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OPTIMAL NUMBER AND PLACEMENT OF POWER QUALITY MONITORS FOR MONITORING VOLTAGE SAG IN POWER SYSTEM NETWORKS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
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Dedicated to

Mak, Abah, my husband Abdul Aziz and my children
Abdul Rashid, Abdul Hakim and Nur Nadia,
Who have always encouraged me to go on every adventure,
especially this one.

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ABSTRACT

The occurrence of voltage sags often interrupt the operating process of modern equipment, especially in manufacturing and semiconductor plants. To avoid high production loss in industries, power quality monitoring is essential. Monitoring the whole power system will provide important data to a utility company. As most power system networks are large, allocating a Power Quality (PQ) monitor at every bus in the system is costly. Therefore, the optimal number of PQ monitors should be determined. In this thesis, an optimum number of PQ monitor locations is identified through a searching procedure developed based on the method of fault position combined with certain network characteristics such as the number of connecting lines and the size of the coverage area, or sag vulnerability area. The proposed searching procedure will be enhanced with the usage of monitor redundancy level. To allow redundancy in monitoring sags, a minimum of three recordings are required. This is to allow functioning of two recordings when a monitor fails. The monitor redundancy criterion is used to ensure that every fault in the power system can be observed and validated with sufficient redundancy to ensure the monitoring system is not affected when one of the monitors fails to function. The monitor searching procedure is developed by using the MATLAB software. The monitor searching procedure is simulated to three different IEEE standard test systems: IEEE 30, 118 and 300 bus systems. Simulation results demonstrate that it is possible to monitor the occurrence of a voltage sag in the entire power system with an optimum number of power quality monitors. The monitor searching procedure is then validated through the implementation of monitoring the voltage sag event in the Peninsular Malaysia's utility network project. The number of monitors used under this project has been able to record sag events with optimum redundancy and the introduction of remote monitoring has enhanced the monitor searching procedure as the monitors used are able to upload data automatically to the database.

ABSTRAK

Kejadian voltan lendut sering mengganggu proses operasi peralatan moden terutamanya dalam loji pembuatan dan semikonduktor. Untuk mengelakkan kerugian yang tinggi di bahagian pengeluaran sektor industri, pemantauan kualiti kuasa adalah penting. Pemantauan keseluruhan sistem kuasa akan memberikan data penting kepada syarikat utiliti. Oleh kerana rangkaian sistem kuasa adalah besar, meletakkan monitor kualiti kuasa (PQ) pada setiap bas yang ada di dalam sistem akan meningkatkan kos. Oleh itu, bilangan monitor PQ yang optimum perlu ditentukan. Di dalam tesis ini, penentuan bilangan monitor yang optimum ditentukan melalui proses pencarian yang dibangunkan menggunakan kaedah kedudukan kerosakan yang digabungkan dengan ciri-ciri rangkaian sistem kuasa seperti bilangan talian setiap bas dan saiz kawasan liputan atau juga dikenali sebagai kawasan kelemahan voltan lendut. Tatacara pencarian monitor yang dibangunkan akan dipertingkatkan dengan menggunakan ciri lewahan rakaman monitor. Untuk membenarkan lewahan dalam pemantauan voltan lendut, tiga rakaman minimum diperlukan. Ini membolehkan dua rakaman lagi berfungsi apabila satu monitor tidak berfungsi. Kriteria lewahan monitor digunakan untuk memastikan setiap kerosakan di dalam sistem kuasa boleh diperhatikan dan disahkan dengan lewahan yang mencukupi bagi memastikan sistem pemantauan tidak terjejas apabila satu monitor gagal untuk berfungsi. Program proses pencarian monitor kualiti kuasa dibangunkan dengan menggunakan perisian MATLAB. Tatacara pencarian disimulasikan untuk tiga sistem ujian piawai IEEE yang berbeza: sistem IEEE 30, 118 dan 300 bas. Keputusan simulasi telah menunjukkan bilangan monitor yang optimum bagi memantau semua kejadian voltan lendut dalam seluruh sistem kuasa. Tatacara pencarian monitor kemudiannya disahkan melalui pelaksanaan projek pemantauan kejadian voltan lendut di rangkaian kuasa di Semenanjung Malaysia. Jumlah monitor yang digunakan di dalam projek ini telah mampu merekodkan kejadian voltan lendut dengan lewahan yang optimum dan pengenalan pemantauan jarak jauh telah menjadi nilai tambah kepada proses pencarian monitor kerana monitor yang digunakan mampu memuat turun data ke pangkalan data secara automatik.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
AQBGSA	-	Adaptive Quantum-Inspired Binary Gravitational Search Algorithm
ASD	-	Adjustable Speed Drives
B	-	Existence Vector
BEA	-	Bus Exposed Area
CEMIG	-	Minas Gerais Energy Company
CEO	-	Chief Executive Officer
CPU	-	Central Processing Unit
CBEMA	-	Computer Business Equipment Manufacturer's Association
CML	-	Critical Monitor Location
CUF	-	Centralised Utility Facilities
CT	-	Current Transformer
DC	-	Direct Current
EC	-	Energy Commission
EPRI	-	Electric Power Research Institute
FP	-	Fault Position
GA	-	Genetic Algorithm
GPRS	-	General Packet Radio Service
GPS	-	Global Positioning System

HV	-	High Voltage
IEC	-	International Electro-technical Commission
IC	-	Integrated Circuit
IGBT	-	Insulated Gate Bipolar Transistor
I/O	-	Input/Output
IP	-	Internet Protocol
IT	-	Information Technology
ITIC	-	Information Technology Industry Council
IEEE	-	Institute of Electrical and Electronics Engineers
LAN	-	Local Area Network
LV	-	Low Voltage
M2M	-	Machine-to-machine
MEA	-	Monitor Exposed Area
MRA	-	Monitor Reach Area
MV	-	Medium Voltage
NUR	-	Northern Utility Resources Distribution Sdn Bhd
OHCO	-	Odin Proprietary Communication Protocol
PC	-	Personal Computer
PCC	-	Point of Common Coupling
PLC	-	Programmable Logic Controller
PQ	-	Power Quality
PQMS	-	Power Quality Monitoring System
PWM	-	Pulse-Width Modulation
RMS	-	Root Mean Square
SD	-	Secure Digital Card
SEMI	-	Semiconductor Equipment and Materials International
SIM	-	Subscriber Identity Module

SMPS	-	Switch Mode Power Supply
SSI	-	Sag Severity Index
TCP/IP	-	Transmission Control Protocol / Internet Protocol
TMRA	-	Topological Monitor Reach Area
TNB	-	Tenaga Nasional Berhad
TCPQ	-	Technical Committee on Power Quality
UK	-	United Kingdom
UPS	-	Uninterruptible Power Supply
USA	-	United States of America
VPN	-	Virtual Private Network

LIST OF SYMBOLS

a	-	Fortescue Transformer a operator
f	-	Fault
FP	-	Fault position
I_f	-	Fault current
I_f^p	-	Fault current in positive sequence
I_f^n	-	Fault current in negative sequence
I_f^z	-	Fault current in zero sequence
L	-	Distance between the f and the PCC
N	-	Number of bus
p	-	Threshold setting
$V_{df(k)}$	-	During-fault-voltage matrix
V^p	-	Voltage in positive sequence
V^n	-	Voltage in negative sequence
V^z	-	Voltage in zero sequence
ΔV_k	-	Changes in voltage at node *k*
v_{kf}^p	-	Voltage at note *k* due to fault for positive sequence
v_{kf}^n	-	Voltage at note *k* due to fault for negative sequence
v_{kf}^z	-	Voltage at note *k* due to fault for zero sequence
v_{pref}^a	-	Voltage reference in positive sequence for phase a

Z_l	-	Feeder impedance
Z_{ff}	-	Diagonal impedance
Z_{ff}^{p}	-	Diagonal impedance for positive sequence
Z_{ff}^{n}	-	Diagonal impedance for negative sequence
Z_{ff}^{z}	-	Diagonal impedance for zero sequence
Z_{kf}	-	Transfer impedance at node *k* due to fault
Z_{kf}^{p}	-	Transfer impedance at node *k* due to fault for positive sequence
Z_{kf}^{n}	-	Transfer impedance at node *k* due to fault for negative sequence
Z_{kf}^{z}	-	Transfer impedance at node *k* due to fault for zero sequence
Z_s	-	Source impedance
ΔV_k	-	Changes in voltage at node *k*
Δv_{kf}^{p}	-	Changes in voltage at note *k* due to fault for positive sequence
Δv_{kf}^{n}	-	Changes in voltage at note *k* due to fault for negative sequence
Δv_{kf}^{z}	-	Changes in voltage at note *k* due to fault for zero sequence

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CHAPTER 1

INTRODUCTION

1.1 Background

The electric power system has been developed enormously due to the increasing demand of power. Today, electricity is generated by several types of generators, and then delivered to customers through the transmission and distribution system in the form of an alternating current (AC). While delivering electricity to customers, the quality of power could be potentially distorted [1]. The distortion in the electric power posed no severe problems to the end-users or utility during the early days of the development of the power system.

The proliferation of microprocessors and power electronics in industrial facilities has greatly increased the sensitivity of the electrical equipment to the power quality. Thus, power quality has become an important technical subject, since most industries are using complex microprocessors to improve their productivity and efficiency. The complexity has increased machine sensitivity, especially to the irregularities in the power supply [2-4]. It is a critical issue to discuss the means of ensuring the reliability and consistency of the power supply, as a short interruption may cause great loss or life-threatening consequences.

An ideal power supply would be one that is reliable, and within voltage and frequency tolerance, without any disturbance. However, reality is not always ideal. In its broadest sense, the term *power quality* could be interpreted as a service quality encompassing three main aspects, namely, reliability of supply, quality of power offered and provision of information. In a more rigorous interpretation, power quality is the ability of a power system to operate loads without disturbing or damaging them, and the ability of these loads to operate without disturbing or reducing the efficiency of the power system [5].

The International Electro-technical Commission (IEC) has defined a set of parameters to quantify power quality variations. These include harmonics, voltage flicker, voltage unbalance, voltage sags, interruptions, voltage regulation, frequency variation, swell and switching disturbances. Among these power quality disturbances, most complaints about poor power quality tend to be associated with voltage sags. For example, a survey in [6] has shown that 68% of power quality problems were due to voltage sags. Production loss occurred when the voltage drops to more than 13% of the rated voltage, and for a duration of more than 8.3ms, or approximately, a half-cycle. As another example, a survey that has been carried out on 210 large commercial and industrial customers in the USA has revealed that each voltage sag event could cost a loss of about US$7, 694 to industries [7].

Since an increasing amount of industries rely on sophisticated equipment, a study on the voltage sag events is a must. Traditionally, the emphasis in voltage sag studies has primarily been on fixing existing problems, rather than preventing future problems. In this thesis, the study of voltage sag is focused on determining a practical method to identify the optimal monitor locations that can capture the events without missing any of the important information.

1.2 Power Quality Issue in Malaysia

Power quality is not a new issue, nor a recent phenomenon. This issue has been well studied around the world. When Malaysia became an industrializing country in the 1980s, industries started to complain persistently about the malfunction of their equipment, which was not accompanied with the loss of supply. At that time, Tenaga Nasional Berhad (TNB) called these complaints "micro-interruptions". Arising from these complaints, TNB started investigations on these problems since 1993. In early 1994, TNB has initiated a voltage study in selected areas and loads by engaging a consultant company, the PTI of the USA [8].

In June, 2009, one of the microelectronics assembly plants in the Klang Valley suffered operational interruptions due to four different voltage sag incidents. The interruptions disrupted the plant and caused losses in terms of manpower and facilities, overhead loss and product spoilages [9]. The losses were estimated by the plant management to cost up to several million Ringgit Malaysia that month. In Malaysia, there are currently over sixty electronic industrial plants of comparable size to the plant mentioned.

In another incident, a fire broke up in one of the government offices due to a small fire in the vicinity of Uninterruptible Power Supply (UPS) equipment. According to the fire rescue department's investigation, the fire looked to have started around a neutral wire which was burnt [9]. Such an accident could have led to more dire consequences than only the damage to the UPS equipment and the immediate surroundings.

These anecdotal incidents represent a much larger sized problem that continually occurs due to power quality events. In fact, in Peninsular Malaysia, the number of customers (among TNB customers, Northern Utility Resources Distribution Sdn Bhd (NUR) and Centralised Utility Facilities (CUF)) that consumed electricity of more than 3MW peak is around 500. TNB has about 30,000 industrial customers who could be affected by voltage sag disruptions in a similar manner. TNB has over one million commercial electricity supply customers, many of whom would be affected in a similar manner to the neutral wire incident described above. Therefore, the extent of the impact of the power quality problem may have cost losses in millions of Ringgit Malaysia, if not billions, as can be estimated from the overall number consumers that could potentially be impacted.

As a comparison to similar experiences of events that occurred internationally, a European Power Quality Survey in 2007 estimated that, on average, losses due to short interruption events for industrial sectors were estimated to be in the range of RM35,000 and RM70,000, and for service sectors in the range of RM90,000 and RM200,000 [10]. For the telecommunication and IT sector, small spikes, surges and sags in the electricity supply may cause 15 times the amount of problems computer viruses cause, as reported by Bahram Mechanic, the CEO of Smart Power System Inc. [11].

Today, many electricity stakeholders realize that proper analysis and standard usage will minimize the losses that occur due to sudden voltage sag events. Unfortunately, in Malaysia, the knowledge and competency in power quality acquired by stakeholders has not reached an acceptable and internationally competitive level. Malaysian practices also lag behind compared to other countries. In the new economic model, this status is not competitive, as a great loss in the manufacturing industry is unattractive in persuading more foreign investment in the country. Malaysia may end up paying more than necessary due to avoidable damage to the available electrical equipment and installation.

In order to improve the level of power quality in the country, the Energy Commission of Malaysia (EC) has been taking a very pro-active approach by setting up the Power Quality Baseline Study for Peninsular Malaysia Consultancy Project [12].

1.3 Power Quality Baseline Study for Peninsular Malaysia Consultancy Project

As a regulator, the EC is monitoring the electricity supply network to ensure the utilities take a rigorous technical management of the PQ problems caused via the networks. The EC has taken the steps required to recognize most of the Malaysian Standards in PQ as voluntary standards among stakeholders. In the future, according to electricity supply industry requirements, it may be possible that a few of those standards will be made compulsory.

Realizing the importance of practical and comprehensive data for the establishment of good standards, the EC is undertaking a two-year study to determine the baseline data of power quality problems in Malaysia, its economic impacts and the means by which existing international PQ standards can be fine-tuned, improved and optimized for the requirements of the country.

A more detailed explanation regarding this project, as well as its implementation on the means to detect voltage sag events is given in Chapter 5.

1.4 Problem Statement

Power quality monitoring has been widely investigated on a global scale, and Malaysia is no exception. During the monitoring period, a large volume of power quality disturbances data is recorded such as voltage sag, voltage swell and harmonics data. In this thesis, the main focus is on the recorded voltage sag events. There are a few issues that arise during the development of the voltage sag monitoring system. The main issues are to identify the number of monitors needed, monitor locations and how to determine areas affected by voltage sag events.

To ensure every voltage sag event in the electrical network could be identified, a monitor can be placed at all of the buses in the system. Unfortunately, this will result a huge amount of duplicate data, or data redundancy. Many studies have been conducted on the redundancy issue. In [3] and [13], the redundancy level has been eliminated to overcome duplicate data, and also to reduce the cost of the power quality monitoring system. On the other hand, redundancy has the advantage to ensure the reliability of recording data in the system.

In this thesis, the concept of redundancy has been used as an advantage to analyze and identify voltage sag events. By using a suitable redundancy level, the continuity of supply (also known as reliability) can be guaranteed. Reliability is crucial, especially for industries such as manufacturing and semiconductor sectors, since a short interruption may potentially cause great loss.

Redundancy data can also be used as a voltage sag event verification tool. Verification is important to ensure the recorded data is free from false recording, and it can also assist in determining voltage sag or fault locations.

The suitable location to allocate the monitor should also be identified. Since portable monitors are available in the market, a safe location needs to be identified. The monitors also need to be protected from bad weather. Thus, a suitable location to allocate the monitor is at the substation.

Some issues such as the number of monitor needed, monitor locations, threshold value and the duration of the monitoring programs needed have been raised up in previous work [14]. In this thesis, the above concerns, as well as the practical issues such as communication among the remote sites and the high cost of the monitoring system, have been taken into account [13]. The new advances in electronics and communications offer new options in monitoring large systems in an efficient and low-cost manner. The advancement in communication technology, as well as the emergence of the smart grid, communication between the remote monitors and the database can be implemented through the Internet network [15]. Since most locations have wireless communication network coverage, it is also possible to obtain real-time data of the power system network.

Through the implementation of the Power Quality Baseline Study, the 3G wireless public communication network has been used to download the data to a server via a Virtual Private Network (VPN).This system have been chosen due to it ease of installation. The internal storage is used as a backup mechanism in case of data loss due to network problems.

1.5 Research Aim and Objectives

With the advancement in technology, in order to improve the placement of the power quality monitor, the formulated objectives of this research have been listed as follows:

i. To propose monitor search placement configuration that can ensure all voltage sag events in the power system can be observed and validated.
ii. To develop a cost-effective monitoring system in terms of the number and location of monitors for the power system network.
iii. To identify the affected areas by using the recorded data of voltage sag events.

1.6 Scope of Study

Due to time constraints, the objectives of this research were achieved by concentrating on the research scope, which comprises the following points:

i. This research focuses on analyzing voltage sag problems that occur in the power distribution system due to faults.
ii. The algorithm is validated by using simulation data from the selected international network (IEEE 30-bus, IEEE 118-bus and IEEE 300-bus) and Tenaga Nasional Berhad (TNB).

1.7 Main Contributions of the Research Work

This thesis reports the research work that has been developed by the author during the past five years. It introduces the causes of voltage sags as well as their effects on the power system network and sensitive loads. It also provides a basic review of fault analysis in power systems to better understand the method of fault positions for identifying optimum monitor locations. The main contributions of the work can be summarized as follows:

i. It presented the application of the method of fault positions to an existing power system. It also investigated the contribution of symmetrical and unsymmetrical faults to the total number of monitors needed to record voltage sag events that occur in a network.
ii. The proposed monitoring searching procedure has been successfully implemented in the PQ Baseline Study for Peninsular Malaysia project. This project is a successful power quality monitoring project in which multiple monitors are placed in optimum locations to avoid blind spots, and then networked using machine-to-machine technology (M2M) in a Virtual Private Network through a public wireless broadband system.
iii. The analysis of the data from using several monitors has been successful in reducing the problems of: single events being recognized as multiple events due to differences in the recorder's clock, recording blind spots, and data collection costs.

1.8 Organization of the Thesis

This thesis is organized in six chapters. The first chapter provides a general background on power quality, voltage sag and the work, as well as the aims, objectives and achievements of the research.

Chapter 2 provides a general introduction on voltage sag, and describes the most relevant standards on this subject. This chapter also presents the past works on the engineering aspects of voltage sag events. The work in this thesis uses some facts and important findings from the past works as guidelines.

Chapter 3 presents the results of the application of the method of fault positions. Three different sizes of IEEE network were used to illustrate the method.

The results are presented in the Appendix. The exposed areas are determined for some selected buses.

Chapter 4 introduces the monitoring searching procedure in order to determine the optimum locations for the monitors. The terms monitor exposed area (MEA) and bus exposed area (BEA) are introduced in order to identify the optimum monitor locations that have the ability to satisfy the first research objective. The searching procedure is then tested on three different sized IEEE networks. The results are presented as a list of monitor locations.

Chapter 5 explains in details the implementation of the searching procedure during the implementation of the PQ Baseline Study for the Peninsular Malaysia project.

Chapter 6 presents conclusions derived from this work. Several research issues are identified and proposed for future work.

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