MODIFIED WALSH TRANSFORM FOR HARMONIC ASSESSMENT

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Dedicated to my beloved family for their encouragement and support

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ABSTRACT

Harmonic assessment at end users through energy meter is a part of power quality monitoring to determine harmonics contamination level in distribution network. Integration of harmonics extraction technique with energy meter requires two considerations which are measurement accuracy of the technique and its computational complexity to extract harmonics. These two aspects are main requirements for meter to support the execution of harmonics extraction since it is operated under low-cost microcontroller. In harmonic extraction of Fast Fourier Transform (FFT), the computation burden is quite high and requires additional hardware installation to support the algorithm's operation. Therefore, this thesis presents a Modified Walsh Transform algorithm as an alternative harmonic extraction. The proposed algorithm consumes less arithmetic operations than FFT and suitable to be integrated into energy meter. This study involves with extracting distorted current signal into harmonic components, measuring the harmonics magnitude and calculating Root-Mean-Square (RMS), Total Harmonic Distortion (THD) and Distortion Power Factor (DPF) as well as computational analysis between FFT and Modified Walsh Transform algorithms. The result from simulation indicates that the proposed algorithm has 99% of accuracy percentage with more consistent result than FFT. Moreover, the arithmetic operation in Modified Walsh Transform is less than FFT to show that less computation burden consumed by the proposed algorithm. Meanwhile, a laboratory experiment has been conducted to demonstrate consideration of DPF in harmonics assessment and power factor measurement as complied in IEEE Std.1459-2010.

ABSTRAK

Penilaian harmonik pada pengguna akhir melalui meter tenaga adalah sebahagian daripada pemantauan kualiti kuasa untuk menentukan tahap pencemaran harmonik dalam rangkaian pengedaran. Integrasi teknik pengekstrakan harmonik dengan meter tenaga memerlukan dua pertimbangan iaitu ketepatan pengukuran teknik tersebut dan kerumitan pengiraan untuk mengekstrakan harmonik. Kedua-dua aspek adalah keperluan utama bagi meter untuk menyokong pelaksanaan pengekstrakan harmonik kerana ia dikendalikan di bawah mikropengawal kos rendah. Dalam pengekstrakan harmonik transformasi Fourier cepat (FFT), beban pengiraan adalah agak tinggi dan memerlukan pemasangan perkakasan tambahan untuk menyokong operasi algoritma ini. Oleh itu, tesis ini membentangkan algoritma transformasi Walsh yang diubahsuai sebagai pengekstrakan harmonik alternatif. Algoritma yang dicadangkan ini menggunakan operasi aritmetik kurang daripada FFT dan sesuai untuk diintegrasikan ke dalam meter tenaga. Kajian ini melibatkan dengan pengekstrakan isyarat arus yang terganggu kepada komponen-komponen harmonik, pengukuran magnitud harmonik dan pengiraan *Root-Mean-Square* (RMS), Jumlah Harmonik Penyelewengan (THD) dan Penyelewengan Faktor Kuasa (DPF) serta analisis komputasi daripada algoritma FFT dan transformasi Walsh yang diubahsuai. Hasil daripada simulasi menunjukkan bahawa algoritma yang dicadangkan mempunyai 99% peratusan ketepatan dengan keputusan yang lebih konsisten berbanding dengan FFT. Selain itu, operasi aritmetik dalam transformasi Walsh diubahsuai adalah kurang daripada FFT menunjukkan bahawa beban pengiraan kurang digunakan oleh algoritma yang dicadangkan. Sementara itu, satu eksperimen makmal telah dijalankan untuk menunjukkan pertimbangan DPF dalam penilaian harmonik dan ukuran faktor kuasa sebagaimana dipatuhi dalam IEEE Std.1459 2010.

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LIST OF SYMBOLS

a_h	-	Fourier coefficient determination for cosine
a_o	-	constant value of Fourier coefficient $f\,(t)$
b_h	-	Fourier coefficient determination for sine
CAL	-	Coefficient matrix from *cal* group function
$cal\ (t)$	-	Cal group of Walsh function
$cos\ \phi$	-	Cosine difference between voltage and current
$f\,(t)$	-	Waveform function
h	-	Harmonic order
$H(2^k)$	-	Hadamard matrix in power of two function
$i\ (t)$	-	Instantaneous current
I_{1peak}	-	Peak value of fundamental current
I_{1RMS}	-	RMS value of fundamental current
I_o	-	Reference current
I_{RMS}	-	RMS value of current
M	-	Magnitude
P_{avg}	-	Average power or Real power
$Rn\ (t)$	-	Rademacher function
s	-	Total samples
S_{RMS}	-	RMS value of Apparent Power
SAL	-	Coefficient matrix from *sal* group function
$sal\ (t)$	-	Sal group of Walsh function
$sgn\ (x)$	-	Sign function
S_{Total}	-	Apparent power
T	-	Time interval
THD_i	-	Total harmonic distortion of current

$v\ (t)$	-	Instantaneous voltage
V_o	-	Protection voltage
V_{peak}	-	Peak value of voltage
V_{RMS}	-	RMS value of voltage
$wal\ (n,t)$	-	Walsh function
W_n	-	Walsh transform order
$x\ [k]$	-	value of voltage or current at k^{th} sample
α	-	Coefficient of nonlinear load
ψ	-	Flux

LIST OF ABBREVIATIONS

ACO	-	Ant Colony Optimization
AMI	-	Advanced Metering Infrastructure
AMR	-	Automatic Meter Reading
ANN	-	Artificial Neural Network
APM	-	Adaptive Prony Method
ASIC	-	Application-specific Integrated Circuit
CFA	-	Curve Fitting Algorithm
CFS	-	Correlation Feature Selection
DFT	-	Discrete Fourier Transform
DPF	-	Distortion Power Factor
DTC	-	Direct Torque Control
DWT	-	Discrete Wavelet Transform
EKF	-	Extended Kalman Filter
ESPRIT	-	Estimation of Parameter via Rotational Invariance Technique
Fast-ICA	-	Fast Independent Component Analysis
FDR	-	Frequency Deviation Ratio
FFBP	-	Feed Forward Back Propagation
FFT	-	Fast Fourier Transform
FIS	-	Fuzzy Inference System
FLOP	-	Floating Point Operation
FPGA	-	Field Programming Gate Array
FWHT	-	Fast Walsh Hadamard Transform
GB	-	Giga Bytes
HSE	-	Harmonic State Estimation

IEC	-	International Electrotechnical Commission
IEEE	-	Institutes of Electrical and Electronics Engineers
IHDR	-	Instantaneous Harmonic Distortion Ratio
ILWT	-	Integer Lifting Wavelet Transform
IPQMS	-	Integrated Power Quality Monitoring System
IRMS	-	Instantaneous Root Mean Square
ISP	-	Instantaneous Space Phasor
IWDR	-	Instantaneous Waveform Distortion Ratio
kVArh	-	kilo Volt-Ampere reactive hour
kWh	-	kilo Watthour
LCD	-	Liquid Crystal Display
LMS	-	Least Mean Square
LNI	-	Load Nonlinearity Indicator
LPPI	-	Load side Power Performance Index
LV	-	Low Voltage
MA	-	Matrix Algebra
MCB	-	Miniature Circuit Breaker
MCCB	-	Molded Case Circuit Breaker
MGS	-	Modified Gradient Search
MIFS	-	Mutual Information Feature Selection
MOV	-	Metal Oxide Varistor
MV	-	Medium Voltage
MWF	-	Modified Walsh Function
NRMSE	-	Normalized Root Mean Square Error
NSTDE	-	Normalized Short Time Disturbance Energy
PC	-	Personal Computer
PCAT	-	Principal Component Analysis Technique
PF	-	Power Factor
POI	-	Power Oscillation Index
PPI	-	Power Performance Index
PQ	-	Power Quality
QAP	-	Quadratic Assignment Problem
RAM	-	Random Access Memory

RDFT	-	Recursive Discrete Fourier Transform
RMS	-	Root Mean Square
RMSE	-	Root Mean Square error
rpm	-	Revolution per minutes
SDR	-	Symmetrical components Deviation Ratio
SIARFIx	-	System Instantaneous Average RMS variation Frequency Index
SMARFIx	-	System Momentary Average RMS variation Frequency Index
SMPT	-	Smart Multi-Power Tap
SNR	-	Signal to Noise Ratio
SOA	-	Seeker Optimization Algorithm
SPPI	-	Supply side Power Performance Index
STARFix	-	System Temporary Average RMS variation Frequency Index
STDE	-	Short Time Disturbance Energy
STFD	-	Short Time Frequency Deviation
STHD	-	Short Term Harmonic Distortion
STK	-	Short Time K-Factor
STLS	-	Self Tuning Least Square
SVM	-	Support Vector Machines
TFA	-	Time Frequency Atom
TFD	-	Time Frequency Distribution
THD	-	Total Harmonic Distortion
THUD	-	Total Harmonic and Unbalanced Distortion
TPF	-	True Power Factor
TRD	-	Total Rated Distortion
UPQI	-	Unified Power Quality Index
WDR	-	Waveform Distortion Ratio
WPT	-	Wavelet Packet Transform

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The issues of Power Quality (PQ) have been of concern since about two decades ago due to increasing of non-linear loads in distribution network. Reports of electrical faults and equipment malfunction without any reason(s) have led to investigation of signal condition in power system [1]. Since then, research on power quality issue increases yearly and international organizations such as IEEE and IEC have established standards and guidelines in order to preserve good power quality in the system [2 ,3].

Harmonic pollution is one of the main power quality issues prominent at distribution network where most of harmonic injection comes from consumers' loads. Adjustable Speed Drives (ASDs) in inductance motors as well as electronic appliances such as compact fluorescent lamps, computers and televisions are examples of non-linear loads that are frequently used in distribution network. The widespread use of these loads can lead to bad consequences such as power outage, shorten life span of electrical equipment and overheating in motors.

The introduction of power quality monitoring can prevent such circumstances from occurring. The PQ monitoring can be divided into two categories namely power quality event monitoring and power quality variation monitoring. Event monitoring specifies to sudden disturbance that occur in a short time while variation monitoring is the term used for continuous measurement [4]. For harmonic case, the variation monitoring is used since it disturbs power system continuously. Overall, both monitoring are necessary to prevent the aforementioned consequences that take place in power system.

There are many locations where monitoring is required such as bus bar monitoring, transformer monitoring, supply side and load side of monitoring, generator monitoring and end user monitoring. In this research, the end user monitoring is selected as power quality assessment technique by using energy meter. Furthermore, deployment of smart meter is still in progress which offers opportunity to utility company to integrate power quality monitoring into smart meter.

Nowadays, development of smart meter has facilitated utility company to adapt remote measuring, remote billing and detecting fault location. This technology in smart meter is called Automatic Meter Reading (AMR) where data measured by energy meters are transmitted to utility base station through wireless or wired communication. Moreover, the second generation of smart meter which is named as Advance Metering Infrastructure (AMI) is the latest development of smart meter where additional features have been added into previous AMR meter including meter self control system, remote control from utility base station and user interface. In previous AMR meters, only one way communication is available in metering system but the AMI system has implemented two ways communication between consumers and utility base station. This improvement can assist utility as well as consumers to optimize energy usage in power system. Unfortunately, the integration of power quality monitoring into smart meter is still not included in AMI feature. Therefore, this study proposes an integration of power quality monitoring by adding power quality index into smart meter.

Several indices are being used to signify power quality level such as total harmonic distortion (THD), power factor (PF), telephone factor, K factor, crest factor, flicker factor and et cetera [4]. These indices measure voltage and current quality with respect to ideal voltage and current. The ideal voltage is defined as sinusoidal voltage waveform at constant amplitude and frequency while ideal current is sinusoidal current waveform at constant amplitude, frequency and identical to voltage frequency and phase. Amongst these indices, the THD of voltage and current are commonly discussed by researchers to analyze harmonic distortion level. Nevertheless, further discussion upon suitable index for power quality assessment in each point of building will be presented later in Chapter 2.

In conclusion, by employing power quality index into smart meter, the utility company can estimate power quality level at any locations of distribution network more precisely through remote monitoring from utility base station. In the future, prediction of harmonic distortion level at distribution network can be done through this monitoring.

1.2 Problem Statements

There are three problems have been arisen to lead the objectives of this research. These problems are stated as below:

1. Most of algorithms require high speed processor to execute harmonic extraction instantaneously including Fourier Transform and Wavelet Transform. However, such algorithms are not suitable to integrate into smart meter since the meter processor could not support high computation burden of algorithm. Therefore, an alternative algorithm which consumes low computation burden must be developed for harmonic extraction in energy meter.

2. High percentage error in harmonics measurement is one of factors to miscalculation of power quality indices especially Total Harmonic Distortion and Distortion Power Factor. Calibration of proposed technique with standard technique of Fast Fourier Transform is essential as a research benchmark. Hence, the proposed technique should be comparable to standard harmonics measurement to demonstrate its capability to measure harmonics fast and accurately.

3. Some harmonic indices are based on magnitude of certain harmonic order such as third, fifth and seventh harmonic order. Several indices such as THD current and voltage are insufficient to depict harmonic level as well as power efficiency. Meanwhile conventional power factor in most energy meters only measure angle difference between voltage and current instead of degree of harmonic contamination.

1.3 Significance of Study

Implementation of power quality monitoring into smart meter is vital for utility company as well as consumers for a number of reasons:

- The power quality monitoring application is crucial for a utility company to identify factors of equipment malfunction and other power quality problems.
- Data recorded by meter are used for statistical analysis on performance of utility equipment such as transformers, relays and etc.
- Power quality monitoring provides early precaution to the utility company before an interruption occurs in the distribution network.
- By implementing power quality index into smart energy meter, it increases awareness of consumers about power quality condition.

1.4 Aims and Objectives

This study has carried out three objectives to be accomplished which are:

1. To develop harmonic extraction technique using proposed algorithm for harmonic assessment and power quality indices calculation.
2. To validate the accuracy of proposed harmonic extraction based on simulation platform.
3. To recognize Distortion Power Factor as harmonics level indicator based on laboratory experiment

1.5 Scope of Study

The scope of study covers four aspects to achieve the aforementioned objectives which include literature reviews, mathematical formulation, simulation and experiment setup and finally, analysis of results. In literature review, historical development of smart meter, power quality index and index estimation techniques are reviewed to determine smart meter potential in integrating with power quality index. All reviews will be concluded by highlighting seven criteria for implementation of power quality index into smart meter.

The mathematical formulation is divided into two parts which are index derivation and algorithm formulation. Several algorithms are studied to search simple harmonic estimation technique which compatible to smart meter devices. A modification on selected algorithm is proposed to improve its accuracy and diminish its computation process further. The suggested index will be derived by considering harmonic component in derivation. Then, the modified algorithm is reformulated according to index equation.

A simulation procedure for three models of non-linear load will be designed in MATLAB/*Simulink* environment to evaluate the proposed algorithm. Those models are non-linear resistance, direct torque control of induction motor and non-linear inductance which simulate current distortion in three different conditions namely stationary distortion, non-stationary distortion and inrush current. The proposed algorithm is programmed into MATLAB software to estimate harmonic and calculate the index. For index assessment, an experiment procedure will be prepared. The current and voltage source of harmonic load bank will be measured by fluke meter and energy meter to compare parameters from both meters. Then, data recorded by fluke meter is transferred into MATLAB for index analysis.

All simulation results are verified by standard harmonic estimation technique which is Fast Fourier Transform. A *Simulink* model of Fast Fourier Transform is build to measure non-linear load models. Data will be plotted to observe any differences between the proposed technique and standard measurement technique. Meanwhile, the suggested index is validated based on IEEE 1459-2010 standard.

1.6 Organization of the Thesis

Chapter 1 presents an introduction to power quality, the research background study, the problem statements and the significance of the study, the research objectives and the research scope.

Chapter 2 reviews the smart meter development, deployment of power quality meter, novel indices in power quality assessment, algorithm implementation for some novel indices, real-time implementation approach, algorithm for global indices, distortion power factor as power quality index for energy meter and algorithm implementation for power factor indices.

Chapter 3 briefs the fundamental theory of Walsh Transform algorithm, the proposed technique of Modified Walsh Transform and derivation of distortion power factor index. Some explanations of power factor, total harmonic distortion and root mean square are presented in this chapter as well.

Chapter 4 elaborates research methodology that covers simulation and experiment methodology. All models of harmonic load, the MATLAB program of proposed technique and specifications of software and experimental equipments are defined in this chapter.

Chapter 5 illustrates results from five case studies obtained by simulation and experiment. The results are presented in tables and figures with some discussions upon the result obtained. Finally, chapter 6 concludes the study with several suggestions for future works.

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