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Effects of Harmonics on Distribution Transformer Efficiency

Thursday, 30 March 2023 | Technical Engineering Webinar

Presented By

Dr. Mohammad (Mo) Salay Naderi | EIT Lecturer & Electric Power Systems Expert

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Introduction - Presenter

Dr. Mohammad (Mo) Salay Naderi

Lecturer at the Engineering Institute of Technology
Electric Power Systems Expert

Mohammad Salay Naderi (M’10 – SM’11) did his B.Sc. (1996), M.Sc. (1998), and Ph.D. (2006) in the field of electric power engineering at Sharif University of Technology (SUT). In 2004, he joined the energy systems research group in the school of electrical engineering and telecommunications (EE&T) at UNSW as a visiting research associate and completed his PhD research work. He worked with Iran power generation, transmission, and distribution management company (Tavanir) as the deputy managing director of the bureau of technical and administration of transmission network with effect from 2005 to 2010. In 2010, he joined the school of EE&T at UNSW as a lecturer in the energy systems group. Subsequently, in 2013, he joined MicroTex Labs and worked as a principal electrical engineer and simultaneously an engineering manager in the field of renewable energy sources. He led a team to complete the installation, advance testing, and commissioning of PV+BESS systems in the ME region.

In addition, he was an international consultant at the university of Nazarbayev, Kazakhstan, with effect from Jan. 2018 to Dec. 2021. The consultation scope was in the areas including smart energy solutions, development and requirements of smart cities, power products manufacturing, high voltage engineering, condition monitoring of power equipment, and sustainable energy systems analysis and development. He served as the executive technical officer for investment plans and financial engineering of transmission network at Tavanir with effect from Feb. 2021 to Dec. 2022.

He has been serving as the managing director at Smart Energy Solutions Group (SESG) Pty Ltd since 2016, where he has been involved in developing and executing the company’s business strategies, preparing and implementing comprehensive business plans to facilitate achievement, and acting as the public speaker and public relations representative of the company. In 2023, he joined Engineering Institute of Technology (EIT) as an online instructor.

Agenda

1	Welcome and Introduction
2	Effects of Harmonics on Transformer Efficiency
3	Transformer Loading Capability
4	Case Studies: Lamps and Transformer Losses / De-rating
4.1	Experiments
4.2	Simulations
5	Conclusions and Q&A

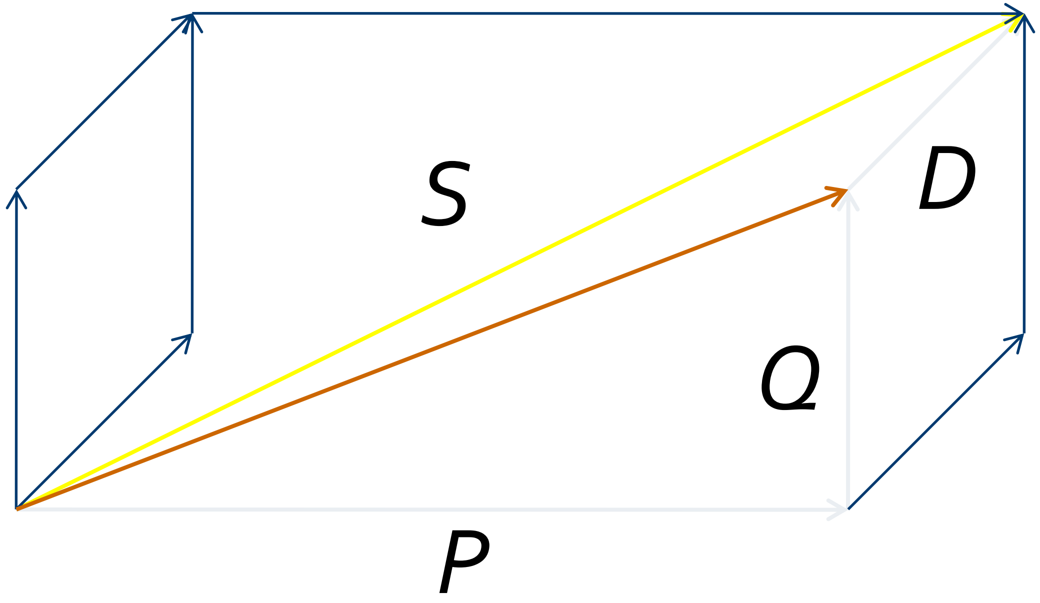
1. HARMONICS

$$I$$

$$I = \sqrt{\sum_{h=1}^{1} I_1^2} = I_1 \quad \leq \quad I = \sqrt{\sum_{h=1}^{h_{\max}} I_h^2}$$

1. HARMONICS

The presence of harmonics increases the apparent power that must be delivered to do a certain amount of work, therefore lowering the PF.



$$\sout{S^2 = P^2 + Q^2}$$

$$S^2 = P^2 + Q^2 + D^2$$

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Literature (more than 3 decades of academic research):

R. Singh and A. Singh, "Aging of distribution transformers due to harmonics," *14th Int'l Conf. on Harmonics and Quality of Power* (ICHQP), pp. 1-8, 2010.

N. R. Watson, T. L. Scott, S. J. Hirsch, "Implications for Distribution Networks of High Penetration of Compact Fluorescent Lamps," *IEEE Trans. Power Delivery*, vol. 24, pp. 1521-1528, 2009.

E. F. Fuchs, D. J. Roesler, M. A. S. Masoum, "Are harmonic recommendations according to IEEE and IEC too restrictive?," IEEE Trans. Power Delivery., vol. 19, no. 4, pp. 1775-1786, 2004.

M. A. S. Masoum and E. F. Fuchs, "Transformer magnetizing current and iron-core losses in harmonic power flow," IEEE Trans. On Power Delivery., vol. 9, pp. 10-20, 1994.

E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Aging of electrical appliances due to harmonics of the power system's voltage," *IEEE Trans. Power Delivery*, vol. PWRD-1, pp. 301–307, July 1986.

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Selected AS/NZS Standards:

AS/NZS 61000.3.2:2007
Electromagnetic Compatibility (EMC) - Limits - Limits for harmonic current emissions (equipment input current (16 A per phase) (IEC 61000-3-2, Ed. 3.0 (2005) MOD)

AS 2279.2-1991 (obsolescent)
Disturbances in mains supply networks - Limitation of harmonics caused by industrial equipment

DR AS/NZS 61000.4.13 CP
Electromagnetic Compatibility (EMC) - Testing and measurement techniques - Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests

DR AS/NZS 61000.4.7 CP
Electromagnetic Compatibility (EMC) - Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Selected IEEE Standards:

IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, ***IEEE Standard 519-1992***.

IEEE Recommended Practice for Monitoring Electric Power Quality, ***IEE Standard 1159-1995, Jun. 1995***.

IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents, ***IEEE Standard C57.110- 1998***, Jul. 1998.

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Transformer losses:

$$P_L = P_{NL} + P_{DC} + P_{EC} + P_{OSL}$$

Effects of Voltage Harmonics

Effects of Current Harmonics

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Effects of Voltage Harmonics (P_{NL})

Faraday's law in time domain:

$$\varepsilon = N\frac{d\varphi}{dt}$$

Faraday's law in frequency domain:

$$\varepsilon_h = j\omega h\varphi_h$$
$$h = 1,2,3,\ldots,n$$

Flux magnitude is proportional to the voltage and inversely proportional to the harmonic order *h*.

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Effects of Current Harmonics (P_{DC}+P_{EC}+P_{osl})

Effect of harmonics on DC Power (P_{DC})

$$P_{DC} \propto I^2$$

$$P_{DC} = R_{DC} I^2 = R_{DC} \left(\sum_{h=1}^{h=\max} I_h^{\;2} \right)$$

Effect of harmonics on Eddy Current Power (P_{EC})

$$P_{EC} \propto I_h^2, h^2$$

$$P_{EC} \cong \frac{\pi^2 f^2 T^2}{3\rho} k^2 \sqrt{\sum_{h=1}^{h-\max} I_h^2}$$

Effect of harmonics on Other Stray Loss Power (P_{osl})

$$P_{osl} \propto I_h^2, h^{0.8}$$

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=\max} h^{0.8} \left(I_h / I_R \right)^2$$

2. EFFECTS OF HARMONICS ON TRANSFORMER EFFICIENCY

Harmonic loss factor according to IEEE standard:

$$F_{HL} = \frac{\sum_{h=1}^{h=h\max} h^2 I^2}{\sum_{h=1}^{h=h\max} I^2} = \frac{\sum_{h=1}^{h=h\max} h^2 \left(I_h / I_1 \right)^2}{\sum_{h=1}^{h=h\max} \left(I_h / I_1 \right)^2}$$

Winding losses can be normalized to either the fundamental or the RMS current:

$$P_W = P_{DC} + P_{EC} \qquad P_W(pu) = I^2(pu)\left[1 + P_{EC-R}(pu) F_{HL}\right]$$

3. TRANSFORMER LOADING CAPABILITY (DE-RATING)

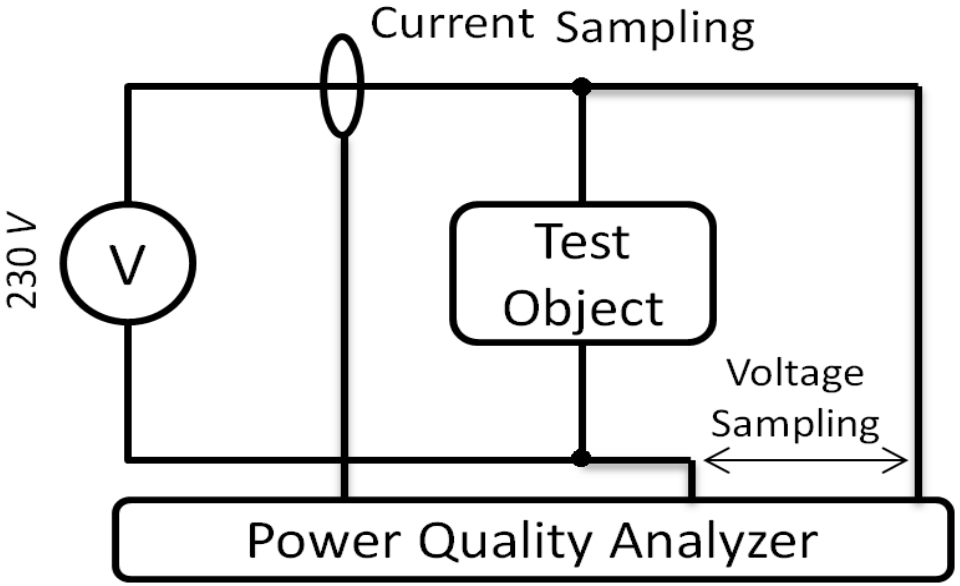
International standards recommend a method to determine the loading capability of transformers subject to non-sinusoidal load currents.

The recommended method for transformers is based on the condition that per unit value of the non-sinusoidal current will cause the same hot spot losses as the rated sinusoidal current.

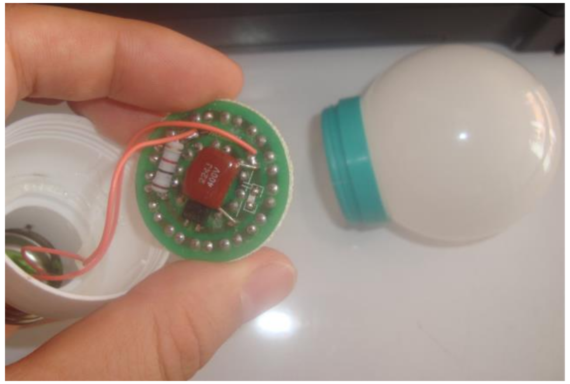
$$I_{\max}(pu) = \sqrt{\frac{P_{W-R}(pu)}{1 + F_{HL} \times P_{EC}(pu)}}$$

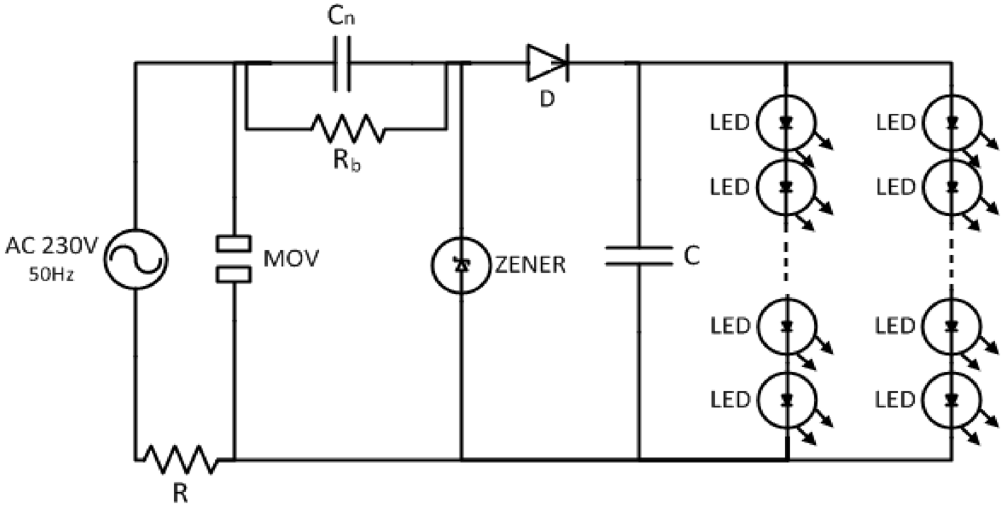
To reduce transformer eddy current losses, you need to decrease Zmit parameter, as it is recommended less than 33% in Seimens transformers

4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.1. EXPERIMENTS



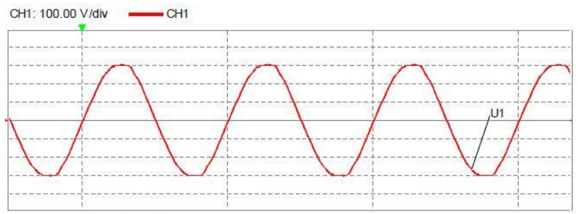
LED Lamps



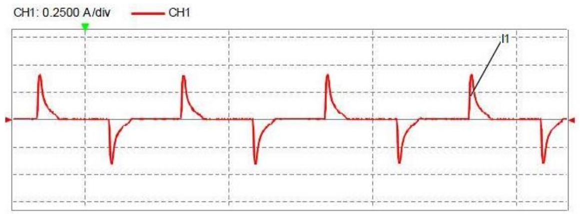


4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.1. EXPERIMENTS

CFL Waveforms

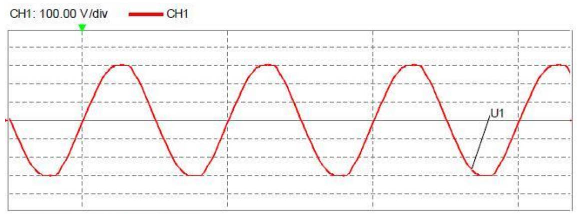


Voltage waveform

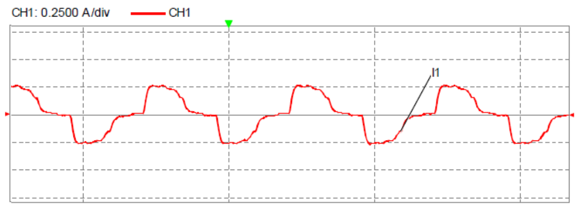


Current waveform

LED Waveforms



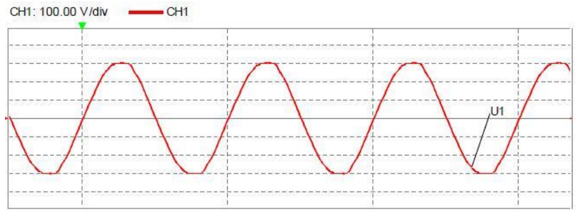
Voltage waveform



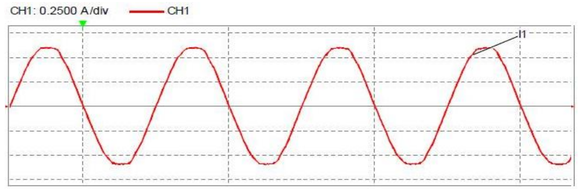
Current waveform

4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.1. EXPERIMENTS

Incandescent Waveforms

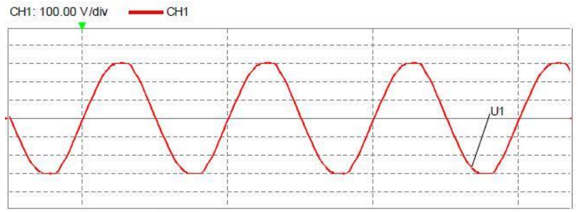


Voltage waveform

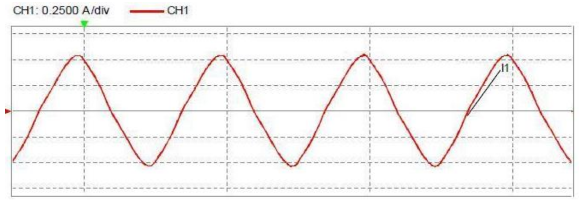


Current waveform

Fluorescent Waveforms



Voltage waveform



Current waveform

4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.1. EXPERIMENTS

CFL Harmonics

Order	(%)
1	100
2	0.11
3	83.39
4	0.11
5	59.88
6	0.09
7	44.57
8	0.18
9	40.71
10	0.12
11	36.76
12	0.12
13	29.83
14	0.1
15	25.42
16	0.13
17	23.94
THD = 139.14%	

LED Harmonics

Order	(%)
1	100
2	0.33
3	27.38
4	0.21
5	14.91
6	0.23
7	8.37
8	0.14
9	7.81
10	0.15
11	3.36
12	0.15
13	4.16
14	0.25
15	1.31
16	0.11
17	3.27
THD = 33.99%	

4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.1. EXPERIMENTS

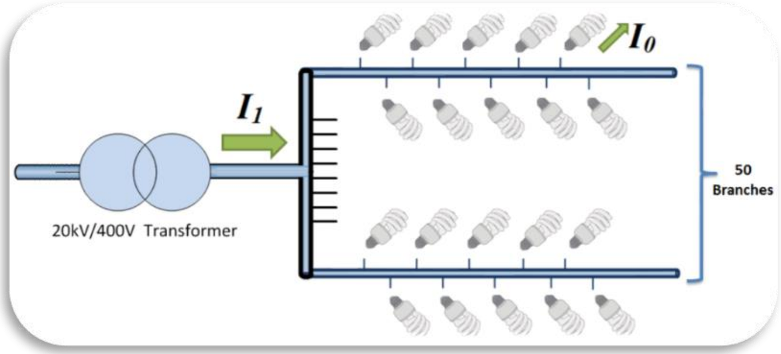
Incandescent Harmonics

Order	(%)
1	100
2	0.02
3	1.08
4	0.01
5	1.47
6	0.01
7	0.54
8	0.01
9	0.49
10	0.01
11	0.49
12	0.01
13	0.23
14	0.01
15	0.39
16	0.01
17	0.25
THD = 2.1%	

Fluorescent Harmonics

Order	(%)
1	100
2	0.26
3	6.15
4	0.14
5	1.59
6	0.08
7	1.23
8	0.02
9	0.15
10	0.02
11	0.29
12	0.03
13	0.14
14	0.02
15	0.1
16	0.01
17	0.07
THD = 6.49%	

4. CASE STUDIES: LAMPS AND TRANSFORMER LOSSES / DE-RATING
4.2. SIMULATIONS



In this circuit one 20 kV/400 V distribution transformer feeds 50 branches of consumers and each branch has ten identical lamps in parallel.

Rated Power	**500 kVA**
S.C.	**6 %**
Voltage level	**20/0.4 kV**
Cooling	**ONAN**
No load loss	**1000 W**
No load current	**1.7 %**
Losses(75 ˚C)	**7800 W**
Rated Frequency	**50 Hz**
V.G.	**Dyn5**
Total weight	**1755 kg**

$P_{EC} = 0.15$ $Z_{mit} = 0.15$

Maximum permissible transformer current:

Incandescent	Fluorescent	LED	CFL
$I_1 = 0.9972\ I_n$	$I_1 = 0.9939\ I_n$	$I_1 = 0.8457\ I_n$	$I_1 = 0.3070\ I_n$

$$I_{\max}(pu) = I\sqrt{\frac{P_{W-R}(pu)}{1 + F_{HL} \times P_{EC}(pu)}}$$

4.2. SIMULATIONS

Transformer loss [kW]:

Incandescent	Fluorescent	LED	CFL
7.8	7.857	12.4	101.34

5. CONCLUSIONS

- Voltage and harmonic levels of various types of lamps were measured.
- The impacts of each lamp on transformer losses were investigated and the worst case was when a pure CFL was transformer load.
- It is recommended to utilize CFL in combination with others lamp for decreasing harmonic distortion levels, which could eventually lead to transformer losses reduction.
- More work is necessary to realize the best combination of lamps.
- Perhaps Electron Stimulated Luminescence (ESL) lamps will be recommended in near future because of their brilliant lumen, full range dimming and long life in comparison to all other types of lamps.

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EIT Lecturer

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EIT Lecturer and AECOM Principal Engineer

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Wednesday 12 April, 2023

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Presented by Dr. Steve Mackay
EIT's Dean of Engineering

3:00PM - 4:00PM (AWST/UTC+8)
Wednesday 19 April, 2023

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Head Office
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