. They limit voltage rise by absorbing excessive system reactive power which is generated by:

- Capacitance of cable networks, particularly in areas of the system where infrastructure is composed of predominantly underground cable. This is a problem in large urban areas, where during the day large amounts of generation is required. However, at off peak times at night, many cables are lightly loaded and can result in voltage to rise.
- The Ferranti effect which causes an over-voltage at the receiving end of long overhead during no load or lightly loaded periods [31].

Similarly, to shunt capacitor banks, shunt reactors are used as a voltage control tool by system operators, so consequently they can be potentially switched in and out multiple times a day depending on the system voltage control requirements.

However, switching of shunt reactors has long being recognised as problematic, unlike normal loads which have a power factor close to unity, shunt reactors have a phase angle difference of 90° between the voltage and current. Therefore, switching presents difficulties for both system components and the reactor circuit breaker. Problems occur during both the energisation and de-energisation process of shunt reactors, where:

- During energisation of the shunt reactor, long DC offsets occur in the current waveform which may cause instrument and power transformer saturation.
- During de-energisation, steep high frequency over-voltages across the shunt reactor windings may be produced.

As these shunt reactors maybe switched frequently by system operators (typically twice daily), mitigations measures need to be employed to prevent any potential impacts to the transmission system or damage to plant.

6.2 Energisation of Shunt Reactors

Due to the high X/R ratio of shunt reactors, unsymmetrical slow decaying DC offsets may be generated on the energising current waveform. These DC offsets have the potential of lasting up to 1.5 seconds and may cause current transformer (CT) saturation of the local reactor bay CT's or CT's on adjacent bays which provide the energisation current path. The most severe DC offsets occurs when the reactor is energised at the zero crossing of the voltage waveform, as this is when the current is at its peak.

The long DC offset decay time in the reactors current can cause the flux in the CT core to accumulate leaving the CT with significant residual flux by the time the DC component decays [32]. Following consecutive switching operations, the residual flux can accumulate in the same direction and can eventually cause CT saturation. This results in problems for differential protection, where there is an unbalanced current measurement, resulting in potential false operation of protection systems. Figure 6.2 shows energising current waveforms observed by the author during commissioning of a 220 kV- 50 MVAr shunt reactor. High DC offsets can be seen in both R and T current waveforms.

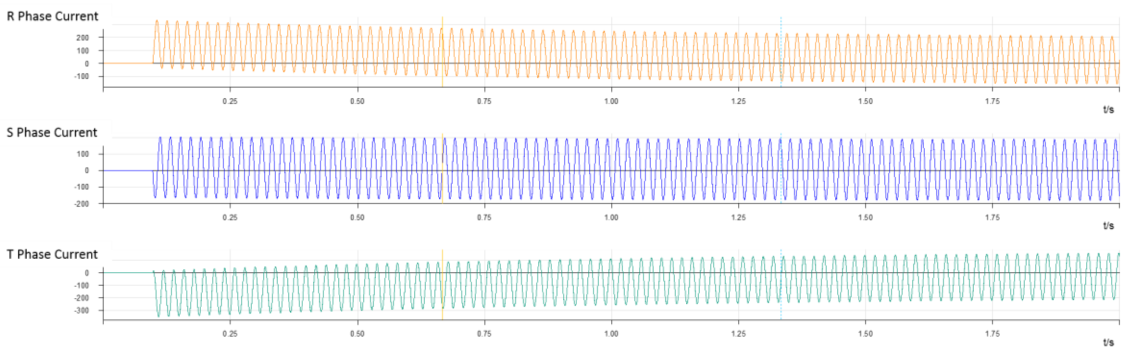


Figure 6.2: Shunt Reactor Energisation Current Waveforms. DC Offsets can be Observed on R and T Phases.

6.3 De-energisation of Shunt Reactors

Modern SF_6 circuit breakers are designed to break short circuit currents in the order of thousands of amperes. This is achieved by a combination of high speed contact separation, excellent dynamic insulating properties and arc quenching abilities which is achieved by forcing SF_6 gas to extinguish the arc generated during current interruption. While the CB must be capable of disconnecting the shunt reactor quickly in the event of extreme fault conditions, it cannot differentiate between current levels of normal load switching and faults. Consequently, the full arc extinction potential of the CB is released against weaker switching arcs. This is a particular problem when de-energising the shunt reactors as the CBs full arc extinction potential may cause current chopping. Current chopping is when the load current flowing through the arc, is prematurely broken and forced to zero prior to the natural current zero [5]. Current chopping prevents the energy trapped in the electro-magnetic field of the reactors winding from being transferred naturally back to its source. Instead this energy oscillates with the electro static field of the stray capacitances of the reactor itself and bay equipment such as windings, support insulators and connecting leads.

The resultant energy of the load following disconnection, is dependent on both the load circuit inductance and capacitance, and the voltage and current at which chopping occurred. It can be calculated using the following equation:

$$E_{Load} = \frac{1}{2} C_L \widehat{U}^2 + \frac{1}{2} L_L {i_{ch}}^2 \tag{6.1}$$

Where:

- E_{Load} = Energy trapped in the load circuit.
- C_L = Capacitance of load circuit (F).
- $\widehat{U}$ = Peak of chopped system voltage (kV).
- L_L = Inductance of load circuit (H).
- i_{ch} = Current level at chopping instant (A).

The high di/dt associated with current chopping results in high induced voltage in the reactor circuit. This can cause the CB transient recovery voltage, to exceed the dielectric strength of the opening CB resulting in re-ignition. If breakdown occurs again, this results in a situation known as voltage escalation, where the amplitude of the transient recovery voltage can be further increased in the load circuit by the accumulation of energy due to repeated re-ignitions (>3 times rated voltage) [13]. Re-ignitions will generate high frequency transients typically hundreds of kHz in both reactor voltage and current.

Uncontrolled release of this energy may have detrimental effects for the installed switchgear and other components over time. These include:

- Damage to the CB, perforations on interrupter nozzles.
- The high frequency voltage will be unevenly distributed across the reactor windings, with the highest stress on the initial turns and may lead to puncture of the winding insulation.

6.4 Calculation of Transient Over-voltages during De-energisation

To study the potential over voltage phenomenon that occurs at different levels of current chopping when de-energising the shunt reactor, the following simplified single-phase circuit can be used.

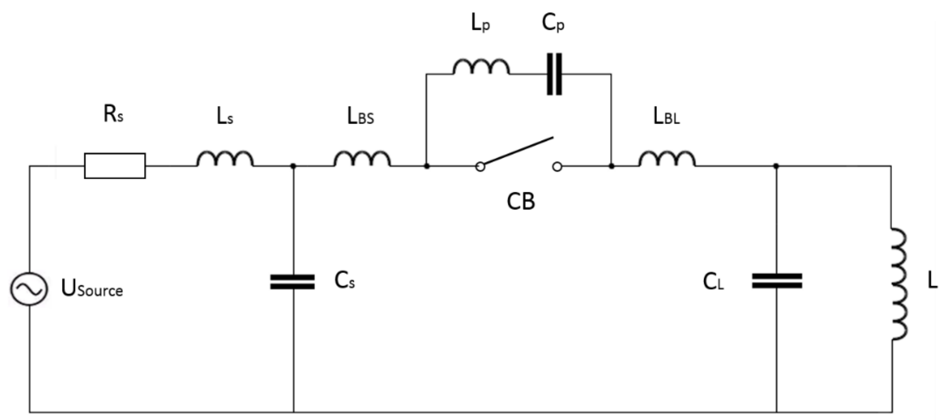


Figure 6.3: Simplified Single-Phase Representation of the Shunt Reactor Circuit.

Where:

- U_S = RMS source voltage (Ph – E).
- R_S = Source resistance.
- L_S = Source reactance.
- C_s = Source side parallel capacitance.
- L_{BS} = Inductance of the source side busbars.

- L_{BL} = Inductance of the load side busbars.
- L_p = Internal inductance of the CB.
- C_p = Internal capacitance of the CB.
- C_L = Source side parallel capacitance.
- L = Reactor inductance.

6.4.1 De-energisation: Load Voltage Characteristic with Re-ignition

The de-energisation voltage waveform in Figure 6.4 shows the important over voltage characteristics which must be considered for shunt reactor de-energisation:

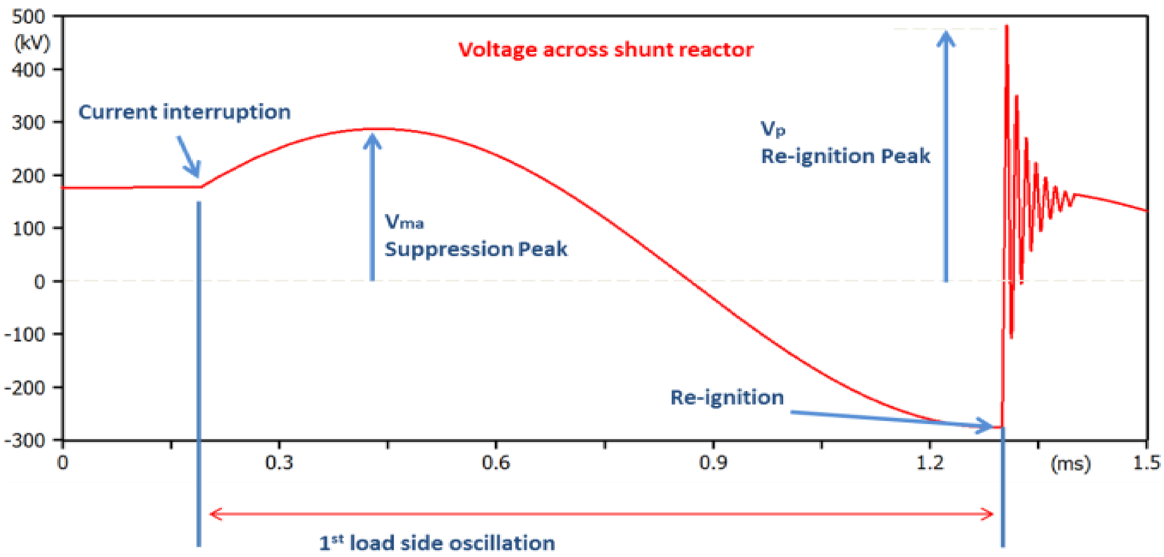


Figure 6.4: Load Voltage Following Interruption of an Inductive Load.

6.4.2 The Suppression Peak Over-voltage V_{ma}

This is the first peak of the oscillation and has the same polarity as the source voltage at the time of interruption [33]. The over-voltage (k_a in pu of V_o) can be calculated as follows:

$$k_a = \frac{V_{ma}}{V_o} = \sqrt{1 + \left(\frac{i_{ch}}{V_o}\right)\frac{L}{C_L}} \tag{6.2}$$

Where:

- i_{ch} = Current level at chopping instant.

- V_{ma} = Suppression peak over-voltage to ground.
- V_o = Peak voltage across the SR at interruption.
- L = The reactor inductance.
- C_L = Effective load side capacitance to ground.

6.4.3 The recovery voltage V_{rv}

This is the voltage across the opening circuit breaker contact. If this voltage exceeds the dielectric strength of the parting CB contacts, re-ignition will occur. The recovery voltage can be calculated (k_{rv} in pu of V_o) using the following equation:

$$k_{rv} = \frac{V_{rv}}{V_o} = 1 + k_a \tag{6.3}$$

6.4.4 Frequency of 1st Load Side oscillation f_r

This is the frequency of the load side voltage oscillation after the first interruption. The oscillation frequency is based on the load side capacitance and reactor inductance and can be calculated as follows:

$$f_r = \frac{1}{2\pi\sqrt{LC_L}} \tag{6.4}$$

Where:

- $L =$ Load inductance (H).
- $C_L =$ Load capacitance (F).

6.4.5 The Re-ignition Peak Over-voltage V_p

The peak value of the high frequency over voltage that occurs after re-ignition can be calculated (k_p in pu of V_o) using the following equation:

$$k_p = \frac{V_p}{V_o} = 1+\beta(1+k_a) \quad (6.5)$$

Where:

- β = Damping factor (can assumed to be = 0.5) [33].

6.5 Mitigation Measures

6.5.1 Metal Oxide Surge Arrestors

In Ireland shunt reactors and their switching CBs are always protected by surge arresters. It is normal to install surge arrestors as close possible to both the circuit breaker and shunt reactor for maximum protection. They are very important in limiting both the chopping over voltages and over voltages from CB re-ignitions. When determining the rating of a surge arrestor, a protective margin is recommended between the maximum protective level of the arrester and the insulation level of the reactor [7].

However, while surge arresters will limit over voltages to earth to acceptable levels, they cannot reduce the steepness of the voltage swings associated with re-ignitions. Also, they are only a method of protecting equipment following a transient over-voltage event, they do not prevent it in the first instance.

6.5.2 Controlled Switching

Controlled switching is an effective solution for eliminating both DC offsets in the energisation current waveform and for controlling de-energisation so as to avoid the re-ignition zone in the voltage waveform. At the moment for shunt reactor CS schemes in Ireland, the author has found that CS has been implemented for de-energising only.

6.5.2.1 Controlled Closing Target for Energising Shunt Reactors

In order to avoid any potential DC offsets in the energising current waveform, the shunt reactor should be energised when the current is at minimum. As the current lags the voltage by 90 electrical degrees, this is achieved by closing each pole of the CB at voltage maximum.

One of the main advantages of shunt reactors, is that the iron core is normally gapped for oil immersed type or the shunt reactors can be of air core construction. Therefore, there is no significant remnant flux in the core to be considered when energising. This implies that unlike power transformers, the CB close target point at each pole will always be the same. However, when determining the optimum closing point, factors affecting the CB should be considered and these include:

- Rate of decrease of the dielectric strength (RDDS) of the CB. When the RDDS of the circuit breaker is less than the system voltage, breakdown will occur before the CB mechanical contacts touch.
- The consistency of the mechanical operating times of the CB mechanism must be considered (see Figure 6.5).

6.5.2.2 Controlled De-Energisation of Shunt Reactors

To prevent the occurrence of current chopping when de-energising the shunt reactor, the goal of the CSD is to avoid the re-ignition window of the CB. It also eliminates short arcing times so that the CB interruption time is controlled in order to allow the switching arc generated to conduct until its natural zero current crossing. This ensures that the RRDS of the CB, exceeds the transient over-voltage across the parting circuit breaker contacts, thus preventing re-ignitions.

The MAT and the re-ignition window of the CB is obtained from CB manufacturer type tests performed according to IEC 62271-110.

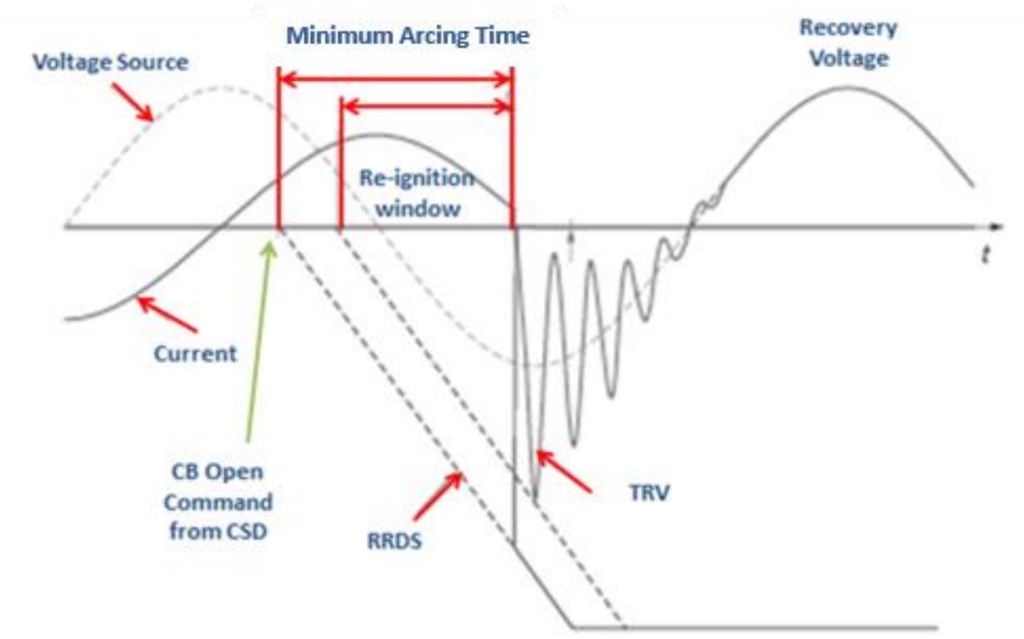


Figure 6.5: Successful De-energisation of a Shunt Reactor

6.5.3 IEC 62271-110: Type Tests to Determine CBs Re-ignition Period and MAT [7]

6.5.3.1 Purpose of Test

Manufacturers perform these type tests on their CBs to determine the current chopping behaviour and ability to withstand the TRV during interruption. These tests can also be used to determine the re-ignition free window of the CB for consideration in controlled switching applications. The author has found that these results are not readily available from most manufacturers.

6.5.3.2 Test Method

There are four scenarios in which the CB will undergo. The test setup will be arranged as per circuit diagram in Figure 6.6. For a 220 kV shunt reactor switching application, there are two load duties which are considered:

- Upper load current of: 315 A (± 20 %).
- Lower load currents of: 100 A (± 20 %).

The load reactance is adjusted to achieve these currents. The lower the current the more onerous the switching duty is for the circuit-breaker to handle. The following measurements are made in the circuit:

- Supply side voltage (Ph – E).
- Voltage across CB terminals.
- Current through CB.
- Load side voltage (Ph – E).

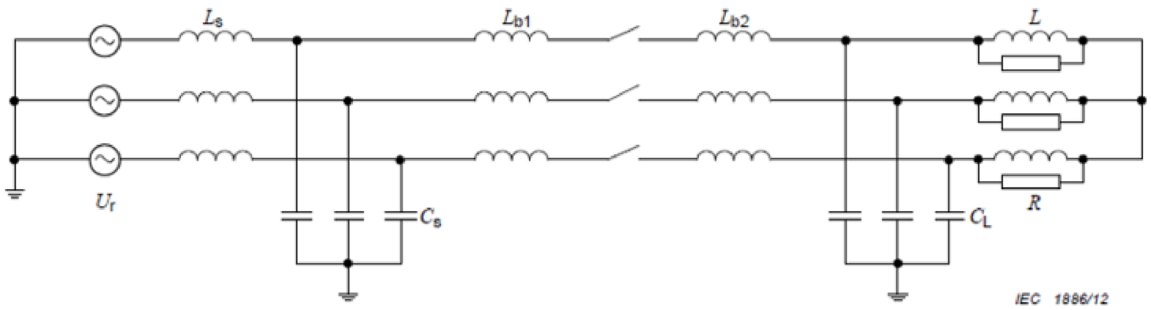


Figure 6.6: Test Circuit Set Up

Where:

- U_r = Voltage source.
- L_s = Source inductance.
- L_{b1}, L_{b2} = Inductance of busbar and conductors.
- L = Reactor inductance.
- C_s = Source side capacitance.
- C_L = Load side capacitance.
- R = Representation of load losses.

6.5.3.3 Test Duties 1 &2

The CB insulating medium is at rated insulating and interruption pressure for the test. Twenty CB interruption operations are then performed at the upper load current and then at lower load current. The CB interruption point for each of the 20 operations is adjusted by 9 electrical degrees on the voltage waveform. So, the CB interrupts the load over the entire sweep of the voltage waveform half cycle.

6.5.3.4 Test Duty 3

Again, with the CB insulating medium at rated insulating and interruption pressure, this time only the lower load current limit is considered for single phase operation.

This time eighteen CB interruptions are performed either:

1. Around the arc duration at which pre-strike occurred:
    a. Six breaking operations at the instant where the highest breakdown voltage occurred.
    b. Six breaking operations, 9 electrical degrees before and after the instant where the highest breakdown voltage occurred.
2. If no pre-strike occurred from test duty 2, then tests must be performed around the region where the shortest arcing time occurred.
    a. Six breaking operations around the point where the shortest arcing time occurred.
    b. Six breaking operations, 9 electrical degrees before and after the instant where the shortest arcing time occurred.

6.5.3.5 Test Duty 4

This time testing is performed with the CB insulating medium at its minimum insulating and interruption pressure. This test is only performed with the lower load current with ten CB interruptions at 18 electrical degree increments across a sweep of the voltage waveform.

6.6 EMTP-ATP Modelling of Shunt Reactor Switching Operations

The following simulations were performed based on data from a 220 kV, 50 MVAr shunt reactor installation in the East of Ireland. The shunt reactor is of air core construction; therefore, no core magnetic flux needs to be considered for the simulations.

6.6.1 Simulation Model

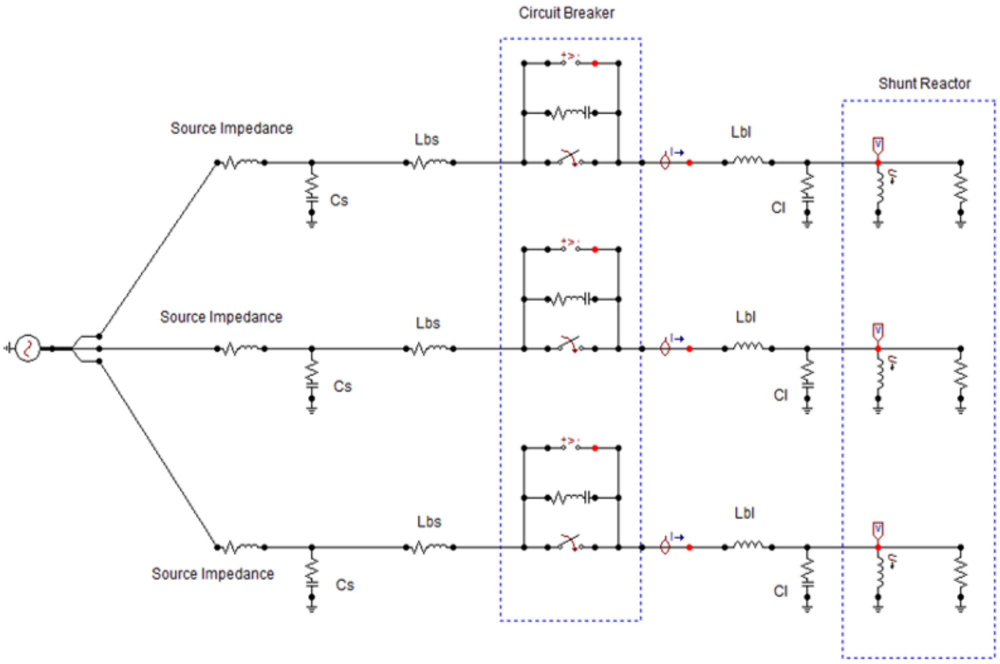


Figure 6.7: 220 kV - 50 MVAr Shunt Reactor Model.

6.6.1.1 Model Data

- Source line to line voltage: *220 kV.*
- Thevenin equivalent source impedance: $R = 2.86\ \Omega$, $X_L = 42.5\ \Omega$.
- Source side capacitance: $C_s = 0.5\ \mu F$.
- Load side capacitance: $C_L = 23.8\ nF$.
- Source side busbar inductance: $L_{BS} = 0.2\ mH$.
- Load side busbar inductance: $L_{BL} = 9\ \mu H$.
- Circuit breaker capacitance: $C_{CB} = 200\ pH$.
- Circuit breaker inductance: $L_{CB} = 1\ \mu H$.
- Shunt reactor inductance: $L_{SR} = 3081\ H$.

6.6.2 Simulation Results for Shunt Reactor Energisation

6.6.2.1 Shunt Reactor Energisation with No Mitigation Measures

In this simulation the CB is set up as a single mechanism operating the 3 circuit breaker poles at the same time. Energisation takes place at the peak of the R phase system voltage wave form.

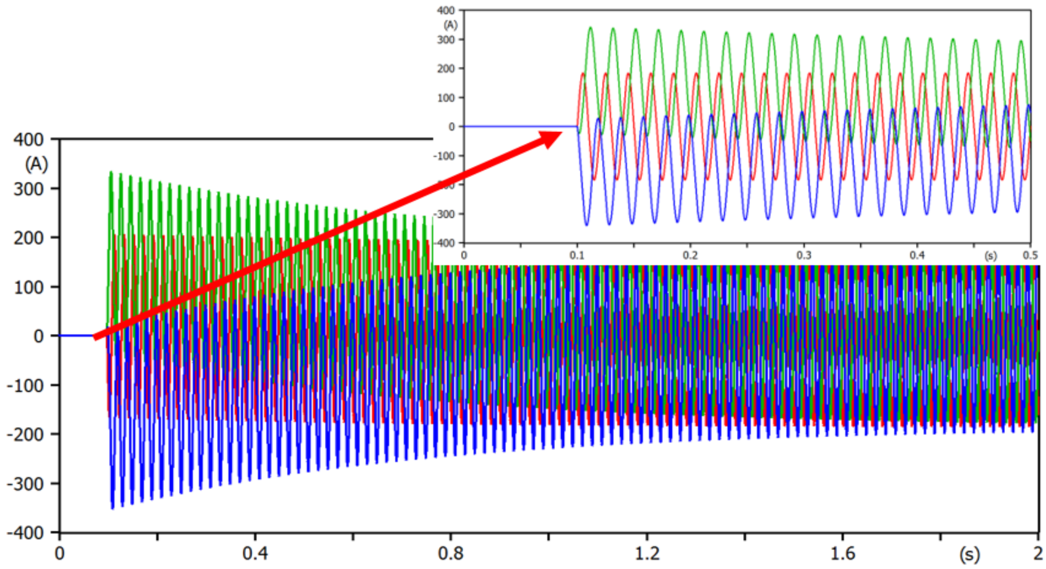


Figure 6.8: Energisation Currents at Zero at Peak of R Phase Current Waveform.

It can be seen from Figure 6.8, that a slow decaying DC offset is produced in the current waveform (in the region of 2 seconds).

6.6.2.2 Shunt Reactor Energisation with Controlled Switching

In this simulation, CS is applied to the shunt reactor CB and the CB has an individual mechanism per pole. The controlled switching strategy employed here is to energise each phase at system voltage peak. An RDDS slope target at the voltage peak was assumed for each phase and the impacts of mechanical scatter on the current waveform were considered minor, so simulation was only performed at peak voltage.

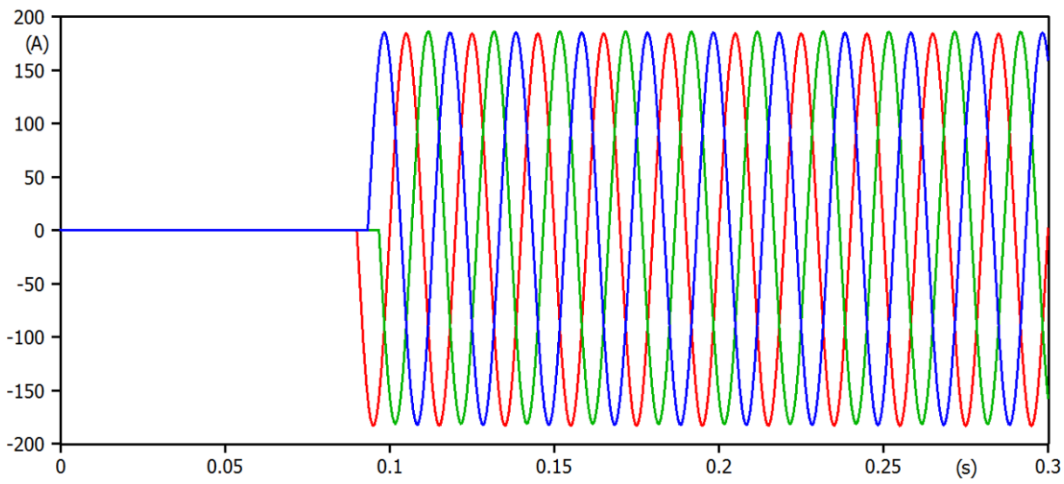


Figure 6.9: Energisation Current Waveforms when Energised at Zero Crossing of Current Waveform.

It can be seen from the Figure 6.9 that CS eliminates the occurrence of any DC offset in the energising current waveform.

6.6.3 Simulation Results for Shunt Reactor De-energisation

The purpose of these simulations is to analyse the potential over voltages that the switching CB and shunt reactor itself has to endure during de-energising. Various levels of current chopping are simulated and the resultant waveforms across the shunt reactor and CB are analysed. In practice the impacts of mechanical scatter is usually considered less for opening times and with CS the CB re-ignition window can easily be avoided, therefore simulations were only performed at the intended targets.

6.6.3.1 Shunt Reactor De-energisation using Mayr Arc Model [9]

In practice, the author has found that CB arc modelling is usually not performed, as the main goal of the simulations is to verify the chopping over voltages, both the shunt reactor and CB have to handle to avoid re-ignitions. Accurate CB arc model data is very difficult to obtain, as its characteristics greatly differ between CB manufacturer and CB technology. Realistically, it can only be accurately obtained in a HV testing laboratory.

The purpose of this simulation is to demonstrate how the Mayr black box arc model can be applied to simulate current chopping. The arcing values used in this simulation are idealised. The system model in Figure 6.7 was modified to place a controlled non-linear resistance across the switching CB contacts to simulate arcing resistance. The non-linear resistance is controlled using the Mayr arc equation which is performed in EMTP-ATP control system TACS. The following values were assumed for the Mayr equation and the shunt reactor current is set to chop at around 15 A:

- Arc time constant τ = 0.5 µs.
- Constant arc power loss N_0 = 10 kW.

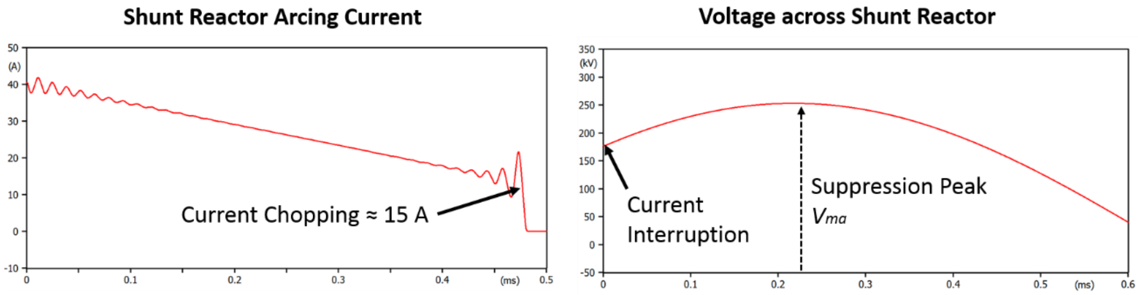


Figure 6.10: Shunt Reactor Chopping Current and Voltage.

In Figure 6.10 it can be seen that the current is chopped around 15 A and this resulted in a suppression peak voltage V_{ma} of approximately 251 kV.

6.6.3.2 Shunt Reactor De-energisation at 10 A Current Chopping

The Mayr arc model is not applied in this simulation, instead the author used an ideal switch to prematurely chop the current at 10 A, on the negative slope of current waveform before the zero crossing.

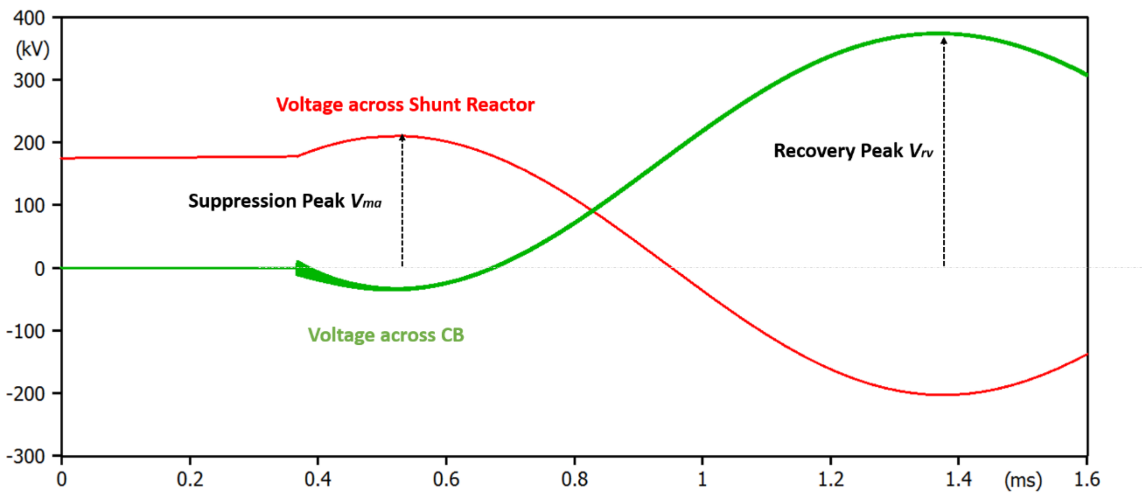


Figure 6.11: Voltage across the CB Shunt Reactor following 10 A Current Chopping.

In Figure 6.11 it can be seen that interruption of the current at 10 A before its zero crossing, results in a suppression peak voltage V_{ma} = 210 kV with the max recovery peak voltage V_{rv} across the CB of 375 kV.

6.6.3.3 Shunt Reactor De-energisation at 20 A Current Chopping

In this simulation, current is prematurely chopped at 20 A in the negative slope of current waveform before the zero crossing. This time the author simulates a re-ignition at the peak of the CB recovery voltage using a separate ideal switch in parallel to the main CB, arc resistance is neglected.

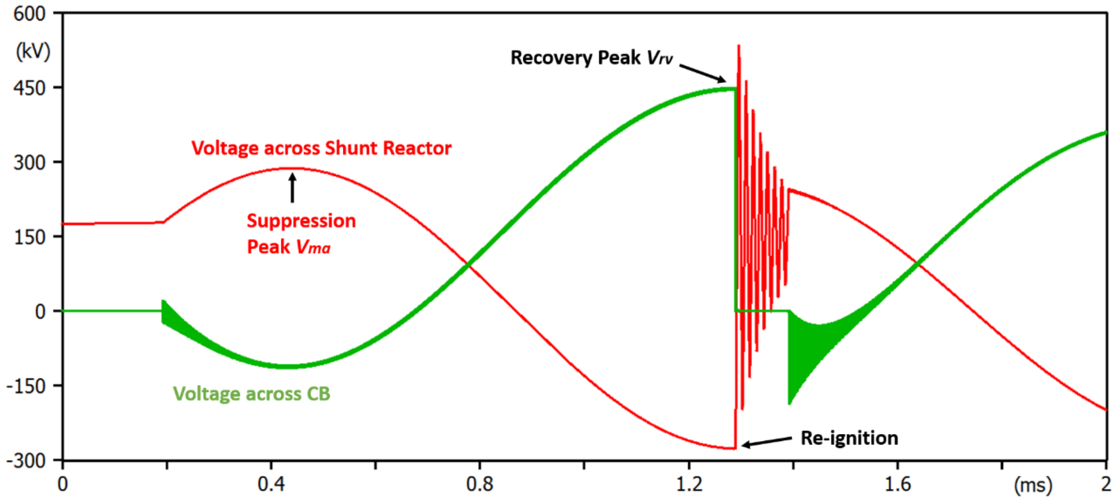


Figure 6.12: Re-ignition at Peak of Recovery Voltage.

It can be seen from the simulation results waveform in Figure 6.12, that suppression peak across the shunt reactor V_{ma} increased to 287 kV, while re-ignition occurred at the recovery peak voltage V_{rv} across the circuit breaker occurred at 488 kV. A peak re-ignition voltage of 533 kV was observed.

6.6.3.4 Shunt Reactor De-energisation with No Current Chopping

In this simulation no current chopping is simulated and the current is allowed to continue to its natural zero crossing.

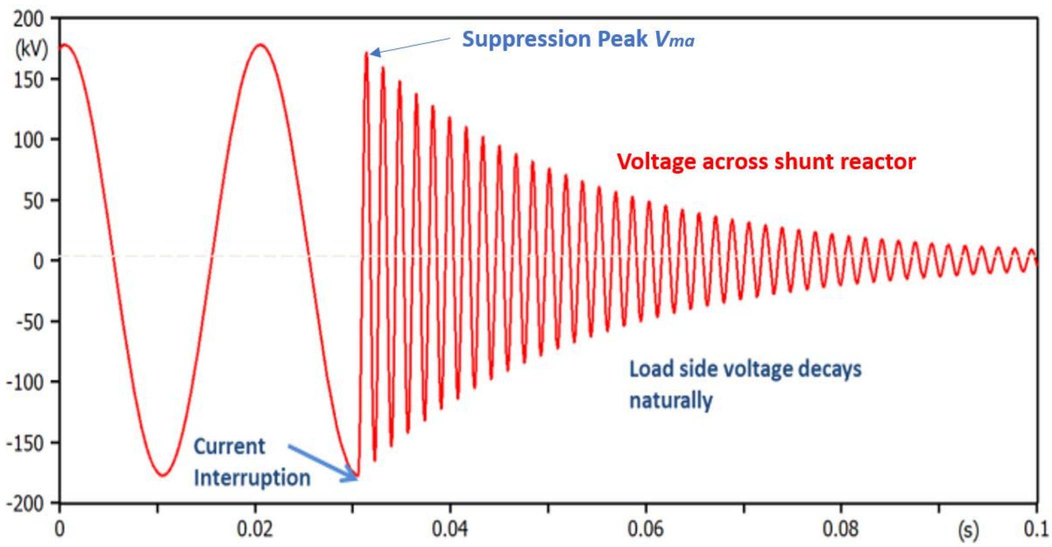


Figure 6.13: Voltage across Shunt Reactor following Interruption at Zero current.

From waveforms observed in Figure 6.13, it can be seen that interruption of the current at its zero-crossing resulted in a manageable suppression peak voltage V_{ma} = 177 kV, with a maximum recovery peak voltage V_{rv} across the CB of 343 kV. It can be seen that load side oscillating voltage quickly decays in a natural oscillatory ring off.

6.7 Irish Experience of Commissioning of Transmission Shunt Reactors

The following results are from a CS project which was conducted by the author in association with the CSD manufacturer for the commissioning controlled de-energisation of a 220 kV – 50 MVAr air core shunt reactor.

6.7.1 Scope of Commissioning

Controlled de-energisation of the shunt reactor using a CSD, was the specified operation by the transmission system operator for this project.

The minimum arcing time specified by the manufacturer for the load, was 7.5 ms. Taking into account that the mechanical repeatability of the CB operating mechanism is typically 0.5 ms, a safety margin of between 0.5 ms to 1 ms was incorporated to give a target for the minimum arcing time of between 8 ms to 8.5 ms for consistent operation.

Design review, point to point wiring checks, instrument transformer injections and primary plant fingerprinting tests have all being completed prior to this stage in the commissioning process.

6.7.2 Influencing and Reference Quantities

High voltage circuit breakers are crude mechanical devices, and to be suitable for de-energising heavy inductive loads they must be controlled to within 1 ms of the expected operating times. Therefore, many important external influencing characteristics and reference quantities must be considered:

6.7.2.1 Determination of Actual CB Position

To determine the actual position of each primary pole, Hall Effect sensors with actuating magnets are fitted to each pole mechanism to allow the CSD to accurately determine the actual pole operating times.

Timing test were performed during CB operations, to determine the error between each reference contact and CB pole. This error value was programmed into CSD to compensate for any timing errors.

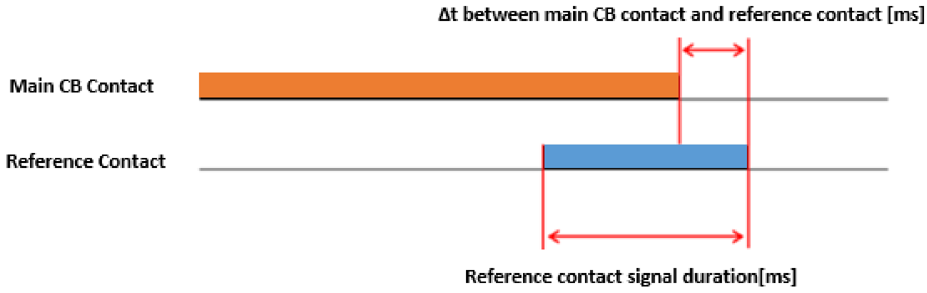


Figure 6.14: CB Main Contact Evaluation Time using a Reference Contact.

6.7.2.2 Ambient Temperature

Variation in the ambient temperature from 20°C can influence the viscosity of lubricants causing friction between sliding or moving parts within the CB mechanism which influences the CB operating time. The circuit breaker manufacturer specified that the CB operates 3% slower at -30°C and 4% slower at 55°C, best performance is at the nominal operating temperature 20°C. The actual temperature is measured via temperature sensor within the central CB mechanism box and is fed back to the CSD for compensation of opening times.

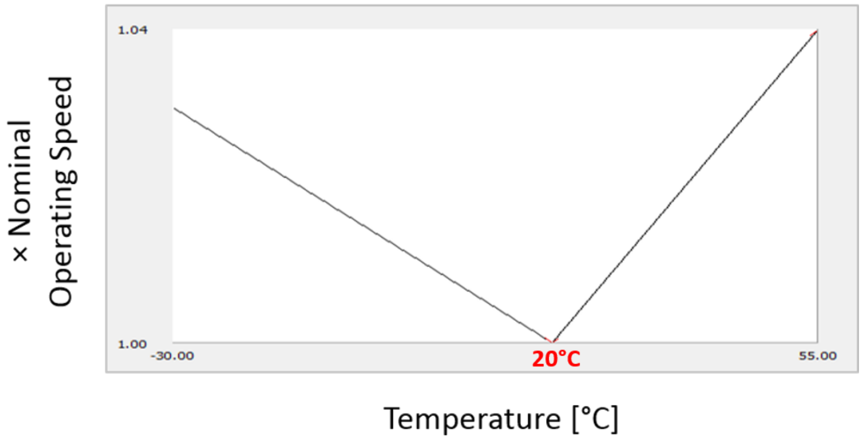


Figure 6.15: Influence of CB Operating Time owing to Mechanism Temperature

6.7.2.3 Operating Control Voltage Compensation

Opening and closing coil control voltage affects the operating speed of the plunger used to actuate the spring mechanism. Increasing the control voltage increases the operating speed of the plunger, while reducing the control voltage slows it down. The nominal control voltage for the CB control coils is 220 V DC. The manufacturer specifies that for every 1V deviation from the nominal operating voltage, causes a 0.1 ms change in operating speed of the opening coil.

6.7.3 Expected Results

Considering external compensation and the repeatability of the CB operating mechanism:

- Measured temperature of the centralised CB operating mechanism box was 20°C. Therefore, there is no additional compensation for temperature.
- The actual measured DC control voltage is 237 V, which results in the speed of the operating mechanism increasing by 1.7 ms.
- There is a possible deviation of +/- 0.5 ms due to mechanical scatter in operating times of the CB spring mechanism.

Therefore, taking into account these factors and commissioning results from the CB timing assessments. Table 6.2 shows the predicted opening times for each CB pole.

Table 6.2: Expected Mechanical Opening Times for each Pole

Phase	- 0.5 ms	Nominal	+ 0.5 ms
R	35.8 ms	36.3 ms	36.8 ms
S	34.9 ms	35.4 ms	35.9 ms
T	35.0 ms	35.5 ms	36.0 ms

6.7.4 On Load Tests

Testing must be performed on load, using actual system voltage to guarantee correct performance of the controlled switching device. To ensure that there is consistent operation of the controlled switching scheme, a minimum of three consecutive recordings within the expected operating periods must be observed before the CSD can be declared fit for service.

It is also important to ensure that:

- No re-ignitions are observed during switching.
- Actual mechanical separation of the CB contacts does not occur within the minimum arcing period.
- There is an adequate safety margin before the minimum arcing time (approx. 1 ms).
- The oscillograph function within the CSD was used to capture voltage and current waveforms.

6.7.5 Results from on Load Tests

Table 6.3 shows the actual recorded opening times from the last three tests. It can be seen that the actual times are well within the expected values derived in Table 6.2 including the mechanical scatter deviation.

Table 6.3: Actual Opening Times Obtained from last 3 Switching Attempts

Phase	Last Operation	2nd Last Operation	3rd Last Operation
R	36.4 ms	36.4 ms	36.4 ms
S	35.5 ms	35.5 ms	35.5 ms
T	35.6 ms	35.6 ms	35.6 ms

It can be seen from Figure 6.16, that interruption of R phase current takes place at its natural zero crossing. Similar results were observed for currents in the other two phases and no additional current spikes were observed following interruption, indicating that no re-ignitions have occurred.

To observe the arcing duration from the actual commissioning results in Figure 6.16 the arcing time can be taken as the difference between the mechanical opening time, which is from R phase open command to when the CB contacts mechanically separate (values obtained from Table 6.3), to the end of current flow when the arc is extinguished. The result obtained during testing with a mechanical opening time of 36.4 ms was found to be 8.1 ms and is within the expected time of 8 – 8.5 ms window defined in the scope of commissioning.

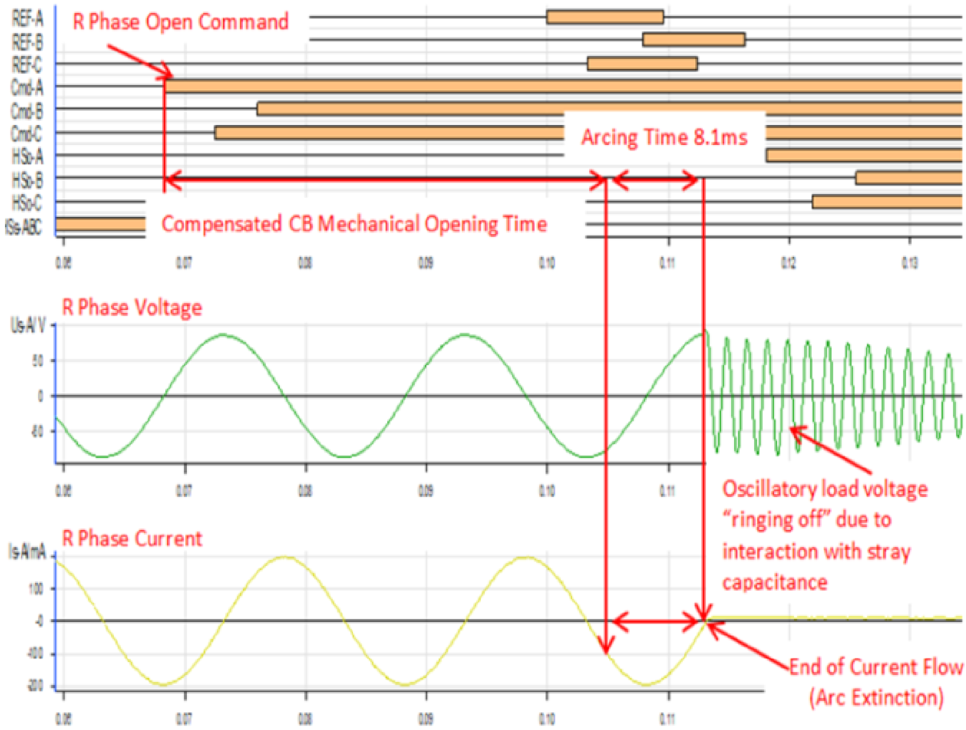


Figure 6.16: Measured Opening Times for R Phase CB Pole.

Figure 6.17 shows the voltages across the shunt reactor at de-energisation. The desired decay of voltages is observed in the actual recorded voltages. No excessive over voltages can be seen here.

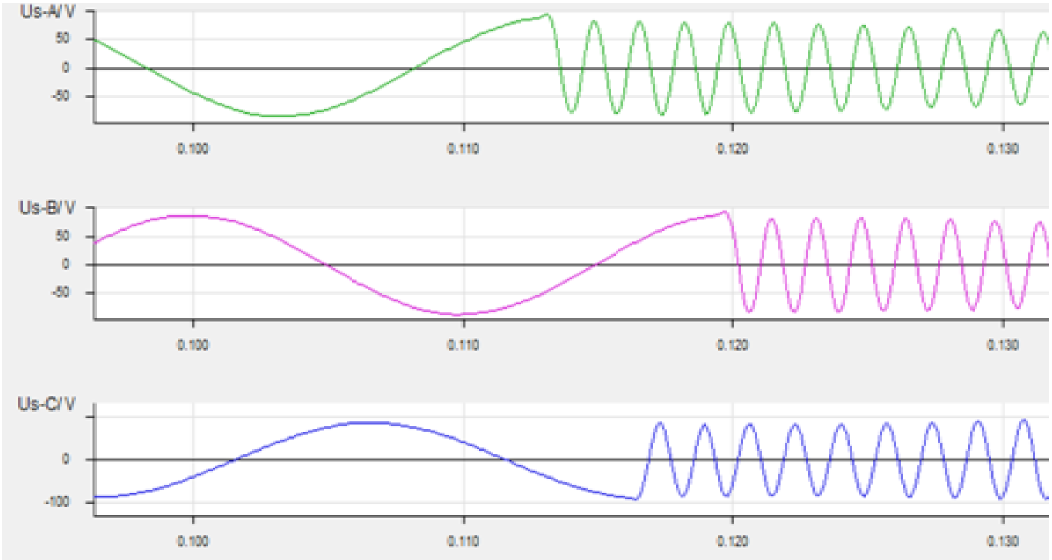


Figure 6.17: Successful De-energisation of R-S-T Phase Voltage Waveforms for the Shunt Reactor

7. Unloaded Power Transformer Switching

7.1 Issues with Unloaded Power Transformer Switching

Power transformers are the single most expensive items in transmission substations, in comparison to reactive compensation plant they are not as frequently switched. However, energising of power transformers may produce high frequency transient inrush current which may be many times the transformer rated load and in the region of 5 – 8 times rated current for large transformers, and may last for a few cycles or up to a few seconds depending on source resistance and transformer losses. The potential impacts of these energisation currents are:

- Electromechanical stresses to transformer windings which may lead to deterioration in winding insulation and mechanical support structure.
- Localised voltage depression which impacts on customers.
- 2^{nd} and 5^{th} harmonic currents which impact on wider system power quality.
- False protection operation, especially transformer differential protection which may lead to plant outage.

To eliminate these transient inrush currents, the main mitigation methods which can be employed are energisation through pre-insertion resistors or controlled switching.

7.1.1 Pre-insertion Resistors

This is an effective method of reducing inrush current during energisation, however the cost of specialised CB or second bypass CB make this solution prohibitive. Also, physical space for additional equipment may not be available in substations in retrofit applications.

7.1.2 Controlled Switching

Controlled switching of unloaded power transformers is becoming increasingly more popular worldwide as its benefits are slowly being realised. Also, in comparison to pre-insertion resistors, CS is a more economical solution.

Unloaded power transformer switching is a relatively new application for CS technology in Ireland. It was introduced for the energisation of larger transmission power transformers in order to prevent depression in system voltage levels below recommended limits during switching (see Table 7.1). This is a particular issue at weaker locations of the network, especially at windfarm transmission interfaces. As of 2018 controlled switching has been implemented in two transformer installations.

Table 7.1: Irish TSO Voltage Quality Limits [34]

System Event	Limits
Step change event (transformer OLTC operation, shunt reactor, shunt reactor, switching).	+/- 3 %
Temporary voltage depression (50 ms – 3 secs)	- 5 % for 3 seconds
Transient voltage depression (< 50 ms)	- 10 %

7.2 Switching of Unloaded Power Transformers

Transformer inrush current is greatly dependent on the energisation instant of the voltage waveform, as this influences the prospective flux. The greater the difference in prospective flux to that present in the core, then the higher the current inrush that will be drawn when flux enters the saturation region of the transformer core material. During switching, the virtual applied flux (prospective) corresponds to the integral of the applied voltage and therefore leads the voltage waveform by 90 electrical degrees, see Equation (7.1.

$$\Phi = \int U.dt \tag{7.1}$$

Where:

- Φ = Core magnetising flux.
- U = Instantaneous voltage.

7.2.1 The Optimum Energisation Instant

The optimum energising instant corresponds to the positive voltage peak. This is the instance the prospective core flux is zero assuming no flux is present in the core. In this situation, switching at voltage peak causes flux to increase from zero to the positive peak following a steady-state sinusoidal pattern and in this idealised scenario there will be no transient inrush current.

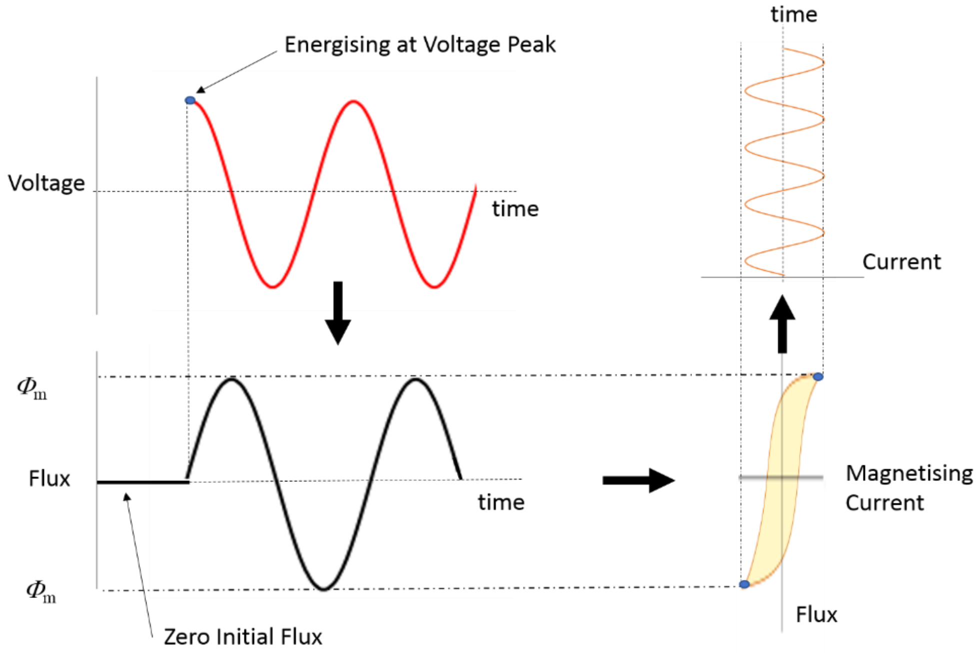


Figure 7.1: Inrush Current at Peak Voltage.

7.2.2 The Worst-Case Energisation Instant

Conversely the worst case corresponds to transformer energisation at voltage zero. In this instant the flux rises from zero to a twice the normal peak flux of $\Phi_{m,}$ significant inrush current can be observed in this situation (typically 5 to 8 times rated current).

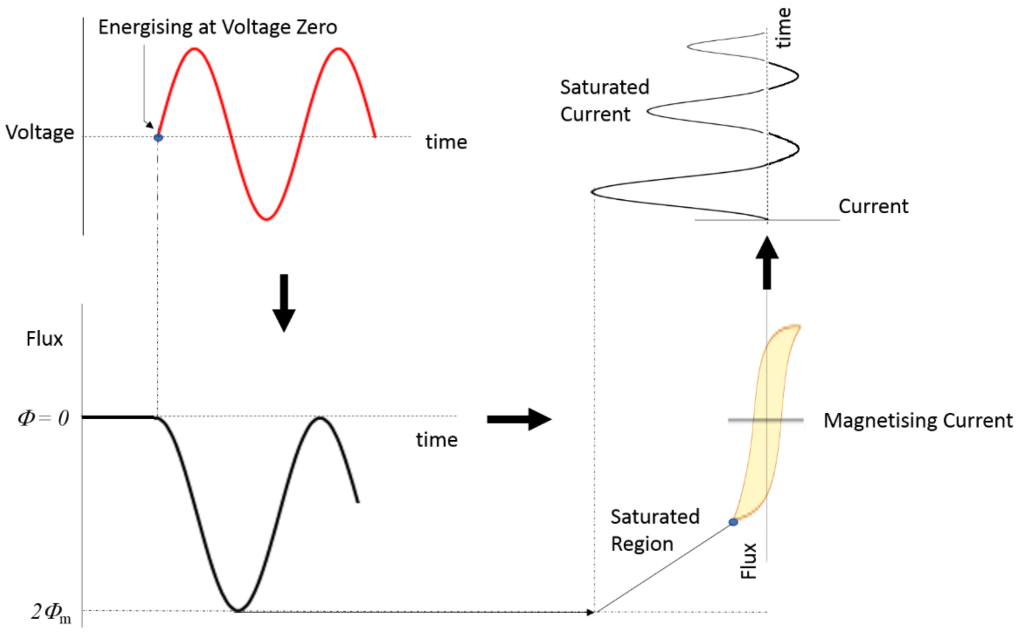


Figure 7.2: Inrush Current at Zero Voltage.

7.2.3 Impacts of Remnant flux

The inrush current not only depends on the prospective flux at energisation, which is influenced by the instant on the voltage waveform. But also, by remnant flux in the transformer core following the previous de-energisation. The effect of remnant flux is to provide an offset to the base of the prospective flux at energisation. This can push the flux in the core to enter into an even higher saturation region, resulting in a greater transient inrush current. Theoretically, if the residual Φ_1 is locked in at either peak positive or peak negative, then the flux could be potentially increased to $2\Phi_m + \Phi_1$, if the residual flux already present in the core is in the same direction as that to be influenced by the first half-cycle of flux growth.

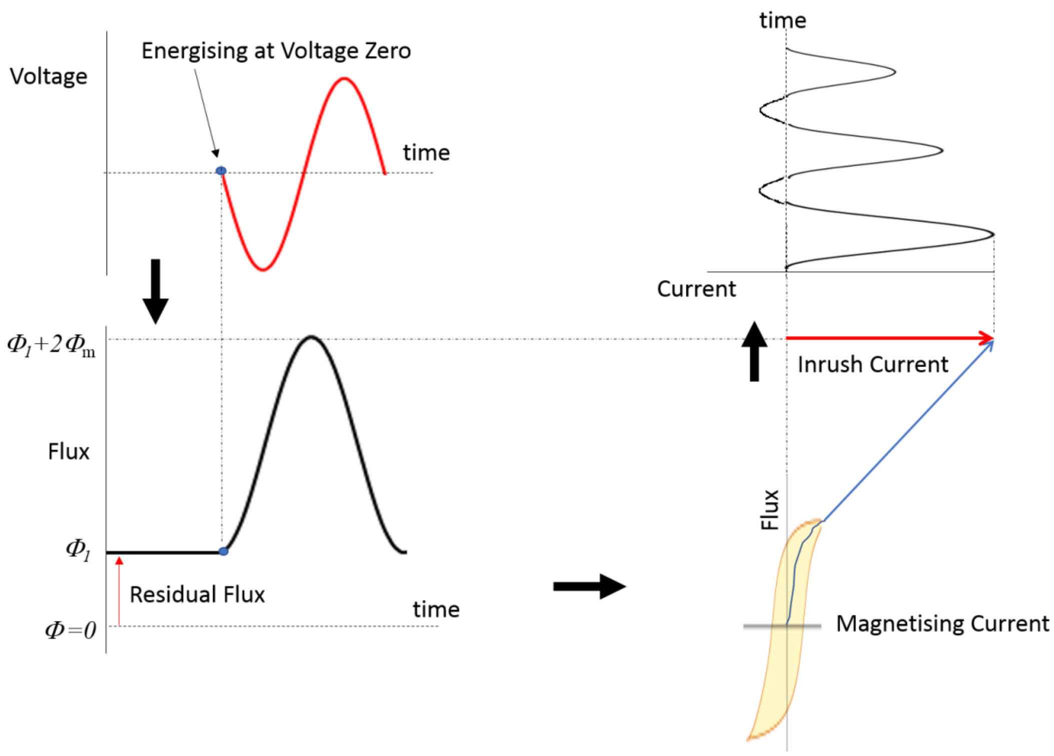


Figure 7.3: Inrush Current at Peak Voltage.

In real life applications however, the remnant flux is reduced to a maximum of 90 % due to parasitic capacitance of the transformer winding and bushings. Remnant flux can further be reduced by the grading capacitors on circuit breakers. In 2015, de Leon et al, also suggested a method of eliminating residual flux in transformer core by using an alternating polarity DC source [35]. The re-design of power transformers to include gapped cores could also eliminate remnant flux, but this is at the expense of the economic performance of the transformer.

7.3 Controlled Switching Strategies

In this research it has been found that there is no single multi-purpose CS strategy that can be employed for energising unloaded power transformers [14]. The optimal switching point to eliminate high transient inrush currents, is to switch each phase at the point when the residual flux in the core is equal to the prospective flux. However, depending on the transformer core configuration energising a single phase may induce dynamic fluxes on the other two phases which must also be considered. Dynamic fluxes may exist in the following situations:

- A three-limbed transformer core.
- Arrangements with a single-phase transformer per phase with delta connected secondary or tertiary windings.

Conversely, transformer cores are considered to be magnetically independent with the following arrangements:

- A five-limbed transformer core;
- Single-phase transformer per phase with no delta connected secondary or tertiary windings.

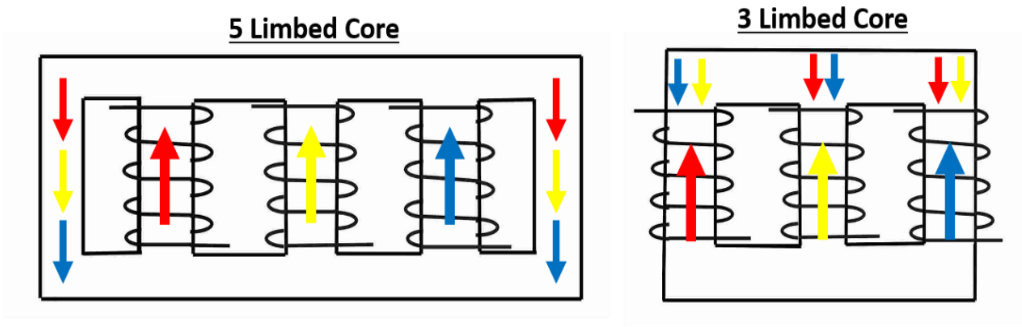


Figure 7.4: Transformer Core Configurations with Flux Paths.

To consider for the purpose of explanation, the following examples are based on a 3-limbed power transformer with YnD5 winding configuration, which would be a typical transformer type at many IPP interfaces in Ireland.

7.3.1 Control of Remnant Flux

In practice in Ireland remnant flux measurements are not taken into account and therefore, it is fair to say that these CS schemes are truly not optimised. To ensure the best performance of the scheme, it is important to compensate for any remnant flux in the transformer core. This may be achieved by:

a. The CSD measuring the instantaneous winding voltage on each phase at the moment of supply disconnection, these measurements must then be integrated to obtain the value of the residual flux on each phase.

b. Implement a controlled open strategy in order to lock in known values of remnant flux in the core.

With the current generation of CSD technology utilised in Ireland, it is not possible to process residual flux values from the de-energising voltage measurement. Therefore, locking in the residual flux is a much more practical solution to implement.

7.3.1.1 De-energisation Strategy

One solution to lock in known values of residual flux in each phase is to de-energise each phase of the transformer at its voltage peak, this ensures remnant flux values of approximately 0%, 65% and -65% respectively for R, S and T phases.

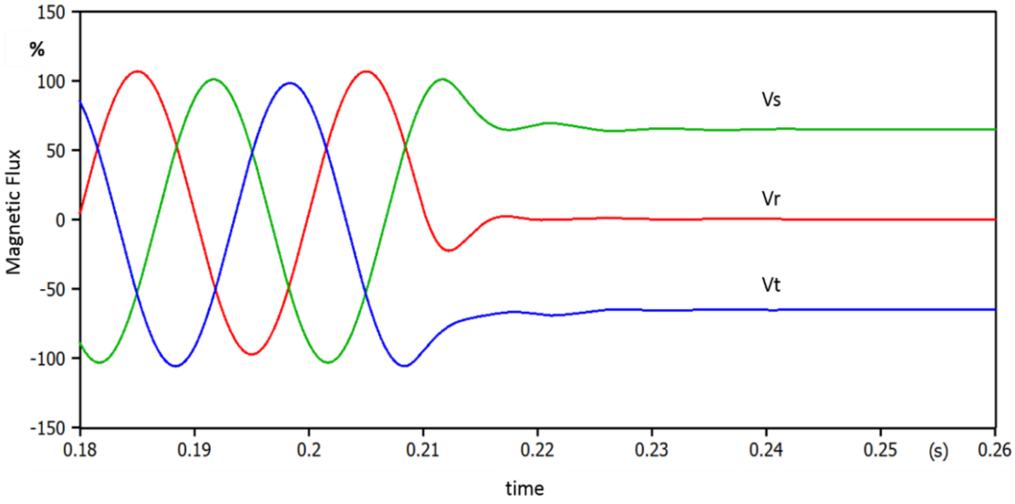


Figure 7.5: Locked in Remnant Flux following Controlled De-Energisation.

7.3.2 Energisation Strategies

In practice there are two main transformer energisation strategies employed in industry. These are the rapid energisation strategy and delayed energisation strategy. Although there are slight variations in philosophies used for switching the first phase. CIGRÉ Working Group A3.07 (2004) recommend energising the centre phase first which is at a high remnant flux (65%), as prestrike voltage is low thus avoiding steep voltage transients [12]. The optimum switching point using this method is when the prospective flux matches the trapped remnant flux. In the second method, some manufacturers recommend switching at peak voltage of the first phase (R phase), assuming ideal scenarios with no remnant flux present in the core [36].

One method which can be used to calculate the optimum switching time t_{opt} for the first phase to be switched is:

$$t_{opt} = \frac{1}{\omega_o}\left[\arccos\left(\frac{\phi_{Res}}{\phi_0}\right) + 1\right] \qquad (7.2)$$

Where:

- ω_0 = angular velocity ($2\pi f$).
- ϕ_0 = Prospective flux peak.
- Φ_{Res} = Residual flux.

There exist no analytical methods for calculating the optimum closing times for the other two phases, only the general rules apply for each method. However, studies and commissioning tests must be performed to ensure best performance.

7.3.2.1 Rapid Energisation Strategy

In this method, all phases are energised within one power frequency half cycle of each other. The first phase is energised at the optimum instant, based on the philosophy used in section 7.3.2. The second two phases are energised simultaneously approximately 5 ms later, when the prospective and dynamic flux of each phase are equal. To implement this method, knowledge of the residual flux on each phase is required.

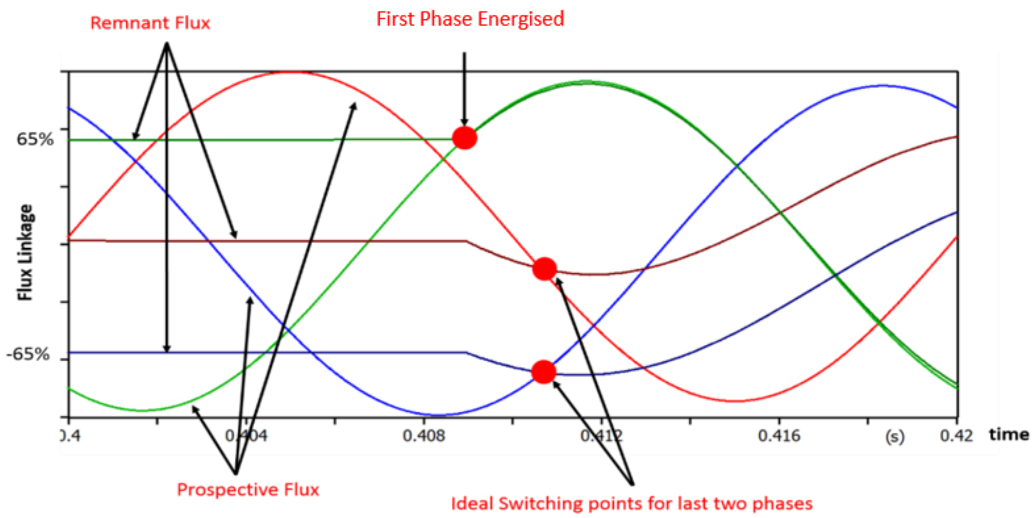


Figure 7.6: Rapid Energising Strategy.

7.3.2.2 Delayed Energisation Strategy

Similarly, to the rapid energisation strategy, the first phase is energised at the optimum instant based on the philosophy used in section 7.3.2. The second two phases are then energised around the zero crossing of the voltage of the first phase following decay of the offset of the dynamic flux on the second two phases. This can take typically 3 to 5 cycles and this method only requires knowledge of the residual flux to energise the first phase.

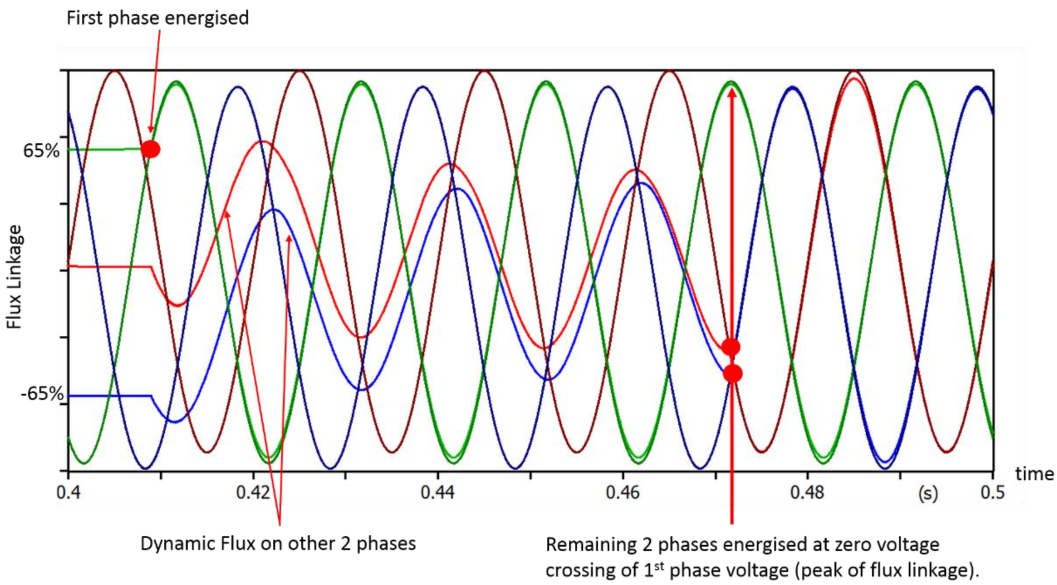


Figure 7.7: Delayed Energising Strategy.

7.4 EMTP-ATP Modelling of Unloaded Power Transformer Switching Operation

Data for this model was obtained from a 110:10 kV, 50 MVA IPP interface transformer located in the west of Ireland. The 110 kV station to which the transformer is connected is fed via OHL from a 220 kV station located 9.5 km away. The main purpose of this simulation is to examine:

- Transformer inrush current and local busbar voltage during non-optimum energisation points.
- Both the rapid and delayed energisation strategies to manage inrush current and local busbar voltages.

7.4.1 Network Model

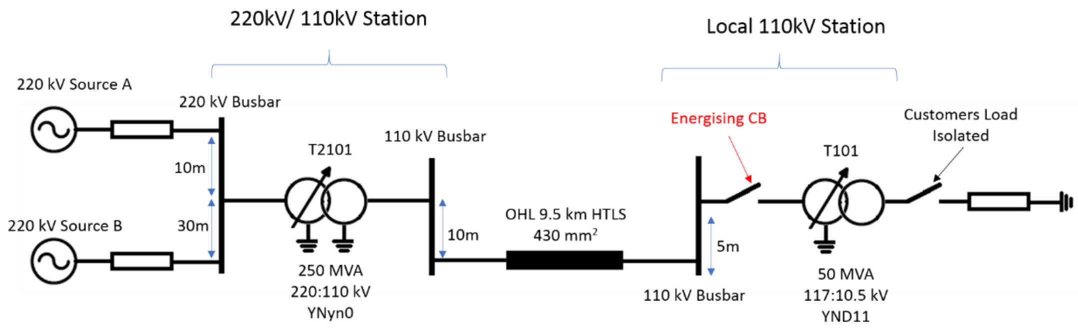


Figure 7.8: Model Network Overview

7.4.1.1 Model Data

- 220 kV Source A impedance*: R = 6.12 Ω,* X_L *= 38.01 Ω.*
- 220 kV Source B impedance*: R = 7.83 Ω,* X_L *= 37.7Ω.*
- Busbar inductances: *0.856 µH/m.* [6].
- Transformer T2101: *250 MVA, 220:110 kV, YNyn0+d5, Z% = 16%.*
- Overhead line data:
  - *9.5 km* of *430* mm^2 HTLS OHL conductor with R_{DC} *= 0.07482 Ω / km @ 20 ºC,* r_{in} *= 0.087 cm* and r_{out} *= 0.1342 cm.*
  - Tower geometry (wood pole, horizontal conductors, no guard wire):
    - Distance between conductors: *4.5 m.*
    - Average conductor height at tower: *22 m.*
    - Average conductor height at mid span: *16 m.*
  - Soil resistivity R_{ho} taken as: *200 Ω meters*.
- Transformer T101;
  - Main data: *50 MVA, 117kV/10.5 kV, YNd11, 10.31 %.*
  - Short circuit losses:

% Impedance	Rating (MVA)	Losses (kW)
10.31 %	*50 MVA*	*155 kW*

- Open circuit losses:

% Voltage	Loss (kW)	Io %
95 %	*20.24 kW*	*0.058 %*
100 %	*23.23 kW*	*0.077 %*
105 %	*27.27 kW*	*0.116 %*

- Capacitance:

Measurement	*C (nF)*
Primary - Secondary	*6.8943 nF*
Primary - Earth	*2.8503 nF*
Secondary - Earth	*101737 nF*

7.4.2 Simulation Results

7.4.2.1 Energisation of Transformer with No Mitigation Measures Applied

In this simulation, a ganged CB with a single mechanism is simulated. All poles are switched simultaneously with R phase pole configured to switch at its zero-voltage crossing. There is a residual flux with pattern 0%, 65% and -65% locked in the core for R, S and T phases respectively.

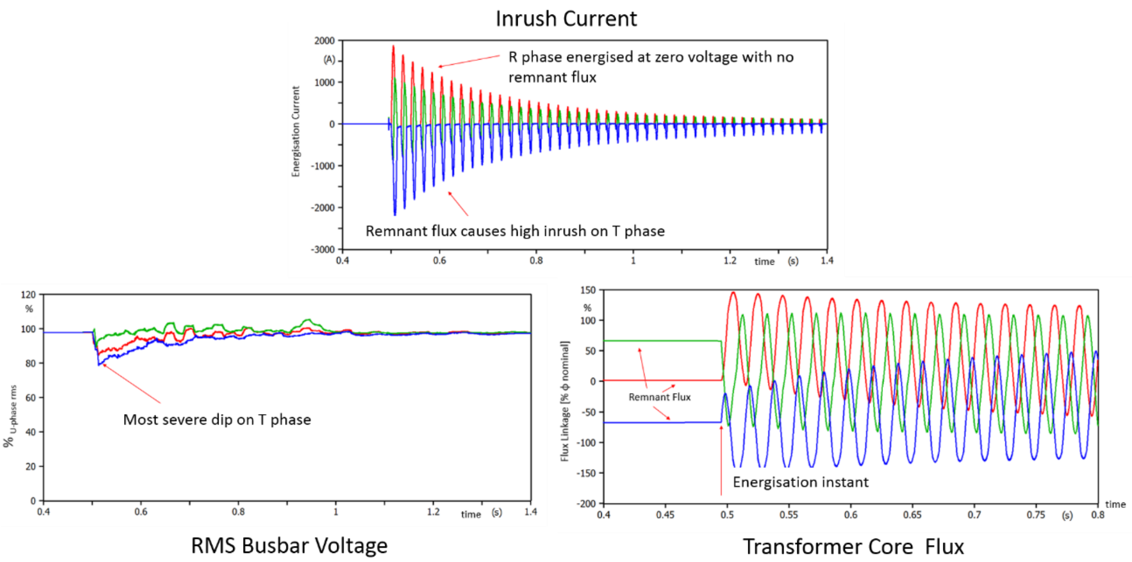


Figure 7.9: Measurements with No CS Applied.

It can be seen from the waveforms results in Figure 7.9, that the transient inrush current observed for R phase is approximately 1900 A, T phase current is in excess of 2000 A due to the non-optimum energisation instant with the incoming prospective flux along with the locked in remnant flux in the core. A dip could be observed in R and T phase voltage in excess of the – 10 % of the rms steady state voltage for approximately 200 ms.

7.4.3 Rapid CS Energisation Strategy of an Unloaded Power Transformer

In this simulation, a rapid controlled switching strategy is applied. The centre phase S is switched first when the prospective and residual flux are the same (65%). The remaining two phases are switched at approximately a quarter of a cycle later when the combination remnant flux (0% and -65%) along with the dynamic flux contribution from the energised phase, matches the prospective flux from the source supply. The remaining two phases were optimised manually by the author in the simulation to achieve this.

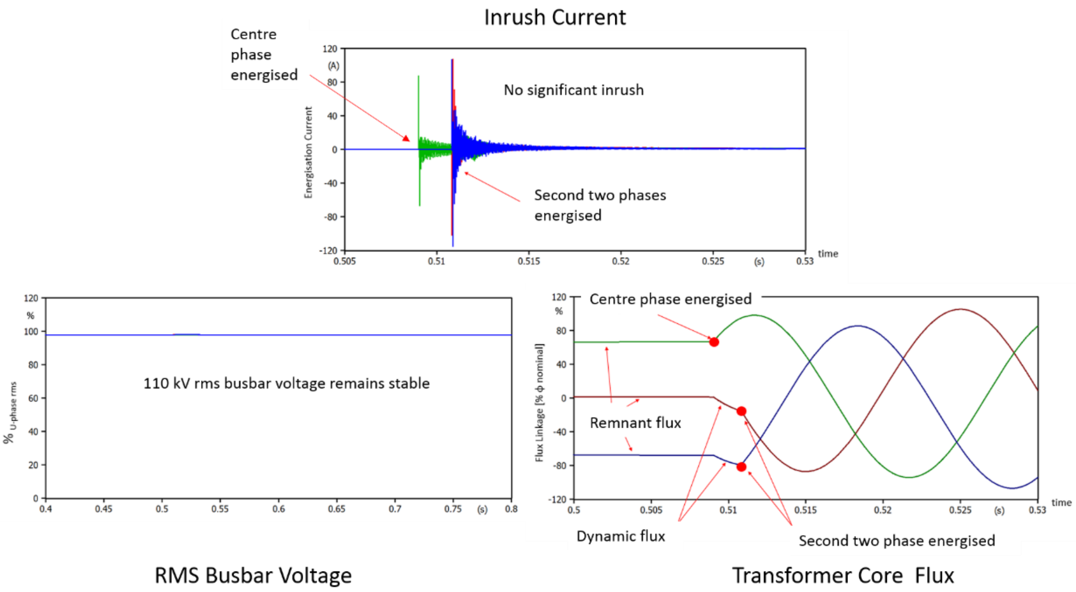


Figure 7.10: Measurements Obtained from Rapid CS Strategy.

It can be seen from the results obtained in Figure 7.10, that the transformer inrush current is vastly reduced and is below the nominal rated current, while the steady state busbar voltage remains unaffected. The disadvantage with this method is the residual and dynamic flux values are required and is difficult to achieve in practice. Also, accuracy was found to be an issue where impacts of mechanical scatter of the CB can greatly increase the current inrush.

7.4.4 Delayed CS Energisation Strategy of an Unloaded Power Transformer

In this simulation, a delayed controlled switching strategy is applied. The centre phase S is switched first when the prospective and residual flux are the same (65%). The remaining two phases are switched four cycles later at the zero crossing of S phase voltage, when the dynamic flux offset has decayed to a steady value.

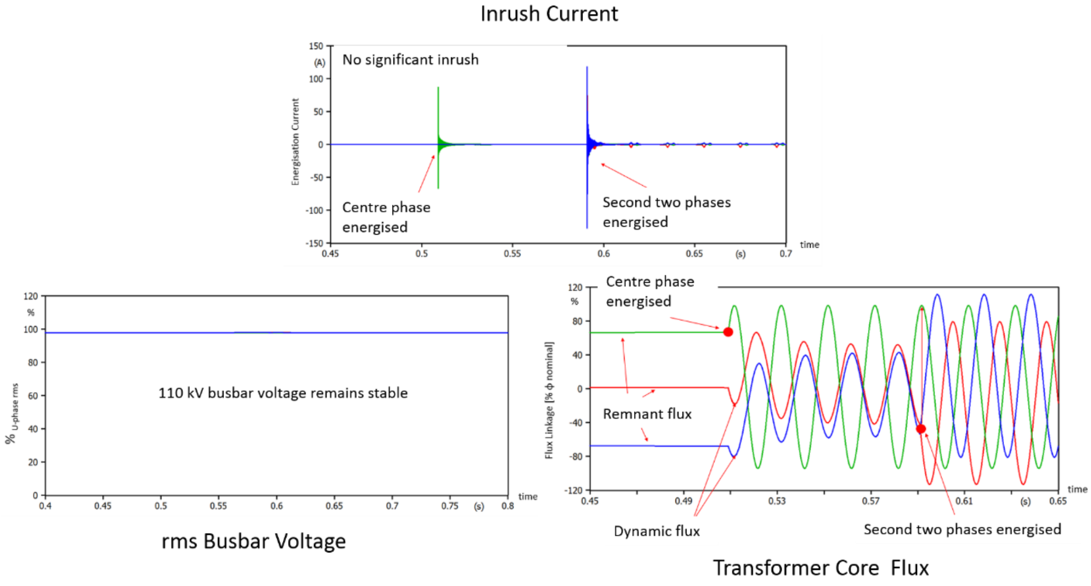


Figure 7.11: Measurements Obtained from Delayed CS Strategy.

It can be seen from the results in Figure 7.11, that the delayed strategy has greatly reduced the transformer inrush current below the rated current and there is no impact to the local 110 kV busbar voltage. This method was found to be much more stable and easier to implement than the previous method, as only the residual flux for only the first phase needs to be known. The remaining two phases are switched in a number of fixed cycles later (when the dynamic flux decays) at the zero-crossing of the energised phase voltage.

7.5 Case study: Controlled Switching of a 220 kV 500 MVA Power Transformer

In this case study CS was implemented on a 220 kV: 21 kV, 500 MVA, YD11 power transformer at an IPP interface. The main motivation for installing CS at this interface was to improve local voltage quality during transformer switching operations.

The commissioning was performed by the author in association with the CSD manufacturer. A controlled switching strategy of energising the first phase (R) at the peak of the voltage waveform, the second two phases were then switched 90 electrical degrees later. No controlled opening strategy to lock in known remnant or flux measurement was implemented. In effect the strategy implemented here was the rapid CS strategy, with no account for remnant or dynamic flux.

7.5.1 Controlled Switching Results

The following test results shown in Figures 7.12, 7.13 and 7.14, are the final three waveforms captured during live commissioning switching operations. This is normal practice to observe three successive waveforms with favourable results to declare the scheme fit for service. However, it can be seen that from the current waveforms captured, there are different magnitudes for each test. This suggests that there is an influence of remnant flux on the inrush current waveforms, the residual flux is dependent on the flux trapped during de-energisation of the transformer and as controlled opening is not implemented here, current inrush magnitude will still be random.

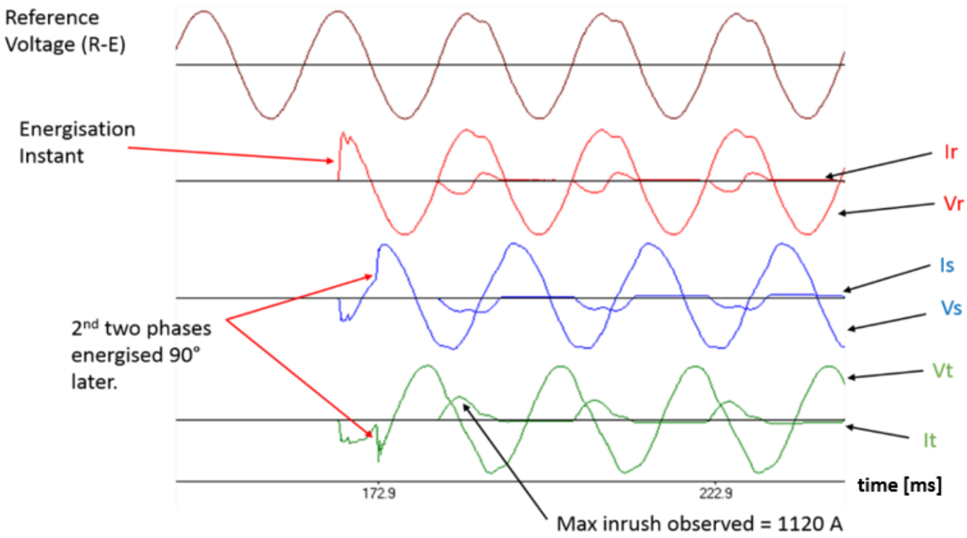


Figure 7.12: Commissioning Energisation, Peak of 1120 A Observed.

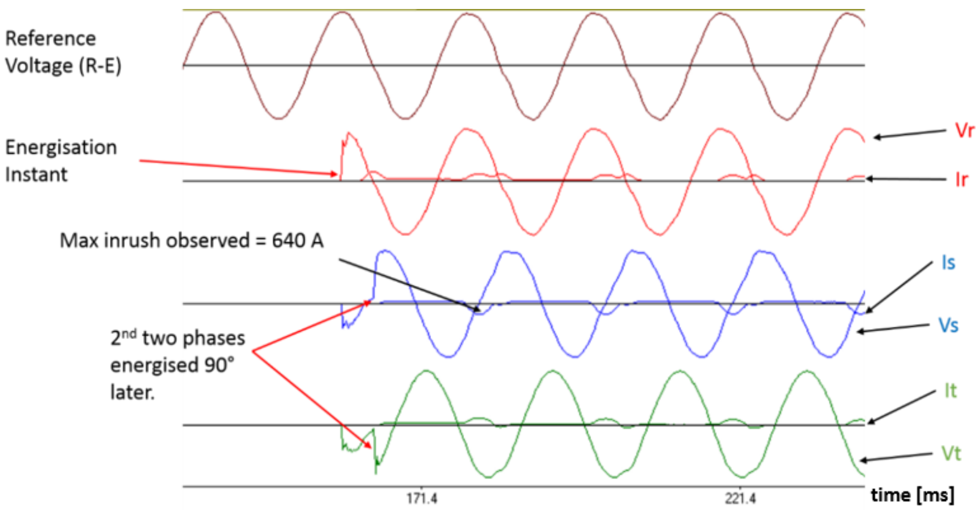


Figure 7.13: Commissioning Energisation, Peak of 640 A Observed.

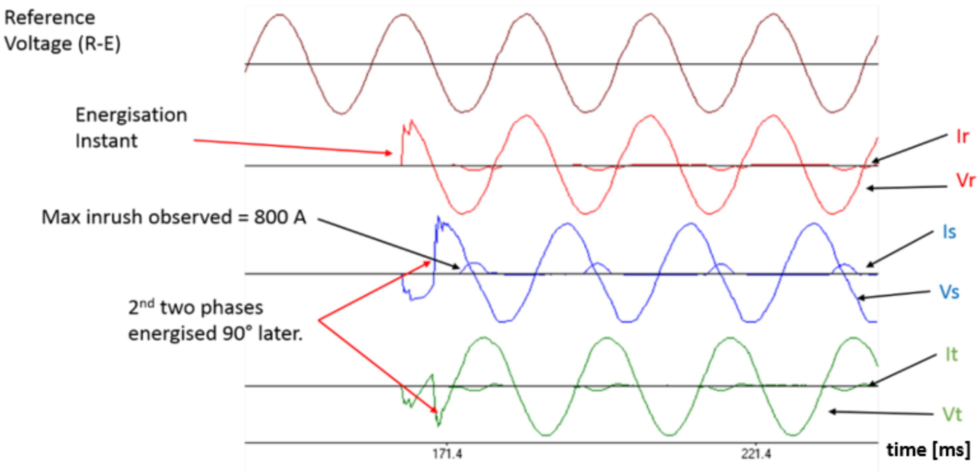


Figure 7.14: Commissioning Energisation, Peak of 800 A Observed.

While peak currents observed were not excessive it could be seen that there is still an unsystematic operation of the current onset and magnitude. This was after three successive operations of the CS scheme during commissioning. It is still possible that a higher current maybe observed during its operation lifetime. However, transformer interfaces like this are rarely switched in practice, and typically only a couple of times per year.

8. Conclusions and Scope for Future Research

8.1 Conclusions

The intention of this thesis was to close the gap in the knowledge and understanding of controlled switching applications as implemented on the Irish transmission system, with a view to investigate the appropriate methods and stages in commissioning of schemes. The particular steps in implementing a CS scheme are:

- Deciding the necessity for such a scheme in the first place, i.e. knowing what the problem is and the appropriate mitigation measures.
- Design and specification of equipment and an appropriate switching strategy, i.e. correct specification of CB and CSD for the intended application and to perform transient simulation studies to ensure it will work and to investigate the optimum switching strategy.
- Commissioning and implementation on site, performing the appropriate tests and knowing the intended results.

For each of the core areas analysed in this thesis, the following were the main conclusions drawn:

1. ***CSD Compensation***: With current CSD technology, external compensation measures can ensure more accurate performance. It was seen for a particular CB that for every 1 V deviation in control voltage that this affected the CB operating speed by 0.1 ms. Temperature of the CB mechanism can also influence a CBs performance, but can normally be overcome by maintaining CB mechanism enclosure at a constant temperature with panel heaters. Performance information such as this differs between CB types and can only be given from

manufacturers or through user experience which may not be practical when considering brand new equipment.

2. ***Circuit Breaker Performance***: Modern SF_6 spring operated are very reliable and operate times can be repeated to within +/- 0.5 ms of the intended target. Other factors which should be considered are the CB dielectric properties. CBs should have a very steep rate of decrease of dielectric strength (RDDS) slope when energising a load to prevent pre-strikes and a very steep rate of rise of dielectric strength (RRDS) to prevent re-ignitions when de-energising a load.

3. ***Transient Simulation Studies:*** Frequency dependent models are more effective when performing transient studies, for transmission lines. The J-Marti model was used, and surge arrestors were simulated using the model proposed by Pinceti – Gianettoni which is based on the arrester's electrical characteristics. The XFRM hybrid model was used to model power transformers and was configured as a frequency dependent model. The main advantage of this model is that it uses direct factory test results data to calculate the magnetising characteristic and dielectric properties of windings and bushings.

4. ***Shunt Capacitor Bank Switching:*** Controlled switching is a proven and effective method of eliminating transients for a single capacitor bank energisation. However, it was seen that CS alone is not sufficient in some instances such as back to back switching arrangements. When performing switching studies, modelling of busbar inductance is crucial as the inductance is the only current limiting factor in these schemes. Mechanical scatter deviation of CB is also an important aspect during simulation studies as the worst cases can be examined over the CBs deviation. CS is usually not required for de-energisation of shunt capacitor banks as there is no steep transient recovery voltage. However, with the introduction of current limiting inductors this may be a consideration in the future. The procedure for commissioning of these schemes was found to be effective, however there is a time element involved when disconnecting the conductors from the capacitor bank and this is

necessary in some locations as continuous switching transients may not be permitted by the TSO.

5. ***Shunt Reactor Switching:*** Shunt reactor switching is an onerous duty for the circuit breaker and shunt reactor to handle, due to steep TRV’s and potential of re-strikes, these are the main problems observed during de-energising. CS maybe used to control the minimum arcing time (MAT), so as to prevent current chopping and can be used to avoid switching during the re-ignition period. However, details of the MAT and re-ignition period are not readily available from CB manufacturers. During energisation, long DC offsets in the current waveforms were observed and these can be eliminated if switching is performed at the peak of the voltage waveform. Modelling of shunt reactor switching is normally performed with the shunt reactor and its immediate source information in isolation, as the recovery voltage across the CB and across the reactor are the main issues being investigated. The Mayr arc model was found to be the most suitable for low current switching, however lack of information again from CB manufacturers to accurately model is a major issue. To overcome this an ideal switch in parallel with the main CB may be used to simulate restrikes by applying a close/ open cycle at a controlled point on the transient recovery voltage waveform.

6. ***Unloaded Power Transformer Switching:*** Power transformers are a relatively new application for CS with two instances in Ireland. Very high inrush current may be observed depending on the point on the energising voltage waveform and the remnant flux in the transformer core. The majority of transformer core types in Ireland are of three limb construction and therefore, if CS is implemented, single pole dynamic flux becomes an issue, as other phases are not magnetically isolated. Currently CSD controllers in use in Ireland don’t have any available algorithm for working out the residual flux based on instant of opening voltage, so controlled de-energisation maybe used instead to lock in a known magnetic flux into the core. However, protection trips from the transformer protective devices, overcurrent and differential protection, oil and winding temperature protection devices bypass the CSD and are routed directly

to the circuit breaker trip coils. Consequently, there will be an unknown value for residual flux for the next energisation attempt. This is also relevant for condition assessment testing of the transformer also, as any residual flux will be essentially driven out of the core following DC winding resistance measurements. The main switching strategies performed world-wide are, the rapid strategy which requires knowledge of the residual and dynamic flux on all phases and can be found through modelling and site tests. It was also found through modelling that the CS performance is highly susceptible to mechanical scatter of the CB. The other method considered is the delayed model and only requires the knowledge of residual flux in the first phase. The strategies implemented so far in Ireland assume no residual flux, hence it is important consideration to ensure a more accurate and repeatable switching performance in the future.

8.2 Further Research

1. In the thesis, the majority of CS studies were performed using ideal switches, which have an infinite resistance while open and have no resistance when closed. To truly model a switching scheme, the properties and dynamics of the switching arc must be considered. The concept of CB block box arc modelling was introduced in Chapter 4 with the overview of the Mayr arc model. By accurately modelling the switching arc, this allows for more precise transient simulation studies by incorporating a more realistic transient recovery voltage behaviour during current interruption. The major drawback with black box arc modelling is that accurate information is difficult to obtain and each CB, according to manufacturer and type, have different properties and can only be obtained during factory tests. For this reason, when performing transient switching studies in practice, the switching arc is usually omitted.

2. Investigate practical methods of managing remnant flux for unloaded power transformer switching applications. Two methods considered are:

    a. A method proposed by de Leon et al in 2015 was to remove the remnant flux by applying a variable polarity DC voltage source to the transformer windings following de-energisation.

    b. Investigate the possibility of a suitable algorithm which can be used to calculate the residual flux present in the core at the moment of de-energisation, then apply a dynamic compensation time for energising the transformer at the optimum instant. This would eliminate altogether the need for controlled opening to lock in known residual flux. Further considerations are required in this algorithm, for the dynamic flux and influences on remnant flux magnitude due to parasitic capacitance of the transformer components.

3. Additional to the CS methods that were examined in this thesis, there are a growing number of specialised CS applications that could be investigated for suitable use on the Irish transmission system, these applications include:

    a. *FACTS transmission interfaces:* Energisation of SVC's, STATCOM's and HVDC interconnector plant at transmission interfaces, where the filter and transformation plant exist in parallel. In the past controlled switching has being implemented in Ireland on these installation types, it was always assumed that any issues with transient inrush current could be eliminated by simply switching on the zero-voltage crossing. However, a number of false protection operations during switching have revealed that this may not be as simplistic as first thought. Hence, these installation types must be studied as an individual case to determine the best switching strategy to be implemented.

    b. *Unloaded overhead lines:* Reduce switching over voltages that occur during the energisation of long overhead transmission lines. These over voltages are a direct result of travelling wave propagation along the line which occur during the CB pre-strike at energisation. The strategy implemented is similar to that used when switching shunt capacitor banks

c. *Controlled fault interruption:* This has recently been investigated as a beneficial CS application for fault interruption. The main principle of this method is to limit the arcing time during fault interruption to the minimum possible duration (above the CB minimum arcing time). This ensures that the fault interrupting CB is put under the least amount of stress, therefore increasing the CBs contact system lifetime. This CS method could potentially allow underrated switch gear to clear faults at higher than rated short circuit levels. This could be particularly advantageous for older generations of CBs in evolving networks with higher short circuit levels.

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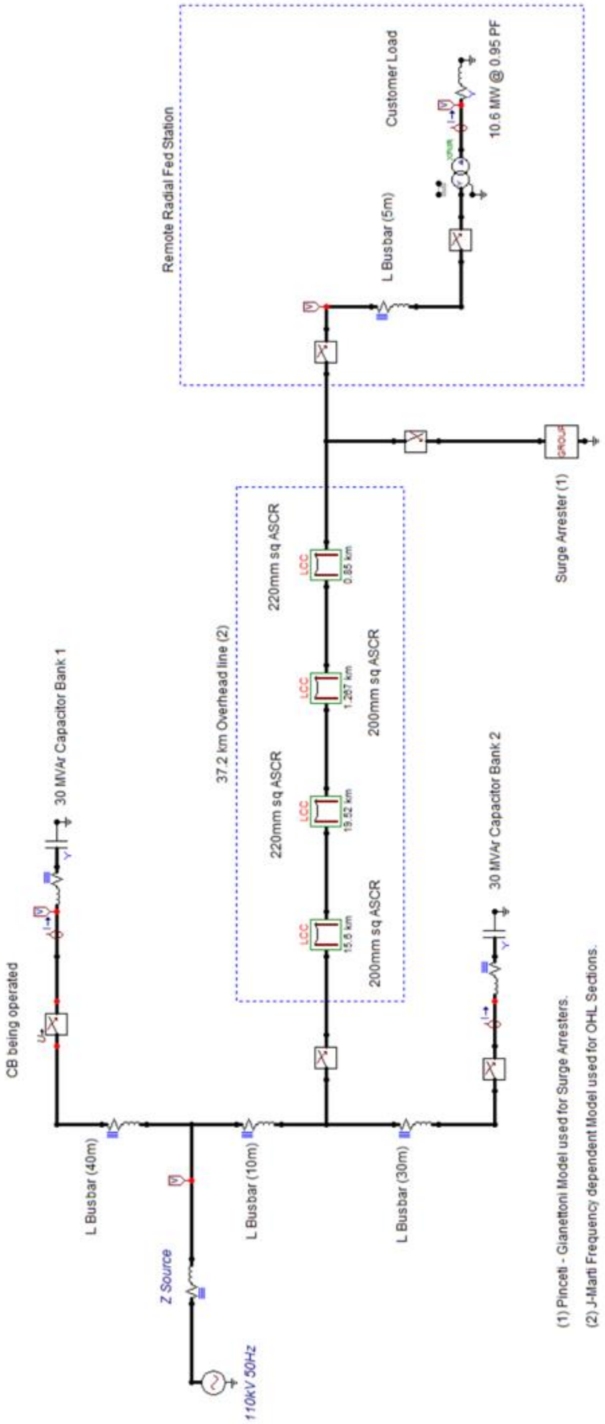
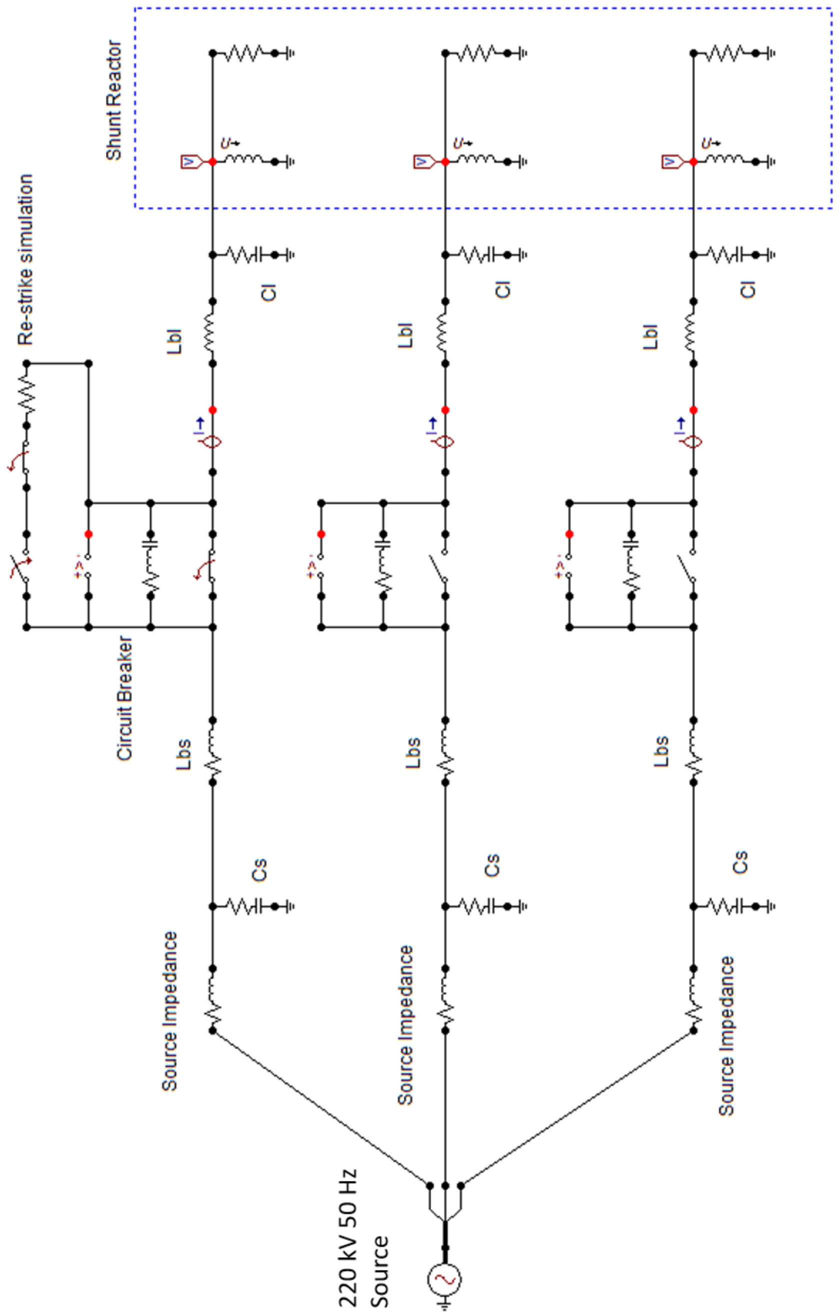
Appendix A

Shunt Capacitor Bank EMP-ATP Network Model



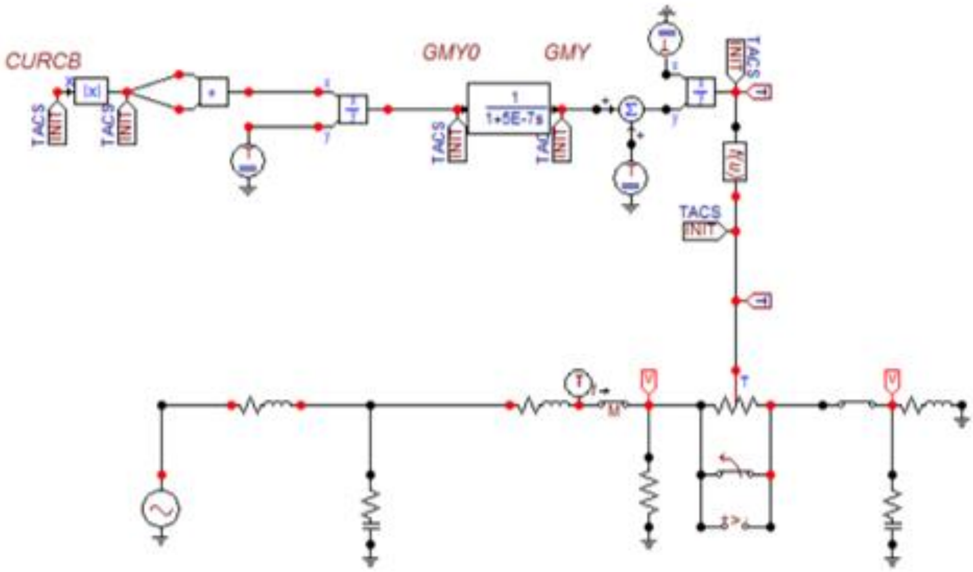
Appendix B

Shunt Reactor EMTP-ATP Model



Appendix C

Shunt Reactor EMTP-ATP Model using TACS MAYR Arc Equation [9]



Appendix D

Unloaded Power Transformer EMTP-ATP Network Model