UNIVERSITI PUTRA MALAYSIA

CHARACTERIZATION OF TRANSIENTS DUE TO CAPACITOR BANKS IN LOW VOLTAGE SYSTEMS

SALIH GWAMI MOHAMMED HAMAD

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

I am dedicating this thesis to the soul of my father and mother, I am so grateful for their kindness, and I will never forget them
&
To, my wife, and my whole family, with love and deep thanks

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Gorakanage Arosha Chandima Gomes, PhD
Faculty : Engineering

The scarcity of literature addressing transients due to capacitor bank switching is obvious. Hence, this study was conducted with three objectives in mind. First, to characterize capacitor bank switching transients generated in a low voltage power system with selected inductive and resistive load. During the energizing and de-energizing processes, capacitor banks generate and inject severe transient overvoltage and inrush current into the system that will result in several issues. Although there are several studies conducted on capacitor bank switching transients in medium voltage systems, there are only a few studies done on the same phenomena in low voltage systems. Previous literature shows that damage due to capacitor bank switching transients is higher in low voltage systems than that in medium and high voltage systems. Characterization of transient voltage and current in low voltage systems due to switching of capacitor banks is an important process, needed to provide solutions to the issues, which has not been done comprehensively so far. Second, to simulate the experimental power system to generate capacitor bank switching transients and validate the results with experiments. Also, it was intended to compare the simulation results by experiment in real low voltage systems in addition to calculate the specific transient energy generated by capacitor bank switching. Third, to find the response of available surge protective device in mitigating capacitor bank switching transient effects.

Power System Computer Aided Design software package has been used in this study to simulate the energization of capacitor bank switching in specific low voltage systems, with and without employing mitigation devices. Besides, the study employed experimental measurements of quantities such as peak transient over voltages, inrush currents, and transient duration for each case in five step shunt capacitor banks. Analysis of voltage and current waves has been carried out to extract acceptable capacitor switching times by observing the transient voltage and current.

The findings showed that there is a severe current for the given loads due to switching of capacitor banks which tends to propagate in the system which may damage the capacitor bank itself and affect the end users. There are increases of transient peak values of current and voltage waveform due to the capacitor size and short rise time. In this case, long duration of transient may lead to high loss of energy in the system. The transients that were generated by both simulation and experimental technique were compared, and found to be slightly different owing to the environmental effects and level of accuracy of the measuring devices. Surge Protective Device meant for lightning transient protection are not efficient in their present form in mitigating transients generated by capacitor switching. It was shown that typical levels of the transient's impulse current magnitude range from 116.9A to 163.1A, and from 113.4 A to 165.5A for simulation and measurement results, respectively when connected to the single phase measurement. It was also shown that the transient current for the three phase connected measurement is ranged from 116.2 A to 166.6A and from 117.7 A to 180.3 A for simulation and experimental results, respectively. Hence, curtailing of the specific energy and the energy dissipation of transients by means of filtering or attenuating devices has been strongly recommended. The comparison of the outcomes clearly shows that there are only minor differences between the simulation results and the experimental results in real low voltage systems.

Severe currents that are produced during capacitor operations in power systems could be harmful to insulation, and capacitor bank control and equipment. The time of occurrence of the transient in the nominal 50Hz voltage waveform due to capacitor switching is a deciding factor for the safe operation of the system and equipment. The application of Surge Protective Devices, in their present form, will be insufficient, as they could not significantly reduce transient inrush current and voltage in low voltage system. This is proven by both experimental and simulation results. Depending on the time position of the transient in nominal voltage waveform and the transient polarity, its effects may vary. The worst scenario is the transient occurring at the peaks of the nominal voltage with the polarity as same as that of the nominal voltage waveform. Furthermore, there is a need to look for electronic switching to reduce the duration of the transient, which indirectly will reduce the effect of transients to the systems. The results can serve as a guidance for manufacturing technologists as well as electrical and electronic engineers in addressing and developing capacitor banks, thus solving transient switching issues for low voltage systems.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KARAKTER DARI TRANSIEN DISEBABKAN OLEH BANK KAPASITOR DALAM SISTEM VOLTAN RENDAH

Oleh

SALIH GWAMI MOHAMMED HAMAD

Jun 2017

Pengerusi : Profesor Gorakanage Arosha Chandima Gomes, PhD
Fakulti : Kejuruteraan

Kekurangan kesusasteraan yang berkaitan transien disebabkan oleh pertukaran bank kapasitor adalah jelas. Kajian ini dijalankan dengan tiga objektif dalam fikiran: Pertama, ia menonjolkan transien pertukaran bank kapasitor yang dihasilkan dalam sistem kuasa voltan rendah dengan beban yang dipilih. Semasa proses menyalurkan tenaga dan proses memutuskan salur tenaga (nyah-tenaga), bank kapasitor menjana dan menyuntik voltan berlebihan dan arus masuk ke dalam sistem yang akan menghasilkan beberapa isu. Walaupun terdapat beberapa kajian yang dilakukan pada transien pertukaran bank kapasitor dalam sistem voltan sederhana, hanya terdapat beberapa kajian yang dilakukan pada fenomena yang sama dalam sistem voltan rendah. Sastera terdahulu menunjukkan bahawa kerosakan yang disebabkan oleh transien pertukaran bank kapasitor lebih tinggi dalam sistem voltan rendah berbanding dengan sistem voltan sederhana dan tinggi. Pencirian voltan semasa dan transien sementara dalam sistem voltan rendah disebabkan oleh pertukaran bank kapasitor merupakan proses penting, yang diperlukan untuk memberikan penyelesaian kepada isu-isu, yang belum dilakukan secara komprehensif setakat ini.

Kedua, untuk mensimulasikan sistem kuasa uji kaji untuk menghasilkan transien bank kapasitor dan membuktikan keputusan dengan data eksperimen. Selain itu, ia bertujuan untuk membandingkan hasil simulasi dengan eksperimen dalam sistem voltan rendah sebenar selain untuk mengira tenaga sementara tertentu oleh peranti pelindung yang tersedia dalam mengurangkan kapasiti penukaran bank kapasitor. Pakej perisian Sistem Pembekalan Komputer Kuasa (PSCAD) Kuasa Komputer telah digunakan dalam kajian ini untuk mensimulasikan penjanaan pemancaran bank kapasitor dalam sistem voltan rendah khusus, dengan dan tanpa menggunakan peranti pelupusan. Selain itu, kajian ini menggunakan pengukuran kuantiti eksperimental seperti titik tertinggi sementara melebihi voltan,arus masuk, dan tempoh transien bagi setiap kes dalam lima langkah kapasitor bank.

Analisis voltan dan gelombang semasa telah dijalankan untuk mengekstrak masa penukar kapasitor yang boleh diterima dengan memerhatikan voltan semasa. Penemuan menunjukkan bahawa terdapat arus yang teruk bagi beban yang diberikan disebabkan oleh pertukaran bank kapasitor yang cenderung menyebarkan dalam sistem yang boleh merosakkan bank kapasitor itu sendiri dan menjejaskan pengguna akhir. Terdapat peningkatan nilai puncak semasa dan voltan disebabkan saiz kapasitor dan masa kenaikan pendek. Dalam kes ini, jangka panjang membawa kepada kehilangan tenaga yang tinggi dalam sistem. Jangka masa ini dihasilkan oleh teknik simulasi dan eksperimen dan dibandingkan. Hasil simulasi dan hasil eksperimen dalam sistem voltan rendah sebenar adalah dalam persetujuan yang baik.

Peranti bermaksud perlindungan perlindungan kilat tidak cekap (dalam bentuk sekarang) dalam mengurangkan transien yang dijana oleh pertukaran kapasitor. Telah ditunjukkan bahawa tahap keganjilan magnitud semasa khas dari 116.9A hingga 163.1A dan dari 113.4 A hingga 165.5A untuk simulasi dan pengukuran masing-masing apabila disambungkan kepada ukuran fasa tunggal. Ia juga menunjukkan bahawa arus transien untuk pengukuran tiga fasa bersambung adalah dari 116.2 A hingga 166.6A bagi hasil simulasi dan dari 117.7 A hingga 180.3 A untuk keputusan eksperimen. Oleh itu, mengurangkan tenaga tertentu dan pelesapan tenaga transien dengan cara penapisan atau peranti melemahkan telah sangat disyorkan. Keempat; Perbandingan hasil jelas menunjukkan bahawa terdapat hanya perbezaan kecil antara hasil simulasi dan keputusan eksperimen dalam sistem voltan rendah sebenar. Dari penemuan, kesimpulan berikut boleh dibuat. Arus yang teruk dihasilkan semasa operasi kapasitor dalam sistem kuasa yang boleh membahayakan kawalan dan peralatan kawalan penebat dan kapasitor bank. Semasa berlakunya transient dalam bentuk gelombang voltan nominal 50Hz disebabkan penukaran kapasitor adalah faktor penentu bagi operasi sistem dan peralatan yang selamat.

Penerapan SPD, dalam bentuknya sekarang, tidak mencukupi, kerana mereka tidak dapat mengurangkan aliran semasa dan voltan sementara dalam sistem voltan rendah. Ini terbukti dengan keputusan eksperimen dan simulasi. Bergantung pada kedudukan masa transien dalam bentuk gelombang voltan nominal dan kekutuban sementara, kesannya mungkin berbeza-beza. Senario terburuk adalah berlaku pada puncak voltan nominal dengan nilai kekutuban sama dengan bentuk voltan nominal nominal. Selain itu, terdapat keperluan untuk mencari pertukaran elektronik supaya dapat mengurangkan tempoh sementara.

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I certify that a Thesis Examination Committee has met on 21 June 2017 to conduct the final examination of Salih Gwami Mohammed Hamad on his thesis entitled "Charaterization of Transients Due to Capacitor Banks in Low Voltage Systems" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF SYMBOLS

C	Capacitance in F
h_1	Resonant frequency due to CBs
I_C	Capacitor current
L	Inductance in H
P	Active power
Q	Quality factor
Qc	Reactive power capacitive
QL	Reactive power inductive
S	Apparent power
VAR	Volt- Ampere Reactive
ν	Velocity of the waves propagation m/s
Z_0	Surge impedance
ω_n	Natural frequency
τ	Time constant

LIST OF ABBREVIATIONS

AC	Alternating Current
CBs	Capacitor Banks
CBST	CB Switching Transient
CBs	Circuit breaker
EHV	Extra High Voltage
FFT	Fast Fourier Transform
FS	Fixed capacitor
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
LV	Load Voltage System
MOV	Metal Oxide Varistor
MVA sc	The short circuit rating of source
MV	Medium Voltage system
PF	Power Factor
RMS	Root Mean Square
SPDs	Surge Protection Devices
STATCOM	Static Synchronous Compensator
SSTL	Symmetrical Structure Transient Limiter
SVC	Static Vars Compensation
SR	Switched resistor
THD	Total Harmonic Distortion
TOVs	Transient overvoltages
TRV	Transient Recovery Voltage
TSC	Thyristor switched capacitor
TCR	Thyristor controlled reactor
VCB	Vacuum Circuit Breaker
ZVC	Zero Voltage Closing

LIST OF SI UNITS

SYMBOL	DEFINITION	SI UNIT
I	Current	A
V	Voltage	V
R	Resistance	Ω
f	Frequency	Hz
C	Capacitance	F
L	Inductance	H
W	Energy	J
t	Time	s
T	Temperature	°C

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CHAPTER 1

INTRODUCTION

1.1 Introduction

There is a widespread discussion of transient disruption phenomena in the literature on the power system, which is generally conceptualised as abnormal or sudden change at a short period of time in the power system [1]. The said attention of literature is related to the fact that transient disruption phenomena in power systems may harm the vital equipment and lead to an enormous influence on system reliability and constancy. It is well established that the introduction of transients may be carried out when normal switching is operating, short circuits cause an interruption, lightning strikes, or when equipment fails. For that reason, the phasor analysis or other simplified analysis procedures become commonly insufficient because of system frequency dependencies and nonlinearities. In this respect, time-domain computer models according to Rufer et al. [2] are characteristically developed to predict the extent of the transient event levels.

Switching transients are transients initiated by the operation of breakers and switches in a power scheme [3], and divided into three main categories, energization, de-energization, and re-closure. The energization phenomena involve the elements of the system such as transmission lines or cables, transformers, reactors and CBs (CB). However with, re-closure, the lines may end up with a trapped charge after the opening of the Initial breaker. As such, the overvoltage of transients can reach the highest value, and de-energization, including clearing faults and rejecting loads. To date, a considerable number of studies on transient have focused on the High Voltage (HV) and Extra High Voltage (EHV) transients. Previous studies have identified switching transients are one of the most problematic disadvantages related to CBs. Very few studies have been focused and investigated the effects of shunt CBs in Low Voltage (LV) systems [4, 5]. CBs in LV systems may generate dangerous voltage and current transients during switching operations. Such observation had vital implications for the development of this study which meant to investigate the switching transients created during the switching of the three-phase shunt CBs.

Transients which are generated by CB switching in LV distribution system is the main interest of this study. CBs are extensively employed for both transmission and distribution grids. The advantages include the ability to compensate reactive power, enhance network capacity, support voltage, and minimize power losses. Central to the CB operation is the use of shunt CBs which in addition to the stated advantages they have low cost and are flexible in the fitting and process [6-9]. In practice, the shunt capacitors are used to perform in the power grid in order to control system voltage, boost power transfer capacity, diminish equipment loading, and ease energy cost by improving the power factor (PF) of the system [10]. The utilization of shunt CBs and circuit breakers in the low voltage system could be the main source of equipment failure due to the high voltage and current transients occurrence. The majority of previous studies reported in the literature address shunt CBs connected to HV transmission lines and MV distribution lines. Previous studies have identified switching transients are one of the most problematic disadvantages related to CBs. to date very few studies were focused on the effects of shunt CBs in LV systems. CBs in LV systems may generate dangerous voltage and current transients during switching operations [11].

Commonly, CBs can be divided into two groups, shunt, and series based on the way in which they are linked to the system. Between these two groups, the shunt capacitors are very commonly used in the power grids of all voltage levels. Shunt capacitor draws almost fixed amount of leading current which is superimposed on the load current and therefore reduces reactive components of the load and thereafter increases the power factor of the system. Series capacitor, on the other hand, has no control over the flow of current. As these are linked in series with the load, the load current continuously passes through the series CB. Essentially, the capacitive reactance of series capacitor neutralizes the inductive reactance of the line henceforth, decreases, the effective reactance of the line. Thus, voltage regulation of the system is enhanced. However, series CB has a main disadvantage as during a failure condition, the voltage across the capacitor may be extremely higher than its rated value. This series capacitor must have sophisticated and intricate protective equipment. Due to this reason, the utilization of series CB is limited only in the EHV system. Devices being applied to the power system are more susceptible to power quality variations than equipment applied in the past. The increasing emphasis on overall power system efficiency is causing a continued growth in the request for shunt CBs. This may happen within consumer services, as well as on the power system. Magnification of capacitor switching transients may be the most important concern due to the fact that the transient overvoltages can be very high and the energy levels associated with these transients can cause equipment failure [12-14].

Generally, CBs are located in distribution and transmissions systems so that they can significantly reduce losses and minimize voltage drop. For that reason, Consumer may be in a position to utilize them in order to increase the performance of the scheme. However, switching of shunt CBs under normal conditions tend to create problems. It has been documented that switching shunt CBs in the presence of nonlinear loads result into intense frequency transients [1, 10]. This means that switching of shunt CBs causes changes to the properties of voltage and current waveforms in power systems, which are different from pure sinusoidal amplitude signals. In such situations, there is a need for advanced processing approaches to attain accuracy and devolving solutions for electrical power transients occur due to Surge Protection Device (SPD), Metal-Oxide Varistor (MOV), power filter, and insert resistance and inductor. Therefore, it is essential to consider the influences of connected CBs in the presence of nonlinear loads, and the increase of extended installation in electrical grids.

Consistent to the CBs disadvantages, researchers have suggested several techniques as solutions. It is argued that applied techniques to solve transient issues caused by shunt capacitor switching should have been based on ways to reduce transient voltages and the removal of transient magnification at LV bus [15, 16]. That understanding has opportune to have numerous approaches to limit transient overvoltage during CB switching at the point of application. Moreover, the current devices are used for transient overvoltage control brand as an effort to reduce the transient overvoltage or overcurrent at the producing time or to limit the overvoltage at local and remote sites. This could be the reason behind the recommendations by the previous research that the efficiency of control procedures of transient mitigation device should depend on the system [17]. Based on this, one could ask what made the study on transients due to CBs and development of addressing issues important at the first place. This study was important as a way to closely analyse the system in order to choose the ideal control protection device. This was important because analysis of distribution network of capacitor applications is not often adequately done. For that reason, CBs are fitted with no control of transient overvoltage leading to consideration for cost requirements on installation, operational maintenance and reliability [18]. Therefore, this study was important as an attempt to address appropriate solutions needed to mitigate transient switching due to CB in LV to the acceptable level.

1.2 Problem Statement

Currently, due to the extended electric grid and development of industries, CBs are widely used in power systems at all voltage levels. The CBs are utilized to increase power transmission capability, compensate a reactive power, and improve the power factor and voltage profile. Moreover, they are used to control system voltage in the grid, reduce equipment loading and decrease electrical consumption charge. During the energizing and de-energizing processes, CBs generate and inject severe transient overvoltage and inrush current into the system that will result in several issues. Many insulation failures have been reported caused by switching transients [19, 20]. The manifestation of the Vacuum Circuit Breaker (VCB) brings a switching appliance with outstanding interruption, and dielectric recaptures characteristics [21]. Despite the advantages of VCB, it has been reported worldwide that numerous transformer insulation failures have occurred probably due to switching operations of VCBs [22, 23]. Although, these transformers have been formerly passed all the standard examinations, and complied with all superiority requirements. The utilization of CBs and circuit breakers in the LV system could be the main source of equipment failure due to the high voltage and current transient's occurrence [24].

Although there are several studies conducted on CB switching transients in MV systems, there are only a few studies done on the same phenomena in LV systems. Previous literature shows that damage due to CB switching transients is higher in LV systems than that in MV/HV systems. Characterization of transient inrush current and transient voltage in LV systems due to switching of CBs is an important process, needed and solutions to the issues are needed, which has not been done comprehensively so far. A validated model simulation of LV systems with CBs under switching operations could provide a significant data bank on transient characteristics, with no previous studies have attempted in such direction. Few studies have discussed the possibility of applying SPD to suppress lightning transients, again, no attempts were made so far in investigating such possibility. The challenges, which exist due to switching transient of CBs, have not been addressed at all or not been addressed thoroughly such related to,

a. characterization of transients due to capacitors banks in LV power system .
b. mitigation of transient overvoltages and inrush currents due to CB switching operations
c. techniques of reducing peak, duration, and energy of transients.

1.3 Objectives of the Research

For this study, these specific objectives are considered:

a. To characterize shunt CB switching transients generated in an LV power system with selected load.
b. To simulate the experimental power system to generated shunt CB switching transient.
c. To find the response of available SPDs in mitigating shunt CB switching transient effects.

1.4 Scope of the Study

The power plants schemes are resulting in the need to reinforce our transmission and distribution systems. One of the measures methods being accepted that is to install extra reactive power in the form of shunt CBs which required details of transient overvoltage simulation studies to promise a successful design. Consequently, shunt CBs are connected in power systems to offer the reactive power compensation, reducing costs and optimizing power distribution systems. The analysis of the effectiveness of the distribution CBs includes measurements and simulation to study the application of the shunt CBs transient overvoltage switching and harmonics. The CBs energizing transient is significant because it is one of the most common utility switching operations. In addition, it produced high phase-to-phase system overvoltages, excite circuit resonances, mechanical and dielectric stresses in the other substation equipment or cause problems with sensitive customer equipment. Therefore, the investigation of the CBs energizing transient is needed to cover the operations switching issues that may arise in the system. Furthermore, it offered and suggested corrective economic measures whenever deemed necessary. The major significance of the study are:

a. identify the nature of transient duties that could happen for any realistic switching operation including the determining magnitude, duration, and frequency of the oscillations.
b. determine if abnormal transient functions are possible to be imposed on equipment.
c. recommend remedial measures to mitigate transient overvoltages and overcurrent including solutions such as resistor preinsertion .pre-insertion inductors, synchronous closing control, high pass damping filter.

There are alternative operating techniques that have been proposed to minimize transient duties if applicable. Moreover, evaluation of transient overvoltage magnitudes for conventional CB energizing operations, including the effects of other CBs and system loads. Evaluation of inrush currents for normal and back-to-back switching operations, and capacitor switching transients on lower voltage systems. With that in mind, this research was focused on investigation on transients due to shunt CBs energization and de- energization in LV side. For that reason, the following limitations were addressed:

a. only five steps shunt CB is applied.
b. variables load and worst cos ϕ are applied
c. constant frequency 50Hz.is applied
d. results are validated by comparing between the simulations and experimental results.

1.5 Thesis Outline

In general, the thesis is organized into five main chapters. The first chapter gives the introduction on the CBs in low voltage systems. The importance and demands of CBs in the distribution network are discussed. This chapter also includes the transient's problem and the available techniques for a solution. The problem statement, the objectives, the scope of the study, the significance of the research, and the organization of the thesis are presented.

The second chapter introduces the basic concept of shunt CB design, insulation, failure modes, and protection, where the switching transient problem and mitigation devices are also intensely discussed.

Chapter 3 provides a detailed representation of the methodology used, where model and equivalent circuit diagram used in the design and simulation were presented. Also, proposed techniques used in developing and improving the mitigation of transients generated by shunt CB switching in LV systems are introduced.

Chapter 4 provides discussions on comparing between simulation and experimental results. While, Chapter 5 concludes the works and recommendations for the future works.

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