TRANSIENT ANALYSIS OF MECHANICALLY SWITCHED CAPACITOR WITH DAMPING NETWORK

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Transient Analysis of Mechanically Switched Capacitor with Damping Network

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ABSTRAK

Pemuat tersuis mekanikal dengan redaman rangkaian (MSCDN) digunakan sebagai unit pemampas kuasa reaktif di dalam sistem kuasa moden. MSCDN menstabilkan voltan dan meningkatkan keupayaan sistem penghantaran dengan memastikan kuasa reaktif yang mencukupi dapat dibekalkan pada bila-bila masa. Fenomena voltan fana sering berlaku pada MSCDN yang berpunca dari pusuan kilat, pusuan pensuisan, resonan, kerosakan, operasi pemutus litar, dan lain-lain. Fenomena fana memberi impak besar kepada MSCDN dan komponennya yang boleh membawa kepada kerosakan penebat, discas, flashover, letupan, dan sebagainya. Oleh yang demikian, kajian tentang kejadian voltan terlampau di dalam sistem kuasa adalah sangat penting. Dalam tesis ini, MSCDN yang dikaji adalah terdiri daripada komponen-komponen seperti pemuat utama (4.54 μF) yang membekalkan kuasa reaktif (225 MVar) pada voltan nominal 400 kV, yang dihubungkan dengan rangkaian redaman. Redaman rangkaian tersebut terdiri daripada pemuat tambahan (35.81μF), perintang redaman (474.07 Ω) dan penapis pearuh (282.94 mH). Tujuan utama kajian ini adalah untuk menentukan voltan dan arus fana bagi sistem satu fasa dan tiga fasa MSCDN dan menentukan keadaan pensuisan yang ideal yang memberikan magnitud voltan yang paling rendah pada setiap komponen MSCDN. Dalam tesis ini, fenomena keadaan fana pada setiap komponen MSCDN ditentukan dengan mengubah masa pemutus litar membuka dan menutup litar satu fasa dan tiga fasa MSCDN. Perubahan masa tutup dan masa buka pada pemutus litar ini mengambarkan keadaan pensuisan MSCDN secara segerak. Untuk analisis sistem satu fasa MSCDN, pengiraan secara analitikal menggunakan jelmaan Laplace telah dibuat untuk mengira arus dan voltan fana, dan seterusnya keputusan yang diperolehi dibandingkan dengan simulasi ATP-EMTP bagi tujuan pengesahan. Program ATP-EMTP telah dipilih untuk simulasi operasi pensuisan MSCDN salah satunya adalah kerana program ini menggunakan penyelesaian dalam domain masa yang sangat berguna bagi tujuan perbandingan dengan kaedah analitikal yang dibuat dalam tesis ini. Bagi sistem satu fasa MSCDN, didapati bahawa kes pensuisan ideal telah berlaku ketika masa pensuisan ditetapkan pada 0 ms dan 5 ms. Manakala bagi sistem tiga fasa MSCDN, operasi pensuisan tutup dan pensuisan buka telah dimodelkan bagi mengenal pasti voltan dan arus fana dalam keadaan pensuisan segerak. Berdasarkan keputusan yang diperolehi, masa pensuisan tutup segerak yang ideal bagi semua fasa adalah 5 ms. Bagi kajian pensuisan buka MSCDN, keputusan simulasi yang diperolehi menunjukkan bahawa tidak ada keadaan fana yang terhasil semasa MSCDN diputuskan dari sistem kuasa secara segerak. Pemerhatian ini dirumuskan sebagai satu kelebihan MSCDN berbanding litar pemuat yang biasa.

Transient Analysis of Mechanically Switched Capacitor with Damping Network

ABSTRACT

Mechanically switched capacitor with damping network (MSCDN) is used as reactive power compensation unit in the modern power systems. MSCDN stabilizes the voltage and increases the transmission capacity to ensure the availability of reactive power for feeding in the injection of reactive power at short notice. The transient overvoltage phenomenon often occurs in MSCDN due to the lightning surge, switching surge, fault, resonance, circuit breaker operation, etc. These transients impose great stresses to the MSCDN and its components and could lead to insulation breakdown, discharge, flashover, explosion, and so on. For this reason, studying the overvoltage of power system is of extreme importance. In this thesis, the studied MSCDN consists of a main capacitor (4.54 µF) supplying the desired amount of reactive power (225 MVar) at a nominal voltage of 400 kV, connected to damping network providing sufficient damping of switching processes. The damping network consists of an auxiliary capacitor (35.81µF), damping resistor (474.07 Ω) and a filter reactor (282.94 mH). The main aim of this study is to determine transient voltages and currents for single and three phase's system and find the ideal switching condition that gives the lowest overvoltage magnitude at each MSCDN components. In this work, the transient stresses of MSCDN components were determined by varying the closing and opening times of the circuit breaker for both single and three-phase connections. Variations in the circuit breaker times simulate the synchronous switching conditions of the MSCDN. For the single-phase analysis, analytical calculation using Laplace transform was used to calculate the transient currents and voltages, and the results obtained were compared with ATP simulation for validation. Alternative Transient Program (ATP-EMTP) was employed to reproduce the switching operation of MSCDN, as ATP gives solution in time domain and very useful for comparisons with analytical method conducted in this work. For single phase, it was found that the ideal switching cases were obtained when switching at 0 and 5 ms respectively. Furthermore, for three-phase MSCDN, the energisation and de-energisation of MSCDN were simulated to identify the transient voltages and currents for synchronous switching. Based on the results obtained, the ideal synchronous closing time of all phases was 5 ms. For MSCDN de-energisation studies, the simulation results obtained showed that there are no visible transients produced by synchronous de-energisation of MSCDN. This is the advantage of MSCDN circuit as compared to regular capacitor banks.

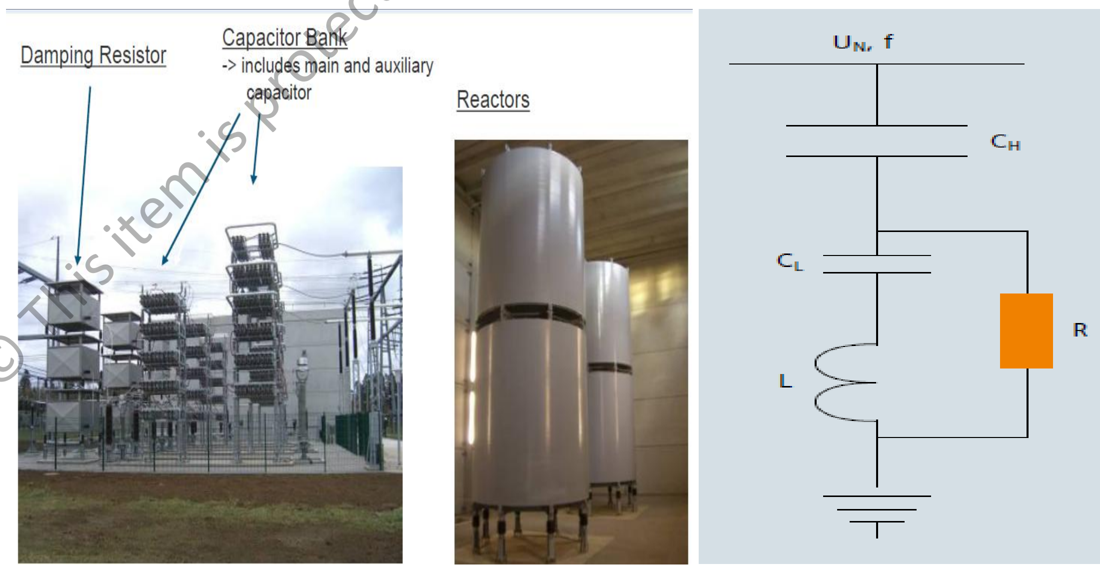
CHAPTER 1

INTRODUCTION

Transient disturbances in power systems lead to damage key equipment, and have a great influence on system reliability. Therefor, the Mechanically switched capacitor with damping (MSCDN) is mainly required to avoid harmonic resonance problems, which consequently could lead to unwanted voltage transients. Besides, MSCDN has designed to assist the dual function of reactive power compensation and harmonic filtering; a simple and low-speed solution for voltage control and network stabilization under heavy load conditions. Transient studies were depended on the system configurations and the switching operation on circuit breakers witch used to connect the unit to power systems. The switching operations also categorized upon condition of circuit breaker as open or close state. To study transient, the easiest way is simulation by simulation software as ATP-EMTP. The simulation was given transient's results as in that happen in the real system. The optimized parameters of any system network were set by simulation, because the simulation was to predict of the voltage and current across all system components.

1.1 Mechanically Switched Capacitor with Damping Network

MSCDN is a version of mechanically switched capacitor (MSC), where it has been designed as C-type filter with additional damping circuit (Fig. 1.1) which provides essentially voltage support without increasing existing system harmonics. Normally, MSCDN can be represented in a circuit form as in Fig. 1.1b. The circuit consists of passive elements: the main capacitor (C_H), the series branch of a tuning capacitor and a reactor (L-C_L), and the damping resistor (R). MSCDN is a suitable reactive power compensation system for HV energy transmission networks (Siemens AG, 2002-2014). Due to that, it is able to stabilize the voltage and raises the transmission capacity to certify the availability of reactive power for feeding in the injection of reactive power at short notice. In practice, at a nominal voltage of transmission grid (380 kV), MSCDN systems allow grid operators to inject up to 250 MVar of capacitive reactive power within seconds. The characteristics to be considered of a filter in power system decrease voltage harmonics, due to the increasing number of power electronics components, producing a higher voltage quality (Siemens AG, 2002-2014).



(a) (b) (c)

Figure 1.1: (a) Real MSCDN (b) Real filter reactors (c) Simplified single line of MSCDN (Kampa, 2012).

The flexible MSCDN system may eliminate any risk of a voltage increase when required; where it supports high capacity voltage levels and on the other hand, may be disconnected from the grid at lower capacity. In addition, MSCDN systems are designed to be disconnected or connected several times per day MSCDN is a proven technology improved to a new market situation. It has common advantages which enlarge the significance of use because transmission capacity by MSCDN is large, and it can easily supply reactive power whenever needed and a quick amortization of investment. Besides the environmentally issues, the integration of MSCDN in substations is environmental friendly, where MSCDN can reduce the power losses which lead to the reduction emission of CO_2. Also, by MSCDN, it can postpone or totally suspend the new construction of overhead lines (Siemens AG, 2002-2014).

1.2 Design of MSCDN

As mentioned in the previous section, MSCDN is one of the simplest forms of power system compensation, where it provides a reactive power compensation for the substation to guarantee that the power system is both balanced and efficient. In general, the major components of MSCDN are:

1) Switch: The switch is a mechanical device to break time, and it should be absolutely essential for effective implementation of all types of switching process. Controlled switching is used to minimize stresses on the power system and MSCDN components. Also, the stresses on the circuit breaker during switching operations by switching on the most favourable time-instant when switching small capacitive and inductive currents or even fault currents can be minimized with controlled switching.

2) Main Capacitor: Capacitors (MSC) is the main component which is used to adjust the flow of reactive power and voltage levels in the power system, thus, reduces the disturbance in voltage waveform.

3) Damping Circuit: Damping circuit is an electrical circuit consisting of a resistor, an inductor and capacitor (RLC), connected to MSC as shown in Fig. 1.1 to avoid the system resonance. Besides, the most important auxiliary component which is attached to MSCDN is a surge arrester, which is designed for the protection of overhead distribution equipment. They protect the major electrical equipment from damage by limiting overvoltage and dissipating the associated energy (Kim, Funabashi, Sasaki, Hagiwara, & Kobayashi, 1996). However, the most common types of surge arresters are metal oxide type and silicon carbide arrester. Choosing a type of surge arrester depends on the high reliability in most application. The significant advantages of a surge arrester were concluded in improving overall quality and decreasing moisture ingress and ability to absorb energy (Hileman, 1999).

1.3 Transient Study

A transient phenomenon is generally an obvious appearance of an unexpected temporary change in the system situations. This change in voltage or current occurs over a short period of time. A transient is defined in IEEE 1100-1999 as: *A sub-cycle disturbance in the AC waveform that is evidenced by a sharp, brief discontinuity of the waveform* (IEEE Std 1100-1999). Transients are divided into two categories which are easy to identify: impulsive and oscillatory. There are a number of causes leading to produce transients in power systems which can summarized to; (i) switching actions or electrical faults namely lightning strikes, short circuits, or equipment breakdown, (ii) changing within the electric power system (circuit configuration) and suddenly, transients caused equipment damage or interrupt operation. Transient phenomenon is certain of 80% of all electrically-related interruption. Effective damping equipment of transient voltage can increase the life of electrical and electronic equipment. For example, the changes which occurred by lightning strikes introduce a big quantity of energy into the power system in seconds. The exposed transmission or circuit configuration (connection or disconnection of elements within the electric circuit) result in variations of voltages and currents which maintained until the further energy is absorbed by dissipative elements as surge arresters. These deviations are a temporary departure of system voltage and current from their normal steady-state sinusoidal waveforms.

On the other hand, the previous transient studies were focused on several cases; namely switching surge analysis, shunt reactor & capacitor switching, vacuum circuit breaker switching, power-electronic device switching and more which can be viewed in reference (Electrotek Concepts Inc., 2002-2014). The researches were performed to evaluate the transients related with energisation of overhead transmission lines and studies related to transients, surge arrester ratings, transient damping methods, energisation of shunt reactors or capacitor banks in industrial or public utility facilities and various switching actions such as fault application and clearance. For more details, there are several transients in electrical power systems which were summarized as; (i) over-voltages (ii) over-currents, (iii) abnormal wave forms and (iv) electromechanical transients.

(i) Transient overvoltages: The overvoltages can be produced by quasi-steady state situations or due to short-duration high frequency phenomenon created by shock excitation of the power system. The quasi-steady state overvoltage conditions are often known as dynamic over voltage. Voltage excursions occur during load rejection, loss of shunt reactor compensation on long overhead lines or cables, and generally results from some abnormal system operating condition. Capacitor switching is considered to be a normal event on a utility system and the transients associated with these operations are generally not a problem for utility equipment, because peak magnitudes are just below the level at which utility surge protection, such as arresters, begins to operate (1.8 pu or above). For example, the transient which originates when a capacitor is switched in or out of the system will diffuse in the distribution feeder direction. Prior to switching on a capacitor, the voltage across the terminals is zero. This is because capacitor voltage cannot change instantaneously, energizing a capacitor results in an instantaneous drop in system voltage toward zero, followed by a fast voltage recovery (overshoot) and finally an oscillating transient voltage overlaid on the 60 Hz fundamental waveform as showed in Fig. 1.2.

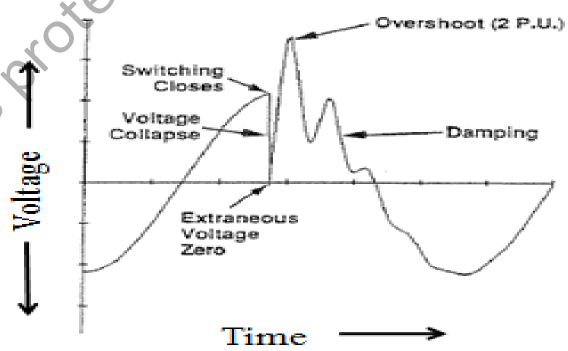


Figure 1.2: Switching Transient

(ii) Transient overcurrents: It is a peak value in current waveform surpassing the regular peak at typical current condition which is caused from system faults. The study of over-current particularly leads to determining the circuit breakers interrupting, mechanical and thermal stresses within system components.

(iii) Abnormal waveforms: It is overall an irregular waveform of voltages and currents in power systems through transient situations compared to its normal steady state situations. The analysis and simulation of these situations need an analytical tool which is capable of representing the whole spectrum of voltages and currents power system.

(iv) Electromechanical Transients: Electromechanical transient was observed in power systems when the closing operation occurs, transient currents will be produced and then followed by an opening operation which causes interruption in a power frequency current of system device as well as a transient recovery voltage. Conventionally, electromechanical transients have been investigated by transient stability programs. These programs imposed positive sequence demonstration and fundamental frequency models for the full system.

1.4 Energisation and De-energisation Transients

Energisation transient is a transient overvoltage originating from connecting some parts of the power system to a potential source which is incapable to store energy. It is a power quality issue because it is one of the most frequent system-switching operations. During normal energisation of the filter banks, the fast-fronted voltage and current waveforms may be generated which lead to producing large rates-of-change in the voltage and current, which consequently may expose the filter components to hazardous voltage stresses. Generally, when a capacitor bank is switched on to a supply, there is a powerful current surge because, for the first instant, the capacitor bank appears as a short circuit to the network.

De-energisation transient is an over-voltage transient produced from disconnecting parts of the free faults power system network. De-energisation of the passive filter may cause restrikes in the circuit breaker due to arc instability, which can subsequently produce severe over-voltages at the filter components. In the MSCDN system, the disconnection of capacitor is usually made at an instant corresponding to the minimum current of the system. Then, followed by the current interruption and the capacitor are charged to full system voltage.

1.5 Problem Statement

Generally, in the electrical operation, the voltage and current system does not remain within specified limits; due to changes in the load conditions and system configuration caused by switching operations that affect the system voltage and current. Thus, the voltage rises in the opening or closing events of a switching which should not exceed the rating limits of the network system equipment. Problems with switching of small capacitive and inductive currents can be controlled by switching time. For normal conditions, controlled switching reduces voltage and current transients to a minimum value. The main goal of this study is to recognize and investigate the single and three-phase MSCDN at switching operations to control and optimize voltage levels.

1.6 Objectives

The main objectives of this work were:

1) To study an analytical procedure for s-domain and time-domain relationships of all components of single-phase MSCDN and validate it with ATP-EMTP simulation.
2) To investigate and simulate the affects of energizing and de-energizing transient stresses produced at all single and three-phase MSCDN components.

3) To reduce the transient of MSCDN by changing the switching time, and then compare the results with rated values.

1.7 Scope of the Study

This study was focused on the transient phenomenon which occurs in a single and three-phase MSCDN. The research elements would be to study and analyze the energisation transient, de-energisation transient in three-phase MSCDN. Besides, it was included background information, analytical calculations which were explained and applied for the transient phenomenon of MSCDN components. The used analytical method is the Laplace transformation method for transient calculation in the single-phase MSCDN circuit. This research was focused on controlling switching operation, which is by changing the switching device and simulation of MSCDN circuit using ATP-EMTP software, the operation of opening or closing the circuit breaker at a pre-determined point on a reference voltage or current shape wave. Computation of overvoltages and overcurrents occurring in all of the MSCDN components (three-phases) were analyzed and compared in all of the following cases: (1) Synchronous energisation (switch-on) and (2) Synchronous de-energisation (switch-off).

1.8 Thesis Organization

This thesis is organized into five chapters. The first chapter introduces the technical background of this study, the brief aspects that are explored in the study, objectives, problem statement and finally gives a view of the structure of the thesis. Brief summaries of the literary reviews related to the MSCDN design, and its transient studies are presented in Chapter 2, while Chapter 3 explains the methodology used in this research which gives the details of the main means to study the transient phenomena and the used tools to simulate the electrical power system. This chapter is divided by two parts; the first part about single-phase MSCDN and the second part about the three-phase MSCDN. Chapter 4 discusses the simulation results of transient in a single and three-phase MSCDN through different cases. Finally, chapter 5 contains the conclusions and our recommendations for future work.