Controlled Switching of High Voltage Shunt Reactor

by

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LIST OF ABBREVIATIONS

CB	Circuit Breaker
EHV	Extra High Voltage
HV	High Voltage
SF_6	Sulphur Hexafluoride
SIL	Surge Impedance Loading
ATP	Alternative Transients Program
POW	Point-on-wave
Imar	Chopping level of the current

Pensuisan Terkawal bagi Reaktor Pirau Bervoltan Tinggi

ABSTRAK

Tesis ini mencirikan model dan mengkaji fenomena alihan pensuisan berkaitan dengan reaktor pirau dan bagi kawalan kuasa reaktif dalam sistem pemancaran. Bank reaktor memainkan peranan penting dalam mengurangkan atau meminimumkan kenaikan voltan, yang dikenali juga sebagai kesan Ferranti, yang mencirikan panjang garis pemancaran yang terbeban. yang mempunyai arus pengecasan berkapasiti tinggi. Pentenagaan dan penyahtenagaan pada bank reaktor memberikan alihan frekuensi yang tinggi, yang mungkin menyebabkan tegasan pada penebatan kelengkapan pensuisan, yang akan mengakibatkan kegagalan kelengkapan. Kajian ini membentangkan fenomena yang berbeza berkaitan dengan penyahtenagaan bank reaktor dan memaparkan isu aplikasi pemutus litar apabila mengganggu arus aruhan rendah dari sudut kejuruteraan Kajian ini mengilustrasi satu kajian kes yang diransang dalam Program Alihan Alternatif daripada pakej Program Alihan Elektromagnet (ATP/EMTP) untuk menunjukkan fenomena pemotongan dan pencucuhan semula, bkaitan dengan pensuisan bank reaktor. Kaedah pengurangan yang dinyatakan di atas, juga dinilai. Kajian ini memberi tumpuan terhadap dapatan alihan voltan yang berlebihan dalam kes sistem satu-fasa atau sistem tiga-fasa, dan menentukan pensuisan ideal yang memberikan magnitud volten berlebihan yang terendah pada komponen reaktor pirau. Kajian ini juga mengkaji pelbagai masa pemutus litar bagi hubungan tiga-fasa untuk menentukan tegasan daripada komponen yang digunakan untuk membandingkan reaktor pirau. Kita boleh merangsang keadaan pensuisan segerak daripada reaktor pirau melalui penggunaan pelbagai masa pemutus masa. Pertama, dalam kes analisis satu-fasa, jelmaan Laplace digunakan untuk mengira alihan voltan berlebihan. Sebaliknya, rangsangan / simulasi ATP digunakan untuk membandingkan keputusan yang diperoleh. Dalam usaha menghasilkan operasi pensuisan reaktor pirau, ATP/EMTP digunakan, dengan alasan bahawa ia mampu menyelesaikan domain masa dan amat membantu dalam perbandingan dengan kaedah analitik yang dijalankan. Dalam kata lain, dalam kes tiga-fasa, penyahtenagaan reaktor pirau digunakan untuk mengenal pasti alihan voltan berlebihan bagi pensuisan segerak. Kaedah pertama yang digunakan dalam kajian ini adalah pensuisan tidak terkawal yang bergantung pada bukaan pemutus litar pada satu masa bagi semua fasa. Sebaliknya, keadah kedua menggunakan pensuisan terkawal, dengan masa pemutus litar yang terbatas bagi setiap fasa, dan masa bukaan berdasarkan nilai arus yang melalui pemutus litar, yang membolehkan alihan voltan berlebihan yang terendah. Kaedah terakhir yang digunakan adalah perangkap luruan bagi perlindungan dan peminimuman alihan voltan berlebihan.

Controlled Switching of High Voltage Shunt Reactor

ABSTRACT

This thesis characterized models and investigations into switching transient phenomena related to the shunt reactors and for reactive power control in the transmission system. Reactor banks play an important role in mitigating the voltage rise, otherwise known as Ferranti effect, which is characteristic to long lightly loaded transmission lines having high capacitive charging current. The energizing and de-energizing of the reactor bank introduces high frequency transients that might stress the insulation of the switching equipment leading to equipment failures. The work presents different phenomena associated with reactor bank de-energisation and addresses the issue of circuit breaker application when interrupting low inductive currents from an engineering stand point. The work illustrates a case study simulated in the Alternative Transients Program part of the Electromagnetic Transients Program package (ATP\EMTP) to demonstrate current chopping and re-ignition phenomenon associated with reactor bank switching. Mitigation methods for the aforementioned issues are also evaluated. This work focus on finding the transient overvoltages in case of single and three phase's system and determine the ideal switching case that gives the lowest overvoltage magnitude at the shunt reactor components. Also in this study, varying opening times of circuit breaker for three-phase connections were used to determine the stress of shunt reactor components. We can stimulate the synchronous switching state of the shunt reactor by variation in the circuit breaker times. First, in case of the single-phase analysis, Laplace transform were used to calculate the transient overvoltages, while ATP simulation for validation were used to compare the acquired results. In order to reproduce the switching operation of shunt reactor, the Alternative Transient Program (ATP/EMTP) was applied. The reason ATP was applied here is because it gives solution in time domain and very helpful in the comparisons with analytical method conducted. On the other hand, in case of the three- phase shunt reactor, the de-energisation of the shunt reactor was used to identify the transient overvoltages for synchronous switching. The first method applied in this study are uncontrolled switching that depend on opening the circuit breaker at one time for all phases, while the second method is controlled switching, in other words, to give the circuit breaker limited time for each phase, the opening time is based on the value of the current across the circuit breaker that allows the lowest transient overvoltage. The final method applied in this work is the surge arrester for the protection and minimize the transient overvoltages.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The voltage level along an AC transmission line is influenced by two main factors; the capacitive charging and the loading of the line. The capacitive charging, which is the source of reactive power generation (Q_C), depends on the line geometry and the line voltage level; and arises because of the capacitance between its conductors and the earth. On the other hand, when the line is loaded, both the load and the line consume reactive power (Q_L) as inductive electrical elements. In an AC transmission system, it is important to keep the balance between generated and consumed reactive power since it is the reactive power balance which decides the voltage stability of the line (Stevenson and Grainger, 1994).

In order to achieve the reactive power balance, the line should be loaded at its natural load surge impedance loading (SIL) where the generation and consumption of reactive power along the line are equal. When the load varies in the system, the consumption of reactive power changes, and consequently the voltage fluctuates along the line. If the generated reactive power is more than the consumed reactive power, the voltage increases, whereas the voltage decreases if the consumption is more than generation of reactive power.

In order to control the line voltage we use the shunt reactors that absorb the reactive power. These shunt reactors are prepared to be linked to the ends of high voltage transmission lines or to the high-voltage cables. The reason Shunt reactors are used is because they can adjust the reactive power balance of a system. This can be accomplished by compensating for the excess reactive power generation of transmission lines or cables. The surplus reactive power appears in two cases, first in case there is an unexpected drop in load due to a failure in some part in the system. Second the surplus reactive power may appear when lines are lightly loaded. Shunt reactor can be used for another purpose for example to control excessive voltage rise (Ferranti Effect) created on long lines that are lightly loaded (Kundur, 1994).

In electrical engineering, the Ferranti effect is an increase in voltage occurring at the receiving end of a long transmission line, above the voltage at the sending end. This occurs when the line is energized, but there is a very light load or the load is disconnected. The capacitive line charging current produces a voltage drop across the line inductance that is in-phase with the sending end voltages considering the line resistance as negligible. Therefore, both line inductance and capacitance are responsible for this phenomenon.

1.2 Background

Voltage stability can be described as the capability of a power system to keep stable voltages at all buses that are available in the system after a disorder occurs from a specific primary operating status, this discretion is introduced by (IEEE, 2000).While the voltage collapse can be defined as the sum of a series of phenomenons that escort voltage instability. This instability can lead to the appearance of abnormal low voltages in a specific section of the system. The abnormal low voltage is not the only damage that can happens, a blackout may also occur in the power system due to this phenomenon.

During the switching operations. Some particular issues were noticed during the disconnection of the shunt reactor specially during heavy load period. One of these issues is the inductive current chopping phenomenon which can be defined as the disconnecting of the reactor current, the circuit breaker acts to chop the current before its prospective zero value. It depends on the level of chopped current, in other words consequence will appears in case of high overvoltages. Thus the overvoltage is referred as chopping overvoltage, and by monitoring the energy balance in the reactor it can be measured.

1.3 Controlled switching of shunt reactor

Controlled switching is one of several terminologies applied to the principle of coordinating the instant of opening or closing of a circuit breaker during energisation or de-energisation of the shunt reactor with a specific target point on an associated voltage or current waveform. Other common terminologies applied include “synchronized switching” and “point-on-wave switching”. Within this project “controlled” and “synchronized” may both be used depending on the specific context.

1.4 Research Problem

The major focus of this thesis is to reduce transient overvoltages produced by shunt reactor de-energization. Therefore, the main question to be asked is "*How to reduce* transient overvoltages produced by shunt reactor de-energisation*?*"

1.5 Research Objective

The objective and purpose of this study are to identify and analyze the unwanted detrimental events that caused by converting processes of shunt reactors, thus we can obtain a steady-state voltage control. In this research, ATP/EMTP software has been applied. The reasons we applied ATP/EMTP is because it is one of the most popular and widely applied program in the electromechanical nature in electric power systems add to that for digital simulation of transient phenomena of electromagnetic. Through the years, it has been constantly improved by the contribution around the world. Applying ATP/EMTP enable to calculate the parameters of interest through electric power systems as functions of time.

So that the aims and objectives for this research are:

1- Determine the resulting transient overvoltages generated by shunt reactor de-energisation, for various switching conditions. The studies are achieved using ATP/EMTP software.
2- Limit the transient stress impose on the shunt reactor during the switching by using:
    - Control switching of the circuit breaker.
    - Surge arrester.

1.6 Research Scope

While there are clearly important motivations for researching controlled fault interruption as applied to HV power systems, it should also be clear from the issues summarized in section 1.3 that it is a complex problem to investigate and solve. The work described in this thesis has been restricted to investigating some of the fundamental issues related to development of a controlled switching interruption methodology during the de-energisaton of the shunt reactor.

1.7 Contributions

The contributions of this research are:

- Studies of overvoltages produced at the shunt reactors that are considered during the de-energisation process.
- A comprehensive review of important cases related to shunt reactor switching transients and research about application of linked techniques.

1.8 Organization of the Thesis

Five chapters are included in this thesis. In each chapter, we discussed various aspects of the main study. The First chapter starts with a short introduction about shunt reactor, followed by discussing the meaning of shunt reactor switching as well as Research Purpose, Research Problems, the value of this thesis and scope of the study, finally the limitations of this research.

The second chapter includes a deep explanation about shunt reactor and its problem, switching shunt reactor. Methods of calculation that are related to transient overvoltages, add to that overcurrent that may occur due to switching operations. Implementations and concepts, as well as the extra information about the switching concept.

In chapter three discuss the details about computer simulation of shunt reactor switching transients, which includes de-energisation of a shunt that may occur at various switching conditions. Add to that, this chapter explains about the analytical calculations of transient overvoltages on the same shunt reactor.

While in chapter 4 we explain the results and evaluations of performance of the switching shunt reactor.

Finally, chapter 5 presents the recommendations to improve this research as well as the conclusion.

CHAPTER 2

LITERATURE REVIEW

2.1 Shunt Reactor

Viewed externally in the substation yard, a large high voltage reactor does not differ much from a transformer. The easiest way to distinguish a reactor from a transformer is to observe its terminals and bushings on top of the device. To explain more, contrary to a 3-phase transformer which has three primary and three secondary voltage terminals, a 3-phase Shunt Reactor has only three voltage connections. Figure 2.1 illustrates a 3-phase Shunt Reactor (Carlson, 2002) .

Figure 2.1: Schematic of a 3-phase Shunt Reactor (Carlson, 2002)

The shunt reactor is the most cost efficient equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables, which are the primary generators of reactive power. The reactor can be seen as the voltage control device which is often connected directly to the high voltage lines. Figure 2.2 shows how the generated capacitive reactive power of the line is consumed by the reactors.

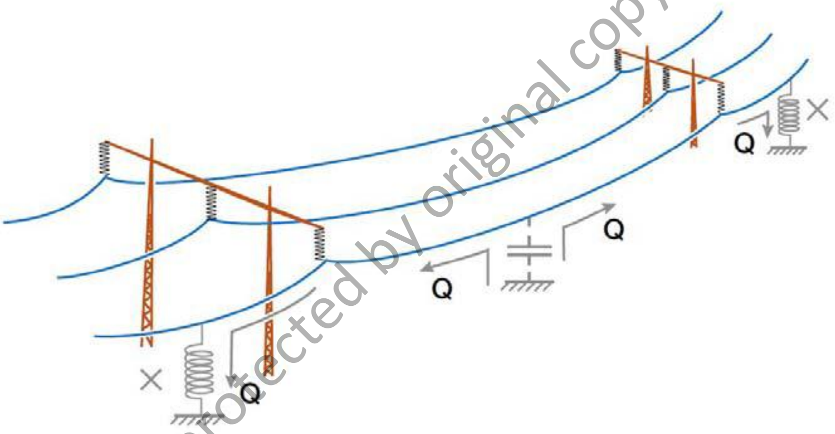

Figure 2.2: Generated reactive power by the line is consumed by the reactor’s inductance (Carlson, 2002)

There are two main applications for Shunt Reactors. First, Shunt Reactors can be used for system stability reasons especially on long transmission lines and cables (EHV and HV lines/cables); which in this case, Shunt Reactors are required to be permanently in service. Second, for the purpose of voltage control, where they can only switched in during light loaded conditions and are used in the underlying system and near to load centers (Gajić et al., 2003). Although Reactors reduce over voltages during light load conditions, they can also reduce the line loadability if they are not removed under full-load condition.

As seen in Figure 2.3, the Switched Reactor is connected to the busbar for voltage regulation while the Non-switched Reactor is connected to the line for stability reason. However, the Switched Reactor could be also connected directly to the line.

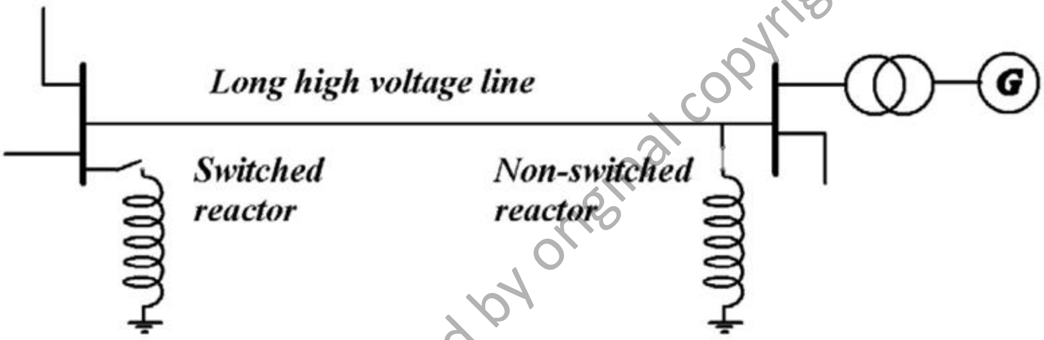

Figure 2.3: General application of Switched and Non-switched Fixed Reactors (Gajić et al., 2003)

Shunt Reactors are commonly installed at both ends of EHV lines, and sized to prevent the line voltage from exceeding a designed value when energized from one end. The reason that they are installed at both ends of the line is that there is usually some uncertainty regarding which end of a line may be energised (or de-energised) first. Figure 2.4 shows the equivalent Π-Model of a transmission line with Switched Shunt Reactors connected at both ends (Gajić et al., 2003).

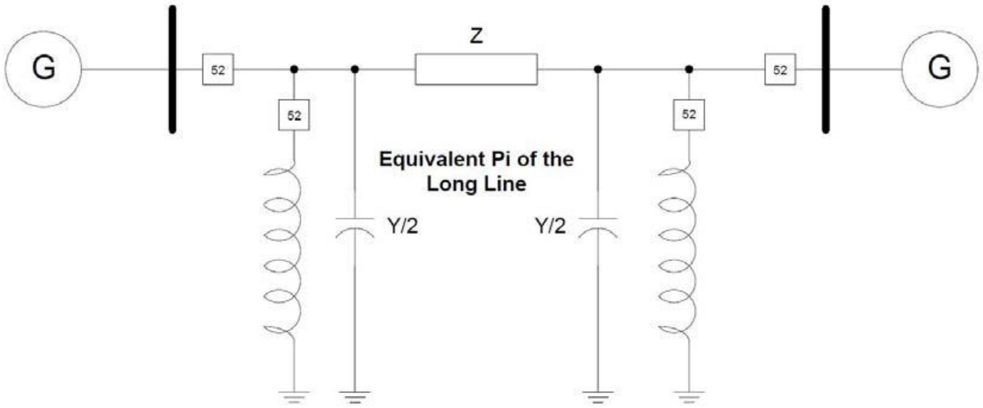

Figure 2.4: Single line diagram of the Switched Shunt Reactors connected at both ends of the line (Gajić et al., 2003)

The shunt reactor could be permanently connected or switched via a circuit breaker. To improve the adjustment of reactive power consumption, the reactor can also be variable.

This chapter will cover the literature review of finding that is related to this study. In the first Section 2.2 a brief review about shunt reactors implementations for recovering the reactive power that present in an electrical system. While in Section 2.3 will discuss the transient phenomena in the switching operation of shunt reactors.

2.1.1 Classification of the Shunt Reactor

In general there are two types of Shunt Reactors. The first one is dry-type Reactor of an air-core or core-less design and the second one is oil-immersed Shunt Reactor. Dry-type Shunt Reactors are limited to voltages up to 34.5kV and are often installed on the tertiary of a transformer (Figure 2.5) or are used in switched virtual circuit (SVC) installations.

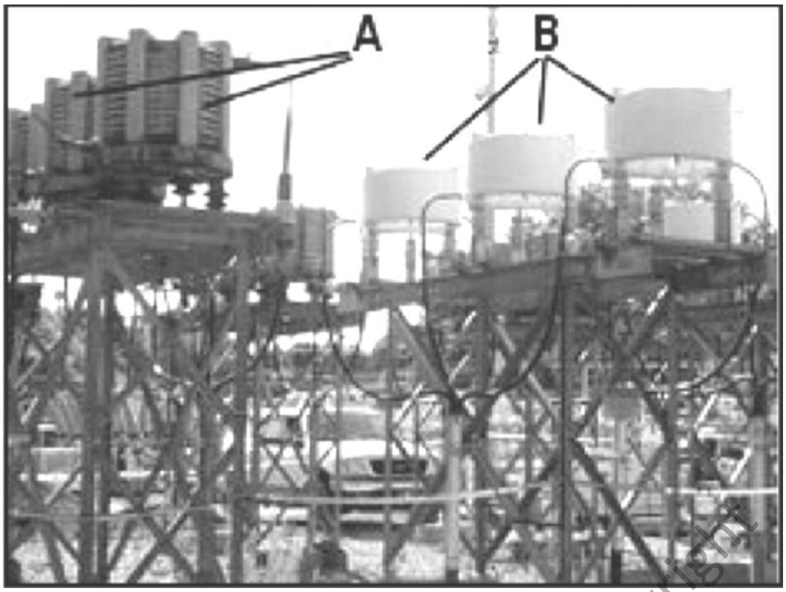

Figure 2.5: An old design air-core Shunt Reactor (A) and a modern air-core Shunt Reactor (B), connected to the tertiary winding of a large transmission network transformer(Shenkman, 2005)

Figure 2.6 illustrates a three-phase core-less Shunt Reactor (dry-type) which is installed in a distribution substation. As seen, there is no iron at all in the core-less concept.

Figure 2.6 : A 3-phase core-less or air-core Shunt Reactor(Rocha and Mendes, 2006)

On the other hand, oil-immersed Shunt Reactors are used for higher voltage levels (higher than 40kV) and are the most compact and cost efficient Reactors. Regarding the core design, two different ways has been used in building oil-immersed Shunt Reactors. First one is referred to as core-type or gapped core, and the second one is called shell-type design.

The gapped core Reactor has a subdivided limb of steel core with air gaps; the limbs are located inside the winding. Figure 2.7 shows a cylindrical segment of the radially laminated core steel sheets which are then moulded in epoxy resin to make a solid piece. Each core module is a core steel block with its stiff ceramic spacers. Core modules are then accurately stacked on top of each other and cemented to make a solid core limb column (Figure 2.8.a).

As mentioned before, it is desired to implement a certain reactance (X_R) in the reactor in order to consume the required level of reactive power. Since it is needed to take a relatively large current in Shunt Reactors to have considerable reactive power consumption, the equivalent reactance in Shunt Reactors should be small compare to a power transformer magnetizing impedance. Therefore the magnetic permeability of the core (μ) should be reduced in Reactors. A good way to reduce the magnetic permeability and the resulting reactance (X_R) is to create air-gap in the core. One way is to create one big air-gap and adjust the gap length in order to achieve a certain level of reactance. However, having one big gap results in large losses.

As can be seen in Figure 2.8.a, instead of having one big gap, numbers of smaller gaps are implemented in order to minimize the losses. On the other hand, the magnetic field in the core limb creates pulsating force whenever it passes through different materials in the core. Since these forces are proportional to square of current