



Cairo University

**HARMONICS EFFECT ON THE THERMAL
PERFORMANCE OF THE DISTRIBUTION
TRANSFORMERS AND HOW TO MITIGATE IT**

By

AHMED ABD EL-MONEIM ABBAS

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of**

**MASTER OF SCIENCE
IN
ELECTRICAL POWER AND MACHINES ENGINEERING**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Table of Contents

Acknowledgements	I
Table of Contents	II
List of Tables	IV
List of Figures	V
Nomenclature	VIII
Abstract	XI
Chapter 1: Introduction	1
1.1 Motivation	1
1.2 Literature Review	1
1.3 Thesis Objectives	2
1.4 Thesis Organization	2
CHAPTER 2: Review of Nonlinear Loads	4
2.1 Basics of Harmonics	4
2.2 Power System Quantities under Nonsinusoidal Conditions	4
2.2.1 Active, Reactive, and Apparent Power	4
2.2.2 Displacement and True Power Factor	7
2.2.3 Triplen Harmonics	8
2.2.4 Resonance	10
2.2.4.1 Parallel Resonance	11
2.2.4.2 Series Resonance	13
2.3 Harmonic indices	15
2.3.1 Total Harmonic Distortion (THD)	16
2.3.2 Total Demand Distortion (TDD)	17
2.4 Harmonic Sources	19
2.4.1 Ferromagnetic Devices	20
2.4.2 Arcing Devices	22
2.4.3 Electronic Converters	22
2.5 Effect of Harmonics	26
2.5.1 Transformers	26
2.5.2 Motors and Generators	27
2.5.3 Cables	27
2.5.4 Switchgear	27
2.5.5 Capacitors	28
2.5.6 Metering	28
CHAPTER 3: Effect of the Harmonics on the Distribution Transformer	30
3.1 Theory of Transformer Losses	30
3.2 Effect of the Harmonics on the Transformer Losses	31

3.2.1 Ohmic Losses (I^2R) in Transformer Windings	31
3.2.2 Eddy Current Losses in Windings	31
3.2.3 Other Stray Losses in Transformers (P_{osl})	33
3.3 Heat Generation in the Transformer	34
3.4 Loading Capability of Transformer Feeding Non-sinusoidal Load Current	36
CHAPTER 4: Transformer Thermal Modeling	39
4.1 Transformer Loading Guide	42
4.1.1 IEEE Top Oil Temperature Rise Model	42
4.1.2 IEEE Hot Spot Temperature Rise Model	43
4.2 An Improved Top Oil Temperature Model	49
4.3 Dynamic Thermal Model	53
4.3.1 Dynamic Top Oil Thermal Model	53
4.3.2 Dynamic Hot Spot Thermal Model	55
4.4 Transformer Thermal Ageing	65
CHAPTER 5: Dynamic Thermal Modeling of the Transformer under Non-linear Loads and Mitigation of the Harmonic Effect	68
5.1 Dynamic Thermal Modeling of the Transformer in the Presence of Non-sinusoidal Load Currents	68
5.2 Mitigation of the Harmonic Effect	73
5.2.1 K-Factor Transformers	73
5.2.1.1 Relationship between K-factor and Harmonic Loss Factor	74
5.2.1.2 Case study for K-factor Transformer	75
5.2.2 An Algorithm for Mitigating the Effect of Non-Sinusoidal Load Currents	75
Chapter 6: Conclusions and Future Work	79
6.1 Conclusions	79
6.2 Future work	80
REFERENCES	82

List of Tables

Table 2.1:	Harmonic order vs. phase sequence	10
Table 2.2:	Harmonic voltage distortion limits in percent of nominal fundamental frequency voltage	17
Table 2.3:	Current distortion limits for general distribution systems (120V through 69000V)	18
Table 2.4:	Current distortion limits for general subtransmission systems (69001V through 161000 V)	18
Table 2.5:	Current distortion limits for general transmission systems > 161 kV, dispersed generation and cogeneration	19
Table 4.1:	Thermal–electrical analogous quantities	39
Table 4.2:	Exponents used in temperature determination equations	43
Table 4.3:	Cooling modes	43
Table 4.4:	Thermal model parameters and losses	44
Table 4.5:	Analogy between oil-to-air model and winding-to-oil model	56
Table 5.1:	K-factor calculation	75

List of Figures

Fig. 2.1:	Relationship between P, Q, and S in sinusoidal condition.	6
Fig. 2.2:	Relationship of components of the apparent power.	7
Fig. 2.3:	High neutral currents in circuits serving single-phase nonlinear loads.	8
Fig. 2.4:	Flow of third-harmonic current in three-phase transformers. (a) wye-delta transformer. (b) Grounded wye-wye transformer	9
Fig. 2.5:	Arc furnace operation in an unbalanced mode allows triplen harmonics to reach the power system despite a delta- connected transformer.	10
Fig.2.6:	System with potential parallel resonance problems.	11
Fig. 2.7:	At harmonic frequencies, the shunt capacitor bank appears in parallel with the system inductance. (a) Simplified distribution circuit; (b) parallel resonant circuit as seen from the harmonic source.	12
Fig. 2.8:	Impedance magnitude vs. frequency for parallel circuits.	13
Fig. 2.9:	System with potential series resonance problems.	14
Fig. 2.10:	Impedance magnitude vs. frequency for series resonant circuit	14
Fig. 2.11:	Simplified distribution circuit	15
Fig. 2.12:	Types of nonlinear loads	19
Fig. 2.13:	(a) Initial of B-H Curve. (b) Flux and magnetizing current waveforms. (c) Fully B-H Curve. (d) Fully flux and magnetizing current waveforms.	20
Fig. 2.14:	Typical B-H curve of soft magnetic material	21
Fig. 2.15:	Defining the excitation current	21
Fig. 2.16:	Arcing device circuit.	22
Fig.2.17:	Arcing device V&I.	22
Fig. 2.18:	Single-phase bridge rectifier.	23
Fig. 2.19:	Voltage and current waveforms of the bridge rectifier.	24
Fig. 2.20:	Single-phase bridge rectifier Fully controlled.	24
Fig. 2.21:	Waveforms of a fully controlled bridge rectifier with resistive load.	25
Fig. 2.22:	Waveforms of a fully controlled bridge rectifier with resistive-inductive load.	26
Fig. 3.1:	Electromagnetic field produced by load current in a transformer	33
Fig. 3.2:	Transformer Cooling Types (a) OA, (b) NDFOA, (c) DFOA.	36
Fig. 3.3:	Transformer thermal diagram according to IEC 354	37
Fig. 4.1:	An electrical RC circuit	40
Fig. 4.2:	The analogous thermal circuit.	41
Fig. 4.3:	Ambient temperature.	45
Fig. 4.4:	Transformer input load.	45
Fig. 4.5:	IEEE/ANSI model by MATLAB Simulink	46
Fig. 4.6:	IEEE model of top oil temperature over ambient temperature.	46
Fig. 4.7:	IEEE model of hot spot temperature rise over top oil temperature.	47
Fig. 4.8:	The top oil temperature over ambient temperature according to IEEE model.	47
Fig. 4.9:	The hot spot temperature over top oil temperature according to	48

	IEEE model	
Fig. 4.10:	The hot spot and top oil temperature according to IEEE model	48
Fig. 4.11:	The thermal improved model by MATLAB	50
Fig. 4.12:	An improved top oil temperature model	50
Fig. 4.13:	The hot spot temperature over top oil temperature model	51
Fig. 4.14:	The hot spot temperature rise over top oil temperature	51
Fig. 4.15:	The hot spot and top oil temperature according to improved model	52
Fig. 4.16:	The top oil temperature of IEEE and improved top oil model	52
Fig. 4.17:	The hot spot temperature of IEEE and improved model.	53
Fig. 4.18:	Thermal model of oil-to-air heat transfer	54
Fig. 4.19:	Predicted and measured top oil temperature	55
Fig. 4.20:	Thermal model for winding-to-oil heat transfer.	56
Fig. 4.21:	The thermal dynamic model	57
Fig. 4.22:	Dynamic top oil thermal model	58
Fig. 4.23:	Dynamic hot spot thermal model	58
Fig. 4.24:	The hot spot temperature and top oil temperature according to dynamic thermal model	59
Fig. 4.25:	The top oil temperature of the IEEE, improved top oil, and dynamic top oil model	59
Fig. 4.26:	The hot spot temperature of the improved and dynamic model with $m=1$ and $K_{\theta} = 1$.	61
Fig. 4.27:	The hot spot temperature of the improved and dynamic model with $K_{\theta}=1$.	62
Fig. 4.28:	The hot spot temperature of the improved and dynamic model without assumptions.	63
Fig. 4.29:	The hot spot temperature of the dynamic HST model with and without assumptions.	63
Fig. 4.30:	The Predicted and measured hot spot temperature according to dynamic thermal model.	64
Fig. 4.31:	The hot spot temperature of the IEEE, improved, and dynamic model	65
Fig. 4.32:	Transformer thermal ageing model	66
Fig. 4.33:	Transformer thermal ageing	67
Fig.5.1:	The thermal dynamic model in the presence of non-sinusoidal load currents.	69
Fig. 5.2:	The top oil thermal dynamic model in the presence of non-sinusoidal load currents.	70
Fig. 5.3:	The hot spot thermal dynamic model in the presence of non-sinusoidal load currents.	70
Fig. 5.4:	The transformer thermal ageing in the presence of non-sinusoidal load currents.	71
Fig. 5.5:	The top oil temperature with & without harmonics input load.	71
Fig. 5.6:	The hot spot temperature with & without harmonics input load.	72
Fig. 5.7:	The transformer thermal ageing with & without harmonics input load.	72
Fig. 5.8:	Flow chart to determine the loading capability of transformer under harmonic conditions.	76
Fig. 5.9:	The top oil temperature in the presence of non-sinusoidal load currents with derating the transformer current loading.	77
Fig. 5.10:	The hot spot temperature in the presence of non-sinusoidal load	77

currents with derating the transformer current loading.

Fig. 5.11: The transformer thermal ageing acceleration factor in the presence of non-sinusoidal load currents with derating the transformer current loading. 78

Nomenclature

B	The magnetic flux density
C_{th-H}	The winding thermal capacitance at the hot spot location (joules/°C)
C	Capacitance of capacitor bank (farad)
$C_{th,rated}$	The rated thermal capacitance (joules/°C)
C_{el}	Elect. Capacitance (farads)
C_{oil}	The thermal capacitance of the oil (joules/°C)
C_{th}	Thermal capacitance (joules/°C)
D	Distortion power
f_p	The parallel resonant frequency (hertz)
F_{HL}	Harmonic Loss Factor for winding eddy currents
F_{HL-STR}	Harmonic Loss Factor for other stray losses
F_{AA}	The accelerated ageing factor
F	The torque of the induction meter (newton.meter)
f_{tuned}	The actual tuned frequency (hertz)
$f_{nominal}$	The specified tuned frequency (hertz)
f	Rated frequency (hertz)
h_r	The resonant harmonic
h	Harmonic order
h_{max}	Highest significant harmonic number
H	The magnetic field intensity
IEC	The International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
I	Peak value of the current waveform (amperes)
I_h	Amplitude of a current waveform at the harmonic component h (amperes)
$I_{resonance}$	The current during the resonance (amperes)
I_{rms}	The rms values of the current (amperes)
I_h	The harmonic current (amperes)
I_1	The RMS value of the fundamental current (amperes)
I_L	The rated load current magnitude (amperes)
IHD_h	The rms value of the individual harmonic current
I_R	The rms fundamental current under rated frequency and load conditions
I(pu)	The rms current in per-unit for nonsinusoidal load
I_{max}	Maximum permissible rms nonsinusoidal load current (amperes)
KVA_{tx}	kVA rating of step-down transformer
K -Factor	The standard measure of the ability of a transformer to withstand nonlinear loads
K_θ	The resistance correction due to temperature change.
L_{eq}	Inductance of combined equivalent source and transformer (henry)
M_h	The rms value of harmonic component h of the quantity M
MVA_{sc}	The system short-circuit MVA
$Mvar_{cap}$	Mvar rating of capacitor bank
n, m	Empirically derived exponent depends on the cooling method
PF	Power factor
P_T	Transformer losses (watts)

P_{NL}	Transformer no load losses (watts)
P_{LL}	Transformer load losses (watts)
P	I^2R loss (watts)
P_{EC}	Winding eddy-current loss (watts)
P_{EC-O}	The winding eddy losses at the measured current and the power frequency (watts)
P_{OSL}	Stray loss in components other than the windings (watts)
P_{LL-R}	Transformer load losses at rated load conditions (watts)
P_{EC-R}	The winding eddy current loss under rated conditions (watts)
P_{OSL-R}	Other stray losses in transformers under rated conditions (watts)
$P_{LL-R}(pu)$	Transformer pu load losses at rated load conditions
$P_{EC-R}(pu)$	Transformer pu winding eddy-current losses at rated load conditions
P_{LL-H}	Load losses due to harmonics (watts)
Q	The quality factor of a resonant circuit
q_{fe}	The heat generated by iron losses (watts)
q_{cu}	The heat generated by copper losses (watts)
q	Heat transfer rate (watts)
q_{rated}	The losses at rated load (watts)
R_{oilR}	The thermal resistance of the oil under rated conditions ($^{\circ}C /watt$)
R_{th-H}	The thermal resistance at the hot spot location ($^{\circ}C /watt$)
R_{th}	Thermal Resistance ($^{\circ}C /watt$)
R_{thR}	The rated thermal Resistance ($^{\circ}C /watt$)
R_{el}	Elect. Resistance (ohms)
S	Apparent power (VA)
T	Periodic time of a waveform
THD	Total harmonic distortion
TDD	Total Demand distortion
T_{el}	Elect. time constant (minutes)
T_{th}	The thermal time constant (minutes)
$T_{th,rated}$	The rated thermal time constant (minutes)
T_o	The top oil time constant (minutes)
T_H	The hot spot time constant (minutes)
$v(t)$	A sinusoidal voltage function that is dependent on time t (volt)
V	Peak value of the voltage waveform (volt)
$v_{non.}(t)$	Non sinusoidal voltage function that is dependent on time t (volt)
V_0	DC component of the waveform (volt)
V_1	Peak value of the fundamental voltage (volt)
V_2, V_3, \dots, V_n	are the peak values of the voltage of the successive harmonics of the periodic waveform (volt)
V_{rms}	The rms values of the voltage (volt)
V_h	Amplitude of a voltage waveform at the harmonic component h
V_p	Voltage drop across the parallel impedance (volt)
V_s	Voltage at the power factor capacitor bank (volt)
$V_{LL,sys}$	The nominal system line-to-line voltage
V_h	The harmonic voltage (volt)
w	Angular velocity of the periodic waveform (rad/sec)
X_{leq}	Inductive reactance of combined equivalent source and transformer (ohm)
X_c	Capacitive reactance of capacitor bank (ohm)

X_{sc}	The system short-circuit reactance (ohm)
Z_{tx}	Step-down transformer impedance (ohm)
β	The ratio of load losses to no-load losses at rated load
Φ_{1m} and Φ_{2m}	The effective fluxes on the disc (webber)
Φ	Difference in phase angle between the voltage and the current waveforms (degree)
$\Delta\theta_{rated}$	The rated temperature rise (°C)
θ_K	The temperature factor for the loss correction (°C)
$\Delta\theta_{oi}$	The initial top oil temperature rises (°C)
$\Delta\theta_{ou}$	The final (ultimate) top oil temperature rises (°C)
$\Delta\theta_{fl}$	The full load top oil temperature rise over ambient temperature (°C)
$\Delta\theta_{Hi}$	The initial hot spot temperature rise (°C)
$\Delta\theta_{HU}$	The final (ultimate) hot spot temperature rise (°C)
θ	The phase difference between the two fluxes Φ_{1m} and Φ_{2m} (degree)
θ_1	The phase angle between the voltage and the current at the fundamental frequency (deg.)
θ_H	The winding hottest-spot temperature HST (°C)
$\Delta\theta_H$	The winding hottest-spot rise over top-oil temperature (°C)
$\Delta\theta_{HA}$	The hot spot conductor temperature rise over ambient (°C)
$\Delta\theta_{H-R}$	The rated winding hot spot conductor temperature rise over top oil temperature rise (°C)
θ_A	The average ambient temperature (°C)
θ_{T0}	The top-oil temperature TOT (°C)
θ_{T0-R}	The rated top oil temperature (°C)
$\Delta\theta_{T0}$	The top-oil rise over ambient temperature (°C)
$\Delta\theta_{T0-R}$	The rated top-oil rise over ambient temperature (°C)
(pu)	This symbol modifier may be added to the listed symbols to represent a per-unit value of that quantity. Current quantities are referred to the rated rms load current I_R quantities are referred to the rated load I^2R loss density. e.g.: I_h (pu) and P_{EC-R} (pu)

ABSTRACT

This thesis focuses on the effect of harmonic distortion on distribution transformers operating near the thermal limit and the ways of mitigating the harmonics effect. The theory of harmonics, its sources, and its effects are studied, a thermal model to predict a transformer hot spot temperature and thermal ageing acceleration factor under non-linear conditions is presented, and the mitigation of the harmonic effect is discussed. It has been focused on distribution transformers due to the high numbers of failures nationally and internationally attributed to unknown causes. A transformer thermal model is presented through theoretical considerations. Finally, a case study is presented on the loading capability of a transformer under non-linear conditions.

The main effect of non-sinusoidal current on distribution transformers is an increase in the transformer losses that lead to a temperature rise of the distribution transformer. The increased heat can lead to failure of insulation, which can reduce the transformer's life and cause eventual breakdown. The transformer load losses are ohmic losses, winding eddy current losses and other stray losses. This harmonics effect on transformer losses is modeled.

The harmonics effect on the transformer capability is studied through a numerical case study of a transformer feeding a non-linear load. The transformer loading capability is evaluated in the standard "IEEE Recommended Practice for Establishing Transformer Capability when Supplying Non-sinusoidal Load Currents", and a transformer thermal model derived from theoretical and mathematical analysis. The results show that an increase in the transformer losses can decrease the maximum permissible non-sinusoidal load current substantially. If the load current of the transformer is derated accordingly, it leads to a loss of the output power capacity of the distribution transformer. The transformer thermal model includes parameters that estimate the losses in the transformer that results in a smaller loss in power capacity.

Finally, a mitigation of the effect of the harmonics on the system is discussed. K-Factor transformer can be calculated according to the harmonics contents of the load current and is an indication of the additional losses. An algorithm is proposed to determine the loading capability of the transformer under harmonic conditions.

Keywords:

Transformer Losses; Top-Oil Temperature; Hot-Spot Temperature; Harmonics Effect; Harmonics Effect Mitigation.

Chapter 1: Introduction

1.1 Motivation:

Transformer has important role in the electrical network. It has different voltage levels, sizes, types, and connections. The non-linear loadings that can inject harmonics through the electrical network are ferromagnetic devices, arcing devices, and electronic components. The majority of loads, which produce nonlinear current, are fed through power-electronics converters. The current harmonics lead to voltage harmonics, hence causing nonlinear supply voltage in the electrical network [1].

Correct evaluation of the losses under a non-linear flux waveform is therefore necessary condition for the transformer design, especially when stringent efficiency standards are required. Nonlinearity in the core significantly affects the behavior of the transformer. The triplen harmonic components in the supply voltage have the most necessary effect on the current harmonics and distortion [2].

The main impact of harmonic currents on transformers is the further losses because of the harmonic spectrum generated by the nonlinear loads which lead to further heat. There are three impacts that result in increased transformer heating when the load current includes harmonic components: [3]

1. The rms value of the load current is increased due to increasing the harmonics contents. Hence, the ohmic losses (I^2R) loss will be increased.
2. The winding eddy-current losses (P_{EC}) are increased.
3. The other stray losses (P_{OSL}) are increased.

The losses because of harmonics and reactive power in European Union (EU) distribution transformers are found 5000 GWh/year approximately. However, total losses of distribution transformers in EU (European Union) are 38000 GWh/year approximately. So, harmonic study with calculations plays an important role in transformers to mitigate harmonics impacts [4].

1.2 Literature Review:

Overloading of the transformer may be because of emergency power interruption of electrical network elements or further loading is required especially during hot summers. Overloading of it is to possess the consistent existence of the loading and also for economical causes [5]. So, it is very important to expect the thermal performance of it during normal loading and especially in case of overloading it.

The thermal performance of transformers depends on the loading current and ambient air temperature. The thermal parameters of transformer are necessary for the customers to study the transformer thermal performance under loading conditions. The