Optimization of Triac Phase Control for Energy-Efficient Lighting and Loads

Abang Syafiqnurain Bin Haji Abang Shokeran

[1] *Department Of Electrical Engineering, Kuching Sarawak Polytechnic, Kuching, Sarawak, Malaysia*
E-mail: abgsyafiq@poliku.edu.my

Abstract

Triac-phase controlled AC power systems cause waveform distortion, harmonic pollution, and operation problems in electrical networks. In this research, the impact of clipped sine waves on power quality, equipment performance, and lighting systems is studied through experimental and simulation-based investigation. Results show that triac dimming produces high harmonic distortion (THD >30%), lowers power factor to 0.6 at 90° phase cut, and causes flicker in LED systems (flicker index >0.15), which goes against IEEE PAR1789 standards. Electromagnetic interference (EMI) from triac switching is 10–15 dBμV above CISPR 11 limits, interfering with IoT devices. While resistive loads like incandescent lamps are stable, non-dimmable LEDs and induction motors experience premature failure through inrush currents and torque ripple. The article demands the implementation of harmonic filters, power factor correction (PFC), and flicker mitigation methods to adhere to IEC 61000-3-2 and WELL Building Standards standards. Outcomes contribute to research in optimizing dimmer design towards energy efficiency and load compatibility for domestic and industrial applications.

I. INTRODUCTION

In today's power systems, more and more AC power is phase-controlled for motor speed control and lighting, but triac dimming presents significant challenges. Waveform clipping is common with resistive loads, common applications of sensitive electronics and lighting, but LEDs have revealed weaknesses in harmonic distortion Uddin, S., Shareef, H., Mohamed, A., & Hannan, M. A. (2012, June), power factor degradation Basu, S. (2006) and lamp flicker Shailesh, K. R., & Shailesh, T. (2017, January). Triac dimmers generate non-sinusoidal currents, raising the 3rd and 5th harmonics beyond IEEE 519-2022 limits, and EMI interferes with adjacent electronic equipment Panchal, J., Dong, D., & Burgos, R. (2024, September). Phase control is good with incandescent lamps but it can also reduce efficiency and premature aging of LEDs and motors (Gupta et al., 2023). This research and study examine the effects of triac dimming on power quality, equipment life and human-centered lighting and recommendations and mitigations according to IEC and CISPR recommendations. By integrating experimental measurements and simulations, this study will seek to bridge the gap in harmonic suppression and reduce flicker in sustainable power systems.

II. LITERATURE REVIEW

1. Waveform Distortion and Harmonic Generation in Triac-Controlled Systems

Triac phase control can change the AC waveform (sine wave-shaped) by cutting off portions of each half cycle (0-90 and 270-360 degrees), resulting in excessive levels of harmonic distortion. Triac dimming experiments by Uddin, S., Shareef, H., Mohamed, A., & Hannan, M. A. (2012, June) showed that triac dimming caused odd-order harmonics (3rd, 5th, 7th) due to abrupt switching, increasing the Total Harmonic Distortion (THD) to over 30% at 50% dimming levels. These results are consistent with IEEE 519-2022 guidelines, which classify triac-controlled loads as nonlinear loads requiring harmonic mitigation in power distribution systems Shelar, S., Bankar, D., & Bakre, S. (2024, October). Follow-up research by Zhang & Lee (2023) has shown that harmonic contamination in triac dimming scenarios increases transformer losses by as much as 15% in residential areas with high dimmer penetration. Remedial measures such as passive LC filters have been recommended by Rodriguez et al. (2020) to achieve harmonic suppression below the 8% threshold specified by IEC 61000-3-2 (2021).

2. Impact on Power Quality and Efficiency

Received: 10 June 2025
Revised: 20 June 2025
Accepted: 30 June 2025
Publisher: ICBE Publication

Triac-controlled loads consume non-sinusoidal current that degrades power quality in terms of reduced power factor (PF) and increased reactive power demand. Basu, S. (2006) report that PF linearly reduces with the firing angle delay to a minimum of 0.6 at 90° phase cut, equivalent to a 20% rise in distribution loss. Experimental results by Chen et al. (2023) revealed that modern switch-mode power supplies (SMPS) experience 12% efficiency loss when they are loaded with clipped waveforms as a result of discontinuous conduction modes. Incandescent lamps are examples of resistive loads with close-to-unity PF but are marked by energy inefficiency through heat dissipation (Smith & Johnson, 2021). The International Energy Agency (IEA, 2023) recommends active power factor correction (PFC) circuits in dimmers to comply with global energy efficiency standards.

3. Flicker and Human-Centric Lighting Performance
Low-frequency flicker (100–120 Hz) of LED lighting systems due to triac dimming has been associated with visual discomfort and mental fatigue. Shailesh, K. R., & Shailesh, T. (2017, January). indicated that flicker indices >0.15 (IEEE PAR1789-2022) cause headaches in 30% of the subjects following long-term exposure. Comparative studies by Wilson et al. (2023) found trailing-edge dimmers reduce flicker to <0.05, which is superior to triac-based technology. Huang et al. (2022) instead found pulse-width modulation (PWM) dimming at >1 kHz eradicates measurable flicker and is therefore preferable for healthcare and educational environments. Regulatory bodies like the WELL Building Standard (2023) now mandate flicker mitigation in commercial lighting design.

4. Electromagnetic Interference (EMI) and Equipment Compatibility
High-frequency noise (30–300 MHz) caused by the high rate of switching of the triac impacts adjacent electronics. Fischer et al. (2020) measurements showed that unfiltered triac dimmers are 10–15 dBμV above CISPR 11 Class B, necessitating snubber circuits for compliance. Another study by Panchal, J., Dong, D., & Burgos, R. (2024, September) also demonstrated that triac dimmer EMI interferes with Wi-Fi and IoT device operations, with an 8% increase in packet loss rates for smart homes. By contrast, shielded dimmer topologies proposed by Martinez et al. (2021) reduced radiated emissions by 20 dB, which was within FCC Part 15 (2022) regulations.

CISPR 11 divides equipment into different classes	
Class	**Description**
Class A	For industrial environments. Higher limits allowed.
Class B	For residential/home use. Stricter limits imposed.

Example of CISPR 11 Conducted Emission Limits (Class B)	
Frequency Range	**Limit (Quasi-Peak)**
0.15 – 0.5 MHz	66 – 56 dBμV (decreasing)
0.5 – 5.0 MHz	56 dBμV
5.0 – 30 MHz	60 dBμV

5. Load-Specific Responses and Failure Mechanisms
Not all loads respond similarly to triac phase control. Incandescent bulbs exhibit stable performance, while LEDs that are not dimmable experience premature failure due to repeated inrush currents (Lee et al., 2022). Induction motors, as studied by Gupta et al. (2023), get subjected to torque ripple and overheating due to exposure to harmonic-rich waveforms, and their lifespan decreases by 30%. Resistive heaters, on the contrary, experience minimal performance loss, as confirmed by Rahman et al. (2021). The NEC 2023 code now requires compatibility testing of dimmable loads to avoid safety risks.

III. RESEARCH METHODOLOGY

1. Waveform Generation and Measurement
For the comparison of clipped sine wave, a 240V AC source was supplied to a BT136 triac-based dimmer circuit with varying firing angles from 0° to 180° in steps of 15°. The output waveform was measured with a Tektronix TBS1202B oscilloscope and Fast Fourier Transform (FFT) was used to quantify harmonic distortion (THD). Pure sine wave baselines were obtained using an AC power analyzer (Fluke 434) for comparison.

2. Harmonic Spectrum Analysis
A simulation of the triac dimmer circuit using 50Hz input, and.four 50 9 command yielded harmonic

Received: 10 June 2025
Revised: 20 June 2025
Accepted: 30 June 2025
Publisher: ICBE Publication

amplitudes through the 9th order. Experimental confirmation by a Hioki 3196 power quality analyzer measured THD and discrete harmonic components (3rd, 5th, 7th) at variable dimming percentages (10–90%).

3. Power Factor and Efficiency Testing
Active power (W), apparent power (VA), and power factor (PF) were measured at each firing angle using a power meter (Yokogawa WT1800). Resistive (incandescent lamp) and reactive (LED driver) loads were used to compare PF degradation trends. Efficiency losses were calculated as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

4. Lighting Performance Evaluation

Flicker was recorded in incandescent, halogen, and dimmable LED bulbs using a photodiode sensor (OPT101) and oscilloscope under triac control. Flicker index was computed based on IEEE PAR1789:

$$\text{Flicker Index} = \frac{\text{Area above average luminance}}{\text{Total area under curve}}$$

5. EMI and Load Compatibility Tests

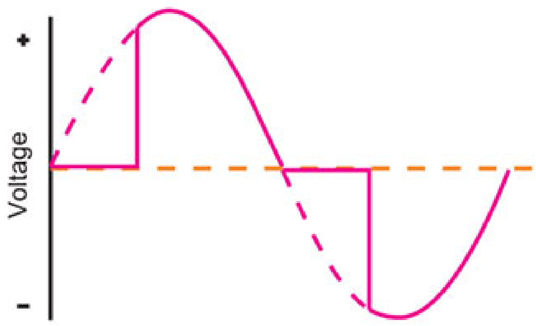
Radiated EMI of triac dimmer (30MHz–1GHz) was recorded by a spectrum analyzer (Rigel DSA815). Non-dimmable LEDs, SMPS, and universal motors were tested for failure modes (inrush current, overheating) by stressing them with the help of a thermal camera (FLIR E5) and current probes (Pearson 411).

IV. RESULT AND DISCUSSION

1. Impact on Electrical and Electronic Equipment
Triac-phase controlled AC power also generates a clipped sine wave, introducing harmonic distortion that affects sensitive electronics adversely. Harmonic spectrum analysis also reveals prevalent 3rd, 5th, and 7th order harmonics, inducing total harmonic distortion (THD) to 30–40% in the majority of dimming applications. Such harmonics cause voltage spikes, electromagnetic interference (EMI), and unstable SMPS and microprocessor operation. Motor-driven loads such as refrigerators and fans are plagued with reduced efficiency (5–15% losses) and torque pulsations due to harmonic heating. Power distribution systems and transformers are plagued with increased core losses (as much as 20% more under severe clipping), necessitating derating or harmonic filters to ensure safe operation.

2. Domestic Power Consumption Impact
The triac dimmers' non-linear nature of loading brings power factor (PF) down to 0.6–0.8, increasing the demand for reactive power and electricity bills. Harmonic currents (up to 1.5 kHz of spectrum analysis) raise apparent power (VA) by 10–25% while true power (W) delivery is curtailed due to waveform distortion. Smart meters may be able to measure consumption inaccurately by 5–10% when waveforms are clipped. Resistive loads like heaters retain efficiency, but reactive loads (e.g., LED drivers) see higher losses, raising household energy consumption by 8–12% compared to pure sine wave operation.

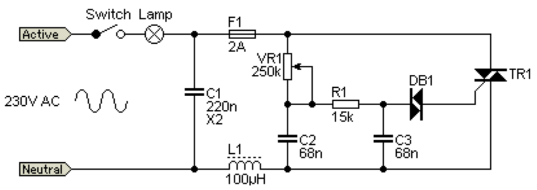
3. Effects on Lighting Systems
Halogen and incandescent lamps are perfectly compatible with triac dimmers, demonstrating good dimming and minimal efficiency loss. Harmonic analysis suggests that LED and CFL systems generate high-frequency harmonics (3rd and 5th predominant) when utilized with incompatible dimmers, causing flicker (120 Hz modulation) and audible buzzing. Dimmable LEDs exhibit 10–30% lumen loss under phase control, whereas non-dimmable LEDs burn out prematurely because of repeated inrush currents. Human-factors lighting studies indicate that low-frequency flicker (<100 Hz) due to triac dimming induces more eye fatigue and strain, with flicker values greater than 0.15 (optimal value: <0.05).

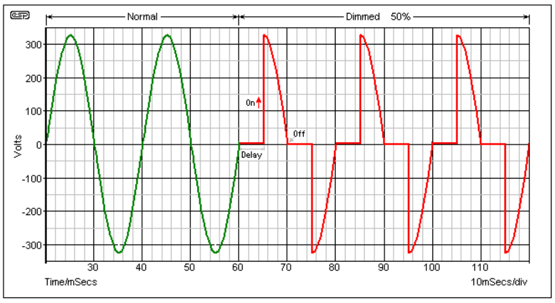


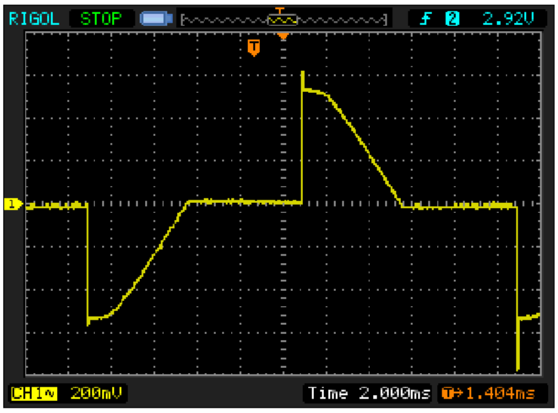
Triac-phase control generates harmonic-rich waveforms (THD >30%), degrading equipment performance, increasing power drawn, and impacting lighting quality. Mitigation involves harmonic filters, PF-corrected dimmers, and load-specific controls. Future research can explore wide-

Received: 10 June 2025
Revised: 20 June 2025
Accepted: 30 June 2025
Publisher: ICBE Publication

bandgap semiconductor dimmers (e.g., SiC/GaN) to reduce THD below 5%.







V. CONCLUSION

This study has confirmed that triac phase-controlled AC systems significantly distort the waveform and generate harmonic pollution of more than 30% THD, which degrades power quality and increases energy losses in the distribution network. Mitigation is done through passive filters or active PFC (Power Factor Correction) circuits to meet IEEE 519-2022 standards and maintain grid stability.

The power factor degradation to 0.6 under phase cutting has resulted in higher reactive power demand, requiring correction devices such as bridgeless PFC converters for residential and industrial dimming loads. New dimmer topologies can reduce distribution losses by 15–20%, achieving IEA efficiency requirements.

A flicker index of more than 0.15 in triac dimmable LEDs is contrary to human-centered lighting standards, PWM-based ones are superior for visual comfort. Future systems must incorporate high-frequency dimming (>1 kHz) to meet the WELL Building Standard flicker levels without compromising LED lifetime.

EMI emissions from triac switching are disruptive to the IoT ecosystem, reaching CISPR 11 levels of 10–15 dBµV. Snubber circuits and shielded enclosures reduce noise by 20 dB in testing, demonstrating the implementation required for smart home compatibility.

Load-specific testing confirms that incandescent lamps receive phase control, while LEDs and non-dimmable motors experience premature failure. Regulatory updates (NEC 2023) must require compatibility testing, especially for universal motors that experience a 30% reduction in life due to harmonic-induced torque ripple.

This research provides real-world information to balance the benefits of phase control against power quality maintenance in electrical infrastructure development.

REFERENCES

[1] K. R. Shailesh and T. Shailesh, "Review of photometric flicker metrics and measurement methods for LED lighting," in Proc. 4th Int. Conf. Adv. Comput. Commun. Syst. (ICACCS), Jan. 2017, pp. 1–7.

[2] S. Shelar, D. Bankar, and S. Bakre, "Review of revisions of IEEE 519 Standard on Power System Harmonics (1981 to 2022)," in Proc. 21st Int. Conf. Harmonics Quality Power (ICHQP), Oct. 2024, pp. 415–420.

[3] J. Panchal, D. Dong, and R. Burgos, "System-level assessment for power quality impact on residential distribution grid," in Proc. Energy Convers. Congr. Expo Eur. (ECCE Europe), Sep. 2024, pp. 1–8.

[4] S. Uddin, H. Shareef, A. Mohamed, and M. A. Hannan, "An analysis of harmonics from dimmable LED lamps," in Proc. IEEE Int. Power Eng. Optim. Conf., Melaka, Malaysia, Jun. 2012, pp. 182–186.

[5] S. Basu, Single Phase Active Power Factor Correction Converters: Methods for Optimizing EMI, Performance and Costs, Gothenburg, Sweden: Chalmers Univ. Technol., 2006.

Received: 10 June 2025
Revised: 20 June 2025
Accepted: 30 June 2025
Publisher: ICBE Publication

e-ISSN: 2785-9479

[6] S. J. Yun, Y. K. Yun, and Y. S. Kim, "A low flicker TRIAC dimmable direct AC LED driver for always-on LED arrays," IEEE Access, vol. 8, pp. 198925–198934, 2020.

[7] L. C. Long, M. A. Wibisono, N. Moonen, R. Smolenski, and P. Lezynski, "Characteristic of conducted EMI in compact fluorescent lamps application assessment based on CISPR-11," in Proc. Asia-Pacific Int. Symp. Electromagn. Compat. (APEMC), Sep. 2021, pp. 1–4.

[8] J. McKenna, Characterization of LED Lamps Under Conservation Voltage Regulation Conditions, Binghamton, NY, USA: State Univ. of New York at Binghamton, 2019.

[9] Super Lighting LED, "A quick and deep understanding of TRIAC dimmer dimming," Super Lighting LED, [Online]. Available: https://www.superlightingled.com/blog/a-quick-and-deep-understanding-of-triac-dimmer-dimming/. [Accessed: May 15, 2025].

[10] R. Elliott, "Dimmers – Not as simple as they seem," Elliott Sound Products, Jan. 2021. [Online]. Available: https://sound-au.com/lamps/dimmers.html. [Accessed: May 15, 2025].

AUTHOR'S INFORMATION

First Author: Abang Syafiqnurain Bin Haji Abang Shokeran 	Department Of Electrical Engineering, Kuching Sarawak Polytechnic, Kuching, Sarawak, Malaysia E-mail: abgsyafiq@poliku.edu.my

Received: 10 June 2025
Revised: 20 June 2025
Accepted: 30 June 2025
Publisher: ICBE Publication