MITIGATION OF TRIPLEN HARMONICS IN 3-PHASE 4-WIRE ELECTRICAL DISTRIBUTION SYSTEM

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DECLARATION

I hereby declare that the work submitted in this thesis is my own, except as acknowledged as references, and has not been previously submitted for the Master of Science degree at Universiti Teknikal Malaysia Melaka or any other institution.

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ABSTRACT

This thesis addresses the mitigation of triplen harmonic distortion in 3-phase 4-wire electrical distribution system that supplies balanced and unbalanced non-linear loads. The main objectives of this thesis are to study, design and build passive mitigation devices suitable for mitigation of the triplen harmonic problems. There are four steps involved in building a harmonic mitigation device. Firstly, the requirements for the device basic mitigation technique and system installation are discussed. Second, the design parameters are calculated and determined to match the components. Third, the investigation is done using off the shelf and specially ordered components for the construction of mitigation device. The final step involves testing of these devices in laboratory environment. There are four selected passive mitigation devices built in this research. The devices are wye-zigzag transformer, neutral 3^{rd} harmonic blocking series filter, 3-phase 3^{rd} harmonic blocking series filter, and a 3-phase 3^{rd} harmonic trap shunt filter. The performances of the various devices are compared. It is found that the wye-zigzag transformer is the most efficient device in reducing the triplen harmonic currents in 3-phase 4-wire electrical distribution system. In contrast the LC tuned 3-phase 3^{rd} harmonic shunt filter generates its own harmonics and the LC tuned neutral 3^{rd} harmonic series filter excessively raises the system neutral voltage. Meanwhile, the 3-phase 3^{rd} harmonic blocking series filter performs well in reducing the triplen harmonic currents of single-phase loads. This thesis is a starting point towards a more detailed research in the development of more harmonic mitigation devices. Further investigation into the device's components characteristic such as material and construction of inductors, different types capacitor that influence the performance of mitigation device could be pursued. Finally, the devlopment of an active filter based on DSP and power electronics would be a challenging future research in mitigating triplen and other harmonics in 3-phase 4-wire distribution system.

ABSTRAK

Tesis ini membicarakan penebatan harmonic gandaan ketiga di dalam sistem pengagihan kuasa elektrik 3-fasa 4-talian yang membekalkan kuasa kepada beban tidak linear seimbang dan tidak seimbang. Objektif utama tesis ini ialah mengkaji, merekabentuk dan membina empat alat penebat harmonik gandaan ketiga pasif yang bersesuaian untuk menebat masalah harmonik gandaan ketiga. Terdapat empat langkah untuk membina alat penebat harmonik. Pertama, perbincangan keperluan asas teknik penebatan and pemasang sistem. Kedua, pengiraan dan penetapan parameter rekabentuk untuk disepadankan dengan komponen. Ketiga, penyelidikan keatas pembinaan alat penebat yang dibina mengunakan komponen sedia ada dan yang dibeli khusus. Langkah terakhir melibatkan ujian keatas alat penebat di dalam makmal. Terdapat empat alat penebatan pasif yang dibina di dalam penyelidikan ini. Alat-alat ini ialah alat-ubah wye-zigzag, penapis seri neutral harmonik ketiga, penapis seri harmonik ketiga 3-fasa dan penapis pirau harmonik ketiga 3-fasa. Perbandingan juga dibuat terhadap prestasi kesemua alat-alat penebat. Didapati alat-ubah wye-zigzag sangat berkesan mengurangkan harmonik gandaan ketiga di dalam sistem pengagihan kuasa elektrik 3-fasa 4-talian. Sebaliknya penapis pirau harmonik ketiga 3-fasa didapati mengeluarkan harmonik tersendiri dan penapis seri neutral harmonik ketiga telah keterlaluan menaikan voltan neutral. Sementara itu, penapis seri harmonik ketiga 3-fasa bertindak baik untuk mengurangkan arus harmonik gandaan ketiga dari beban satu-fasa. Tesis ini adalah titik permulaan kepada penyelidikan yang lebih mendalam keatas lebih banyak penebat harmonic. Penyelidikan seterusnya boleh dilakukan keatas ciri-ciri bahan dalam penapis seperti peraruh and pemuat. Terakhir, penyelidikan keatas penapis aktif berdasarkan DSP menyediakan masa hadapan yang mencabar dalam penebatan harmonik gandaan ketiga di dalam sistem pengagihan elektrik tiga-fasa empat-dawai.

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CHAPTER 1 INTRODUCTION

1.0 Background

Three-phase four-wire distribution systems are widely used to deliver electrical power at low voltage levels. The live and neutral conductors are design to operate with sinusoidal voltages and currents. However, the operating conditions have changed dramatically in recent time due to rapid growth of nonlinear and electronic loads. These loads will distort the steady state sinusoidal AC voltage and current waveforms. By using the Fourier analysis, we could prove that this periodically distorted waveforms contained odd harmonics.

There are growing numbers of available mitigation methods for reducing harmonics in conductors of a three-phase four-wire 415/240V distribution system. Over the years many mitigation methods have evolved and used to address the harmonics related problems; some of the most commonly used are K-rated distribution transformers, delta connected primary winding distribution transformer, L-C tuned filters (Beverly *et al.* 1990), phase shifting transformer and active filters. But few of these solutions are specific for mitigating triplen harmonics. Triplen harmonics are harmonics that are multiples of the 3^{rd} harmonic, ie 3^{rd}, 9^{th}, 15^{th} etc. The triplen harmonics currents add up in the neutral conductor (Dugan *et al.* 2002) of the distribution system feeding the non-linear loads such as personal computers, office equipment, uninterruptible power supplies (UPS) and any other loads with power electronic converters. The increasing use of these types of loads in offices and residential applications increases the current loading in the neutral conductor. Without proper mitigation, this will leads to stray voltages, elevated EMF disturbance (Tran *et al.* 1996) and unstable neutral voltage, overloading of neutral conductor, overheating of distribution transformer and power factor capacitor. To further add to this problem are that the effectiveness of most mitigation devices have not been comparatively studied.

1.1 Literature Review

Harmonics are being introduced into the electrical distribution system at an increasing rate due to the introduction of electronic power conversion in industrial plants, commercial complexes, manufacturing facilities and private dwelling. In his publication, Leon (1996) indicates that all of US Command, Control, Communication and Intelligence sites have its electrical system strained largely due to the high numbers of switch mode power supplies (SMPS) and uninterruptible power supplies (UPS) inside these facilities. Forecasts indicate that this trend will continue for the foreseeable future.

In power system, the definition of a harmonics is a sinusoidal component of a periodic wave having a frequency that is odd multiple of fundamental frequency (Dugan *et al.* 2002, Chang *et al.* 2004, Fadel 2002, Chapman 2001). The origins of harmonics are well known though the effects are different in each network (Anon, 1997). The most common source of harmonics are fluorescent lamp, television, computer and printer, UPS and adjustable speed drive (Maswood & Haque, 2002, McGranaghan, 2003). The combination of these different nonlinear loads can result in high voltage distortion levels throughout the facility, neutral conductor overload, motor heating, transformer heating, increased losses and frequent false tripping (McGranaghan, 2003).

Triplen harmonics are the sinusoidal components of odd multiples of the third harmonics (h = 3, 9, 15, 21,...). They deserved special consideration because system response is often considerably different for triplen than for the rest of the harmonics (Dugan *et al.* 2002). Triplen harmonics become an important issue for 3-phase 4-wire electrical distribution system with current flowing in the neutral conductor. Two typical problems are overloading (Arthur & Shanahan, 1996) and elevated neutral voltage (Tran *et al.* 1996) problem harmonics present into the electrical system, poses additional danger to overload the neutral wire.

Several researchers have studied and proposed various methods to mitigate triplen harmonics problem in 3-phase 4-wire electrical distribution system. Early work by Beverly *et al.* (1993) has studied the use of zigzag transformer to reduce the neutral current. Maswood & Haque (2002) proposed passive shunt filtering and active filtering to mitigate the problem. Leon (1996) has studied and compared various mitigation methods that include passive series-shunt filter, delta-wye transformer, active power line conditioner, ferroresonant magnetic synthesizer and active injection mode filter. Square D (Anon, 1997) in its bulletin recommend detuned capacitor and shunt filter as methods to suppress harmonics in the systems. The most radical approach was proposed by Lowenstein (2003) is to have 3rd harmonic blocking filter inserted in series to the neutral conductor.

In this thesis, we present an analytical framework for development of four passive triplen harmonics mitigation devices. The four passive devices are three-phase 3rd harmonic blocking filter, wye-zigzag transformer, neutral 3rd harmonic blocking filter and three-phase 3rd harmonic shunt filter. The development is based on series of analysis and specific assumptions. However, these assumptions are still valid for a wide range of real life situations.

1.2 Objectives of Research

The objective of this research is to study, design and build the most effective passive mitigation device for reducing triplen harmonic currents in phase conductors and neutral conductor of a three-phase four-wire 415/240V distribution system feeding non-linear loads. The research objectives can be broken into four phases:

i) To select the best available passive triplen harmonics mitigation methods

ii) To develop calculation methods for sizing the mitigation device

iii) To fabricate laboratory size triplen harmonics mitigation devices

iv) To test and compare the performance of triplen harmonics mitigation devices in the laboratory and to compare their effectiveness

1.3 Research Problem Statement

This research wishes to solve the mitigation of triplen harmonic currents in phase and neutral conductors of a 3-phase 4-wire, 240/415V distribution system feeding harmonics generating loads. This research is seeking for a solution that is scalable, cost effective and easy to install from the point of customers.

1.4 Research Methodology

To achieve research goals of this research, a comprehensive research approach was developed. This approach was broken down into a number of tasks. The followings decribe each of the developed tasks:

i) Literature review

A literature review was performed to better understand the problem of triplen harmonics and its effect in the electrical distribution system. As part of the literature review, some reviews were on the theory of the triplen harmonics, typical triplen harmonics producing loads and the various mitigation techniques offered thus far. All these literature review topics were related to the underlying them of mitigation of triplen harmonics in 3-phase 4-wire electrical distribution system.

ii) Harmonic measurements on various facilities

Harmonics data from available sites of interest was gathered to form the basis of triplen harmonics level in a typical building. All harmonic data were obtained from the installed

monitoring data logger at the site. These sites are Hospital Melaka, Fakulti Kejuruteraan Elektrik (FKE) simulation laboratory , FKE administration building and a private dwelling.

iii) Laboratory simulation of harmonic generating loads

A laboratory size harmonic generating loads are necessary to evaluate the effectiveness of each mitigation device built. Their readily availability, low cost, simple design, ease of setup, high and wide range of harmonics content were of concern. After extensive search, PC power supply was found to have the best characteristic that fits the entire above requirement.

iv) Study and review various harmonics mitigation methods

Various mitigation methods were research and compared for their effectiveness and practicality. High cost, complex and unproven methods were discarded.

v) Development of laboratory size triplen harmonics mitigation devices

The prototypes of 4 different passive triplen harmonics mitigation device were design based on available data with some modification and adjustment. The materials used to construct the prototypes were chosen for their readily available access from local supplier. Ease of fabrication was also of concern and no special tools or materials were necessary for construction.

vi) Evaluate and compare performance of the different mitigation devices

The four prototypes mitigation devices were installed at high harmonics content laboratory system. Harmonic data are collected before and after the installation to determine the effectiveness of each mitigation device. Comparison of harmonics data was the most important task in this research because it helped identify the different mitigation device applicability in an electrical distribution system.

vii) Writing of thesis

After the above task were completed, this comprehensive written thesis was prepared that describes, presents and discussed the entire finding from this research. The focus of this document is on mitigation of triplen harmonic current in a 3-phase 4-wire electrical distribution system.

1.5 Contribution of Research

One of the most significant contributions of this research is the method of deriving filters' components values according to the filter rating. Most previous researchers have not discussed in detail the methods to determine each filter's values based on the requirements. The second contribution of this research is the discovery of problems and solutions of fabricating the actual triplen harmonics mitigation devices. This discovery has enhanced the knowledge of filter design. The third contribution is the quantitative evaluation of the ability of various mitigation devices to mitigate the triplen harmonics. Comparisons of performance among the mitigation devices have enriched further knowledge of the actual implementation of the devices.