TRANSFORMER PERFORMANCE MODEL UNDER POWER QUALITY ENVIRONMENT

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Dedicated to my parents for their endless support and encouragement

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ABSTRACT

The widespread use of static rectification and energy efficient equipment in end user loads result in a dramatic increase in harmonic content injection towards transformers connected to upstream power system. Now, due to modern developments, energy efficient equipment, such as compact fluorescent lamps are easily available. The use of energy efficient equipment increases rapidly in our country as saving of electrical energy is the main target of end users and also electric utility. Meanwhile, these types of equipment contribute to power quality problems such as harmonic distortion. The harmonic content generated by load causes the transformer to operate in higher power rating and may cause transformer operating failure in the long term. This work was initially started with experimentation of transformer performance analysis in the presence of harmonic events. The objective of this research is to develop the total harmonic distortion and efficiency model based on data analysis. Experimental tests are performed to obtain transformer parameter. Harmonic loads are modelled by utilizing the unique waveform characteristic of each individual harmonic load type through image processing and curve fitting methods. Harmonic current injection model has been proposed and applied using transformer model through the experimental parameter in MATLAB Simulink. The comparison between harmonic current injection model with the measured load in terms of true RMS current, apparent power, active power, true power factor and total harmonic distortion current have been done. An analysis has also been done on experimental data by comparing the efficiency of transformer with and without harmonic distortion on identical load type. The developed models for analysis of transformer efficiency with harmonic distortion indicate goodness of fit with R-square value close to 1 and Root Mean Square Error of less than 1.

ABSTRAK

Penggunaan meluas penerusan statik dan peralatan cekap tenaga dalam beban pengguna akhir menyebabkan peningkatan dramatik dalam suntikan kandungan harmonik ke arah pengubah yang disambungkan kepada sistem kuasa huluan. Sekarang, disebabkan oleh perkembangan moden, peralatan cekap tenaga, seperti lampu pendarfluor padat, mudah didapati. Penggunaan peralatan cekap tenaga meningkat dengan pantas di negara kita kerana penjimatan tenaga elektrik adalah sasaran utama pengguna-pengguna akhir dan juga utiliti elektrik. Sementara itu, jenis peralatan sebegini menyumbang kepada masalah kualiti kuasa seperti herotan harmonik. Kandungan harmonik yang dihasilkan menyebabkan pengubah beroperasi di peringkat kuasa yang lebih tinggi dan boleh menyebabkan kegagalan operasi pengubah dalam jangka masa panjang. Kerja ini bermula dengan eksperimen untuk analisis prestasi pengubah dalam acara harmonik. Tujuan penyelidikan ini adalah untuk membangunkan model herotan harmonik seluruh dan kecekapan berdasarkan analisis data. Ujian eksperimen telah dilaksanakan untuk mendapat parameter pengubah. Beban harmonik telah dimodel dengan menggunakan keunikan ciri-ciri bentuk gelombang bagi setiap jenis beban harmonic individu melalui teknik pemprosesan imej dan penyuaian lengkung. Model suntikan arus harmonik telah dicadangkan dan diaplikasikan dengan model pengubah melalui parameter eksperimen dalam MATLAB Simulink. Perbandingan antara model suntikan arus harmonik dengan beban yang diukur dari segi arus RMS benar, kuasa ketara, kuasa aktif, faktor kuasa benar dan herotan harmonik seluruh arus telah dilakukan. Analisis juga telah dilakukan ke atas data ujikaji dengan membuat perbandingan kecekapan pengubah dengan dan tanpa herotan harmonik pada jenis beban yang sama. Model yang dibangunkan untuk analisis kecekapan transformer dengan herotan harmonik menunjukkan kebaikan suai dengan nilai R-kuasa dua menghampiri nilai 1 dan Ralat Punca Min Kuasa Dua kurang daripada 1.

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LIST OF SYMBOLS

A_{img}	-	Magnitude of M number of data with N unit substrate the minimum magnitude value of N
A_{rms}	-	Root mean square current
A_{peak}	-	Peak current
A, B, C	-	Coefficient or constant value
(B)	-	Flux density column matrix
B_{img}	-	Median value of A_{img}
C_{img}	-	Bias value of A_{img} toward the horizontal origin axis
D_{img}	-	Inverse value of C_{img}
$\left\|D_{img}\right\|_{peak}$	-	Peak value of current waveform
$D_{img,\mathrm{rms}}$	-	True Root mean Square value of current waveform from Measurement
F_s	-	Sampling rate of the data saved in the image
F_W	-	Frequency of the waveform
F_{HL}	-	Harmonic loss factor
H	-	Magnetic field strength
h	-	Harmonic order
I_D	-	Actual magnitude value of current waveform
$I_{H,i^{th}device}$	-	Harmonic waveform function of i^{th} equipment
$I_{H,\mathrm{Total}}$	-	The individual modelled device controlled with N_i units add together

I_h, i_h, i_H	-	RMS current at harmonic order of h
I_L	-	Load current
I_{ABC}	-	Three phase current
I_{oc}	-	Input current during open circuit test
I_{sc}	-	Rated current
i_1, I_1	-	Current, fundamental frequency component
i_o	-	Direct current
i_p	-	In-phase line current
i_q	-	Reactive current
(M)	-	Equivalent magnetization column matrix
$\max\{A_{img}\}$	-	Maximum value of A_{img}
$\min\{A_{img}\}$	-	Minimum value of A_{img}
$\max\{D_{img}\}$	-	Maximum value of D_{img}
$\min\{N\}$	-	Minimum value of N
n_s	-	Total number of sample
n_W	-	Number of cycle of the waveform
P_H	-	Active power, harmonic frequency components
P_{EC}	-	Total eddy-current losses
P_{EC-O}	-	Windings eddy-current losses
P_{oc}	-	Input power during open circuit test
P_{sc}	-	Input power during short circuit test
P_1	-	Active power, fundamental frequency component
$Pf_{distortion}$	-	Distortion power factor
R_c	-	Core loss resistance
R_{eq}	-	Equivalent winding resistance
R_1, X_1	-	Primary winding parameter

R_2, X_2	-	Secondary winding parameter
$r_{t,w}$	-	Winding turn ratio
$SS_{residual}$	-	Sum of square of residuals
SS_{total}	-	Sum of square of $(Y_i - \bar{Y})$
(T)	-	Coefficient matrix
T_s	-	Interval period between two of the sample
T_W	-	Period of the waveform within n_W cycle
t	-	Time frame of each sampled data in second
u_s	-	Voltage measured in secondary winding
V_{ABC}	-	Three phase voltage
V_{fund}	-	Voltage with fundamental frequency
V_{oc}	-	Rated voltage
V_{sc}	-	Input voltage during short circuit test
V_{peak}	-	Peak voltage
V_{rms}	-	Root mean square voltage
v_h	-	Voltage, harmonic frequency components
v_1	-	Voltage, fundamental frequency component
VA_{full}	-	Apparent power which consider harmonic frequency
VA_{fund}	-	Apparent power which consider fundamental frequency only
W_{full}	-	Power which consider harmonic frequency
W_{fund}	-	Power which consider fundamental frequency only
X_i	-	Independent variable vector
X_m	-	Magnetizing reactance
X_{eq}	-	Equivalent leakage reactance
Y_i	-	Response variable with ith response
$Y_{residual,i}$	-	Residual values
$\bar{Y}$	-	Mean value of observation data

$y_{n,harmonic}$	-	Harmonic waveform function
Z_{SH}	-	Short circuit impedances
$\%f$, THD	-	THD relative to the fundamental
$\%r$, THD_R	-	THD relative to the root mean square
β , α	-	Regression coefficient vector
λ_{p0}	-	Residual flux
ε_i	-	ith noise term
$\varepsilon_{\%}$	-	Percentage of error
ϕ	-	Phase angle
ϕ_n	-	Phase angle of n harmonic order

LIST OF ABBREVIATIONS

AC, ac	-	Alternating current
ASDs	-	Adjustable-speed drives
BNC	-	Bayonet Neill–Concelman or Baby N Connector
CF	-	Crest factor
CFL	-	Compact fluorescent lamp
DC, dc	-	Direct current
DFT	-	Discrete Fourier Transform
DPF	-	Displacement power factor
FE	-	Finite Element
FFT	-	Fast Fourier Transform
FULL	-	Measurement included harmonic frequency
Fund	-	Measurement with fundamental frequency
GA	-	Genetic Algorithm
GUI	-	Graphical user interface
HV	-	High voltage
IEC	-	International Electrotechnical Commission
LV	-	Low voltage
MCB	-	Miniature circuit breaker
PF, *tpf*	-	True power factor
PLT	-	Long term flicker
RCCB	-	Residual current circuit breaker
RLE	-	Run-Length encoding Compression
RMS	-	Root mean square
RMSE	-	Root mean square error
SSE	-	Sum of square error

THD	-	Total harmonic distortion
T5	-	Fluorescent T5 lamp
T8	-	Fluorescent T8 lamp
Variac	-	Variable transformer
VFTO	-	Very Fast Transient Overvoltages

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CHAPTER 1

OVERVIEW

1.1 Overview

Nowadays, the widespread application of static rectification and energy-efficient equipment in end user loads with transformers having small (5M to 40MVA) and medium (40M to 250MVA) power range has resulted in a dramatic increase in the harmonic components of the load current for this equipment. The use of energy-efficient equipment in our country is increasing rapidly as end users and electric utility companies are looking forward to saving electrical energy. Due to modern developments, energy efficiency equipment such as compact fluorescent lamp is easily available. These types of equipment give rise to the power quality problem such as harmonic distortion. Consequently, increased usage of these types of equipment gives rise to the harmonics on the transformer. It is also well known that higher harmonic content in the current can cause higher current loss in winding conductors and structural parts linked by the transformer leakage flux field, and consequently, these losses are dissipated as heat and gives rise to higher operating temperature than normal.

Transformers are one of the most important components from the generating station to end-user equipment; which play an important role in minimizing the losses throughout the stage by stepping up or stepping down the voltage. In end-user equipment, transformer is used to regulate the voltage from single phase 240V ac to the required output voltage.

Common sources of harmonics in the industrial sector are electrical ballast, dc motor drives and rectifiers. In this modern era, direct current power supply to the load of end-user equipment involves the use of rectifiers, since loads connected to the power supply in the end-user equipment will result in current distortion [1]. Voltage distortion and current distortion drawn by these loads are one of the power quality issues on the transformer. Losses in transformer can be categorized into no-load and load losses. The no-load loss arises from the voltage excitation of the core and eddy currents and magnetic hysteresis. Load loss occurs mainly from the resistive losses in the conducting material of the windings [2]. There are three factors resulted by the increased transformer heating when the load current includes harmonic components.

(a) RMS current: Harmonic currents may cause the transformer RMS current being higher than its capacity, if the transformer is sized only for the kVA requirements of the load;

(b) Eddy-current losses: These are due to the magnetic fluxes which caused induced currents in a transformer;

(c) Core losses: In the presence of harmonics, nonlinear core losses may increase depends on the effect of the harmonics on the design of the transformer core and applied voltage.

There are reports regarding failures in transformers under normal operating condition with high levels of harmonic currents [3], such as nonsinusoidal currents drawn by nonlinear load causing excessive loss and heating [4] in transformer. Transformers are commonly constructed to utilize at rated frequency and apparent power. Nowadays, with the presence of nonlinear loads, harmonic distortion often result in higher losses on transformer, which can cause abnormal temperature rise and excessive winding losses [5].

Figure 1.1 shows the well organised document and studied scattering failure data to identify the critical component of transformer. These figures are not appropriate to simply reach conclusions on the causes of transformer fault. This is because the degradation of transformer data was taken under its normal and abnormal operating conditions. Maintenance works are vital to restore the condition, but costly in terms of outage duration, disruption of production line, restore and necessary replacement. With statistical analysis, it is possible to describe the ageing processes of power transformer components statistically. In year 2012, Voros *et al.* reviewed an expert system which evaluates condition of transformer with the status diagram, technical and statistic support to manage transformer lifecycle [6]. Now, the preventive maintenance costs have become more of primary concern. In year 2014, Suwanasri proposed asset management of transformer with failure statistical analysis to diminish operating and maintenance costs [7].

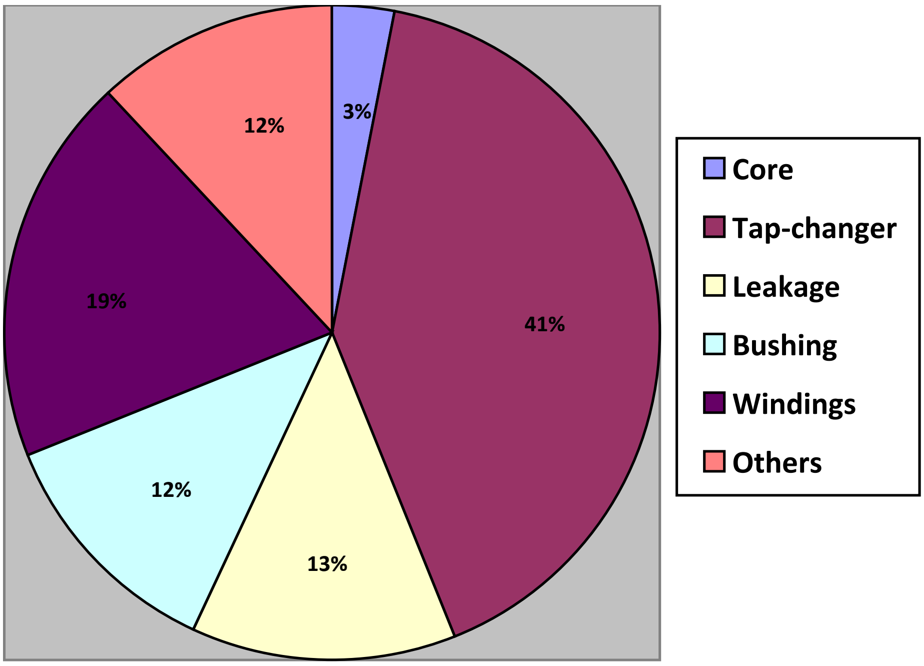

Figure 1.1 Failure statistics chart of power transformer by components as in [8].

1.2 Problem Statement

Harmonic distortion is one of the major power quality concerns for electric utility companies. The non-linearity of end user loads which produces harmonic distortion will affect transformer performance. The increasing use of non-linear loads being connected to the transformer also magnifies the power quality problems. Distortion of sinusoidal current waveforms due to harmonics causes increases in transformer winding losses and possible loss of equipment lifespan.

Previously, other researchers took measurement at the power substation which did not provide details of type of loads operating at that time frame for the data taken. The main focus is on the calculations which relate the losses with and without harmonic to a harmonic distortion factor. This formulation does give an idea of the losses increment between fundamental frequency and harmonic frequencies, but does not model the performance of the transformer under condition of loads quantity and composition in relation with efficiency and harmonic distortion level. This study attempts to fill in this research gap. Therefore, it is necessary to develop model which able to provide and compare detail of the performance of a transformer under the harmonic event. The parameters involved in developing the model and method to relate the variables with a suitable regression model should be investigated. The model which can provide detailed comparison with different input parameter more precise. This developed model is hoped able to be a helping hand in analyzing transformers with harmonic issues. This research involved to setup a laboratory scale experiment initially to collect data which is costly and time consuming. Correspondingly, the cost and expenses can be reduced by avoiding the need of setting up similar experimental work in the future.

1.3 Objectives of the Study

This study embarks on the following objectives:

(a) to **develop** model of efficiency with variation of load,
(b) to **model** the trend of total harmonic distortion under variation of load composition,
(c) to **analyze** the model in term of harmonic distortion and transformer efficiency, and
(d) to **compare** the variation in stage of separation based on weight distribution for transformer equivalent parameter in simulation environment.

1.4 Scope of Study

This research develops a performance model of transformer with start-up with an experiment setup. The data collection and analysis plan provide sufficient amount of information that are relevant to problem of study by using the available resources more efficiently. The factors include transformer efficiency, loads composition, harmonic distortion level, apparent power, fundamental frequency, and harmonic frequency. The overall data collection and analysis plan were utilized to consider how the experimental factors fit together into a model that would fulfil the specific objectives of the experiment and satisfy the practical constraints of time and money. Understanding how the relevant variables fit into the design structure would indicate whether appropriate data could be collected in a way that permits an objective analysis that leads to valid inferences with respect to the stated problem.

The transformer and loads components from the experimental work were digitized into the simulation environment model by analyzing the measurement data.

Each model of the components was compared individually before being combined to build the complete system model. One of the main motivations for developing a simulation model or using any other modelling method is that it will be an inexpensive approach to gain important insights on when the costs, risks or logistics of manipulating the real system of interest are limited or prohibitive.

In this study, all apparatus needed for measurement and test equipment were identified to ensure the measurement units or test equipment were set up according to the user manual provided, if any. This was to minimise risk of making error of results with wrong setting, which would waste time in starting over again in the measurement process. Another reason was to avoid damage to the equipment and also as a cautious step for personal safety. Even though the end user equipment considered as loads were normal household's lighting load, caution and awareness step should be taken from time to time when experimental work is being conducted.

1.5 Thesis Organization

This thesis composes of six chapters, which are arranged as follows:

Chapter 1 describes the overview of the study, which includes the objectives, scope of study, problem statement and methodology throughout the study. Chapter 2 reviews the past research work, and related on-going transformer research on power quality issue. Transformer component model with its measured parameters are also described in this chapter.

Chapter 3 presents in depth explanation of each part of the components involved in the experimental work. Power quality analyser applied for measurement and its merit for quantifying the harmonic level are discussed in detail. This chapter also discusses the application of regression model on experimental data formulation and goodness indication of the fitting.

The overall system model with harmonic current injection model and transformer model in simulation environment are also presented in Chapter 3. The programming of the image processing data requiring mathematical algorithm on load waveform is also discussed. The mathematical theory involved in analysis tool applied in the simulation is presented as well.

Chapter 4 presents explanation on the data analysis with the aim of developing mathematical models using the regression method to describe the studied relationship between the variability of the measurement results. Discussion of the simulation results is also included. Aspects such as transformer's efficiency, total harmonic distortion level and apparent power consumption are discussed as well. Finally, Chapter 5 concludes the study and suggests several potential future works for improving the current work.

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