AC Chopper Harmonic Magnitudes in Narrowband Power Line Communication Frequencies

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***Abstract*—Power Line Communication is becoming more common each passing day. Narrowband Power Line Communication systems use a frequency range from 3 kHz to 500 kHz. Nonlinear loads are common in residences and unfortunately they produce harmonics. It is possible that some harmonics produced by the nonlinear loads may interact with the power line communication system. AC dimmers produce impulse noise. In this study, Fourier series of an AC chopper is computed and its current harmonics magnitudes which is in Narrowband Power Line Communication frequencies are examined with and without a smoothing inductor. Their harmonic magnitudes in the power line communication frequencies are compared. It has been found that the smoothing inductor performs well to decrease the AC chopper harmonics within the Narrowband power line frequencies.**

***Index Terms*—Power Line Communication (PLC), Nonlinear loads, AC chopper, Harmonic analysis.**

I. INTRODUCTION

A residence has different types of nonlinear loads and they produce harmonics [1]–[5]. It is expected that Power line communication (PLC) is going to be a part of smart houses in the future [6]–[10]. PLC allows measuring and controlling of household appliance [6], [10]. Narrowband power line Communication abbreviated as N-PLC is generally described as communication over power line that is typically operating in transmission frequencies of up to 500 kHz [11]. Interference in power lines and data communication over narrow-band PLC is common [12]–[14]. An Analysis of the Broadband Noise in Powerline Networks and existence of non-Gaussian noise in PLC systems are given in [15]–[17]. A summary of EMC norms relevant to both Narrow-band and Broad-band-PLC has been given in detail in [18], [19]. The typical noise on the power line network is both time and frequency dependent [15], [20]–[22] Impulse and tonal noise are of importance in the power line environment, especially in the lower frequency region [2], [3], [15]. Activation of many kinds of electrical loads can be a source of impulse noise. The effects of loads like High Pressure Sodium Lamps are examined in [1], [2], [13].

The most common impulse noise sources are triac-based light dimmers which are AC chopper circuits. These dimmers produce high impulse noise, as they connect the lamp to the AC line part way through each alternance. It is reported that when the bulb is set to medium brightness impulses of several tens of volts are imposed onto the power lines at twice the AC line frequency [23]. A review on AC choppers can be found in [24]. In the countries such as Republic of Turkey, triac-based quartz infrared heaters are commonly used in residential and commercial buildings. That means the impulse noise must be higher in Turkey and it can interfere with N-PLC. That's why it is important to examine the harmonics produced by a triac-controlled quartz infrared heater and their effect on N-PLC frequencies and mitigate them in the smart houses for a better performance.

The impulse noise signals generated by an AC chopper should not reach to the PLC receiver if possible. Smoothing inductors are commonly used to have a less sharp current waveform with a better total harmonic distortion in rectifiers and AC choppers [24], [25]. It is cheaper than using more complicated filters [26]. Using a smoothing inductor in series with an AC chopper may also reduce the impulse noise at PLC frequencies. Such inductors are not usually desired due to their cost however the comfort the PLC provides may be preferable despite the price.

In this study, first the AC chopper current is expanded in Fourier series and then it harmonic magnitudes for N-PLC frequencies are examined. To decrease the effect of the impulse noise source, it is suggested to use a series-connected inductor. For an AC chopper with a series smoothing inductor, its current harmonic magnitudes are compared to that without and it has been found that the harmonics at N-PLC frequencies are significantly lower.

The paper is arranged as follows. In the second section, an AC chopper circuit and its waveforms are given. In the third section, its Fourier series expansion with and without a smoothing inductor is computed. The results are compared in the fourth section. The paper is concluded with the conclusion section.

II. AC CHOPPERS IN RESIDENCES

The most common AC chopper fed loads in residences are AC dimmers and quartz heaters shown in Figure 1. Voltage and current waveform of such a triac-controlled quartz heater are acquired with a Power analyzer and shown in Figure 2. Although the heater voltage is almost sinusoidal, its current has a high harmonic content due to the jump at the triggering angle

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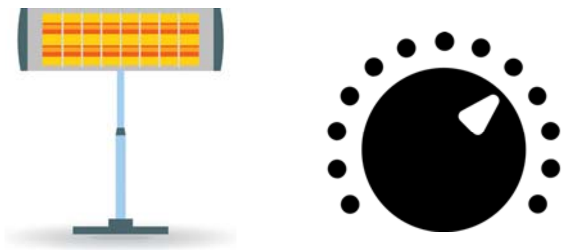
as shown in Figure 2. AC chopper schemas with and without a smoothing inductor are given in Figure 3.



a) b)

Figure 1. a) IR heater and b) AC dimmer

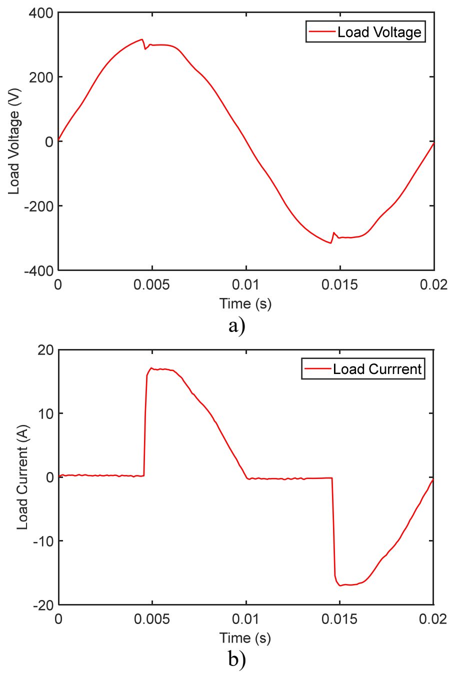


Figure 2. a) Voltage and b) current waveform of such a triac-controlled heater

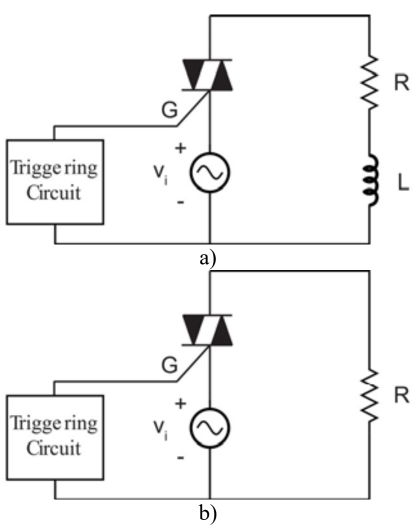


Figure 3. An AC chopper schematic a) with and b) without a smoothing inductor

III. AC Choppers Harmonic Analysis with and without a Smoothing Inductor

The input voltage of an AC chopper is assumed to be sinusoidal and sketched in Figure 4. Power line model is not considered in this study. Since a quartz heater is a resistor, its current is also of a similar but scaled shape without a series smoothing inductor as also sketched in Figure 4.

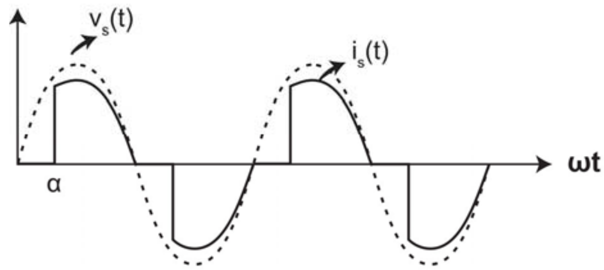


Figure 4. The voltage and current of the AC chopper without a smoothing inductor

The AC chopper output voltage and current is given as

$$v_s(t) = \begin{cases} 0 & , \quad 0 \le t < t_\alpha \\ V_m \sin(\omega t) & , \quad t_\alpha \le t < T/2 \\ 0 & , \quad T/2 \le t < T/2 + t_\alpha \\ V_m \sin(\omega t) & , \quad T/2 + t_\alpha \le t \le T \end{cases} \tag{1}$$

$$i_s(t) = \frac{v_s(t)}{R} = \begin{cases} 0 & , \quad 0 \le t < t_\alpha \\ \dfrac{V_m \sin(\omega t)}{R} & , \quad t_\alpha \le t < T/2 \\ 0 & , \quad T/2 \le t < T/2 + t_\alpha \\ \dfrac{V_m \sin(\omega t)}{R} & , \quad T/2 + t_\alpha \le t \le T \end{cases} \tag{2}$$

where V_m is the maximum value of the AC chopper voltage, R is the load resistance, T is the period, t_α is the triggering time in the first alternance.

If α and ω are the triggering angle and the angular speed respectively,

$$t_\alpha = \alpha / \omega \tag{3}$$

The AC chopper current and voltage can be written in Fourier series and expressed as

$$i_s(t) = \sum_{k=1}^{\infty} I_k \cos(\omega t + \varphi_{Ik}) \tag{4}$$

$$v_s(t) = \sum_{k=1}^{\infty} V_k \cos(\omega t + \varphi_{Vk}) \tag{5}$$

The voltage harmonics are low in the residences. That's why only the current harmonics of the AC chopper are to be calculated. Due to half symmetry, Fourier coefficients of the AC chopper current can be expressed as

$$a_k = \frac{4}{T}\int_0^{T/2} i_s(t)\cos(k\omega t)dt \,, \tag{6}$$

$$b_k = \frac{4}{T}\int_0^{T/2} i_s(t)\sin(k\omega t)dt \tag{7}$$

$$I_k = \sqrt{a_k^2 + b_k^2} \tag{8}$$

The harmonic coefficients are found as

$$a_k = \frac{V_m}{\pi}\left[\begin{array}{l}\left(\dfrac{\cos\left(\pi\left(k+1\right)\right)-\cos\left(\alpha\left(k+1\right)\right)}{k+1}\right)\\ -\left(\dfrac{\cos\left(\pi\left(k-1\right)\right)-\cos\left(\alpha\left(k-1\right)\right)}{k-1}\right)\end{array}\right] \tag{9}$$

$$b_k = \frac{V_m}{\pi}\left[-\frac{\sin\left(\alpha\left(k+1\right)\right)}{k+1}-\frac{\sin\left(\alpha\left(k-1\right)\right)}{k-1}\right] \tag{10}$$

$$I_k = \sqrt{a_k^2 + b_k^2} \tag{11}$$

The AC chopper current fundamental is given as

$$a_1 = \frac{V_m}{2\pi}\left[-1+\cos\left(2\omega t\alpha\right)\right] \tag{12}$$

$$b_1 = 4V_m\left[\frac{1}{4}-\frac{\alpha}{2\pi}+\frac{1}{8\pi}\sin\left(2\alpha\right)\right] \tag{13}$$

$$I_1 = \sqrt{a_1^2 + b_1^2} \tag{14}$$

If a smoothing inductor is used, AC chopper load voltage and current are sketched in Figure 5.

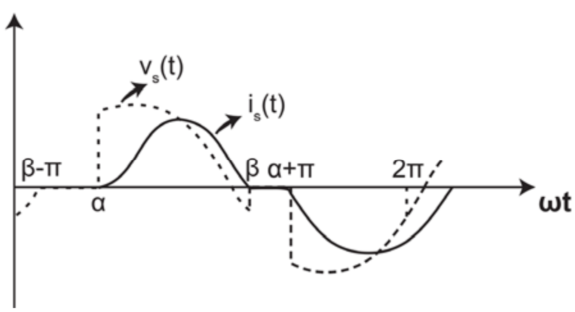


Figure 5. AC chopper load voltage and current with a smoothing inductor

The differential equation describing the AC chopper with a smoothing inductor if the copper current is not zero

$$Ri_s(t) + L\frac{di_s(t)}{dt} = V_m\sin(\omega t) \tag{15}$$

where L is the smoothing inductor inductance.

Its solution is given as

$$i_s(t) = Ae^{-Rt/L} + \frac{V_m\sin(\omega t-\varphi)}{Z} \tag{16}$$

Where the AC chopper load impedance is $Z = \sqrt{R^2 + \left(\omega L\right)^2} = \sqrt{R^2 + X^2}$ and its phase angle is $\varphi = \arctan\left(X/R\right) = \arctan\left(\omega L/R\right)$.

The integration constant is

$$A = -\frac{V_m e^{Rt_\alpha/L}\sin(\omega t_\alpha-\varphi)}{Z} \tag{17}$$

By solving the differential equation, the current is found as

$$i_s(t) = -\frac{V_m e^{-R(t-t_\alpha)/L}\sin(\omega t_\alpha-\varphi)}{Z}e^{-Rt/L} + \frac{V_m\sin(\omega t-\varphi)}{Z} \tag{18}$$

At angle β or its corresponding time value $t_\beta = \beta/\omega$, the current again becomes zero. The extinction angle β is shown in Figure 5 and can be found numerically by solving the following equation:

$$e^{-R(\beta-\alpha)/X}\sin(\alpha-\varphi) = \sin(\beta-\varphi) \tag{19}$$

When there is smoothing inductor, the following is always true:

$$t_\beta > T/2 \tag{20}$$

If a piecewise function is used to write the AC chopper current:

$$i_s(t) = \frac{V_m}{Z}\begin{cases} 0 & , \quad t_\beta - \dfrac{T}{2} \le t < t_\alpha \\ -\dfrac{\sin(\omega t_\alpha-\varphi)}{e^{\frac{R(t-t_\alpha)}{L}}} + \sin(\omega t-\varphi) & , \quad t_\alpha \le t < t_\beta \\ 0 & , \quad t_\beta \le t < \dfrac{T}{2} + t_\alpha \\ -\dfrac{\sin(\omega t_\alpha-\varphi)}{e^{\frac{R(t-t_\alpha)}{L}}} + \sin(\omega t-\varphi) & , \quad \dfrac{T}{2} + t_\alpha \le t \le T + t_\beta \end{cases} \tag{21}$$

The coefficients are calculated using (6)-(8) again. Two Matlab™ codes are written to evaluate the harmonics with and without the smoothing inductor.

IV. AC Chopper Harmonic Magnitudes in Power Line Communication Frequencies with and without a Smoothing Inductor

The smoothing ınductor with an ınductance of 1 mH is added to the system. The harmonics are normalized and the gain in Decibel is calculated for only odd harmonics since the even ones are zero due to half wave symmetry. The gain in decibel is given as

$$T\left(\omega\right) = 20\log_{10}\left(\left|\frac{c_k}{c_1}\right|\right) \tag{22}$$

where c_k is the k^{th} harmonic magnitude and c_1 is the fundamental harmonic magnitude, k is an odd number.

Using MATLAB, the AC chopper current magnitudes at N-PLC frequencies with and without the smoothing inductor are shown in Figure 6. The gain has a ripple in both cases. The ripple is low in the case with a smoothing inductor. The gain with smoothing inductor falls much quickly. N-PLC frequency ranges are shown in Table 1. If the PLC transmitter frequency is chosen as 100 kHz, which is in the CENELECT B band which does not have any restrictions, the harmonic magnitudes which is a measure of impulse noise is reduced by at least 25 dB. The filter performs well to reduce the impulse noise in N-PLC range as shown in Figure 6.

Table 1: Narrowband PLC frequency ranges for various regions

Region	Regulatory Body	Frequency Band	Note
Europe	CENELEC	3-95 kHz 95-125 kHz 125-140 kHz 140-148.5 kHz	A – Energy providers B-Reserved for users C-Reserved for users, regulated CSMA access D-Reserved for users
Japan	ARIB	10-450 kHz	
China	EPRI	3-90 kHz 3-500 kHz	Not regulated
USA	FCC	10-490 kHz	

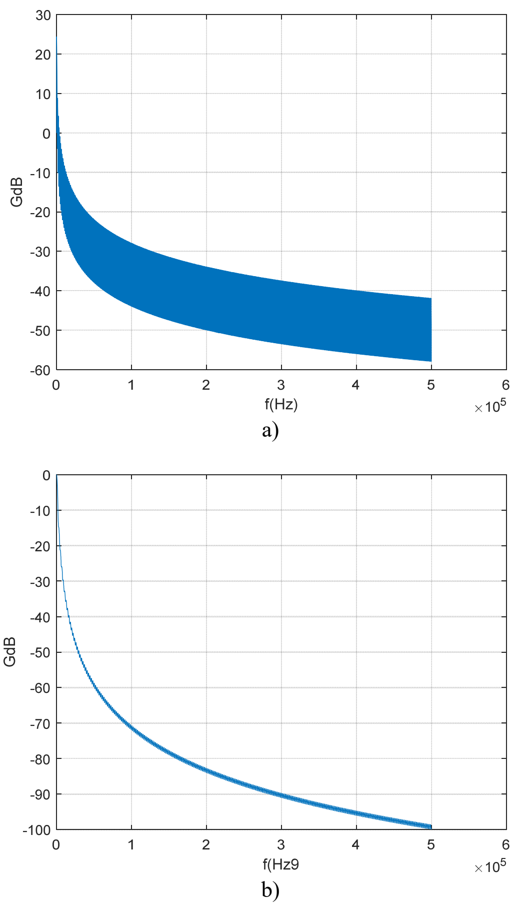


Figure 6. a) The AC chopper harmonic magnitudes at N-PLC frequencies without the smoothing inductor. b) The AC chopper harmonic magnitudes at N-PLC frequencies with the smoothing inductor.

V. CONCLUSION

AC choppers are main source of impulse noise in residences. Their usage worsens narrowband power line communication quality. In this study, current of common household appliances with AC choppers with and without a smoothing inductor are calculated and harmonic magnitudes of these devices are computed using Fourier series The harmonics are compared for the cases with and without a smoothing inductor and it has been found that using a smoothing inductor decreases the harmonics which contributes to the impulse noise within the Narrowband Power Line Communication frequencies. Countries with a heavy quartz heater usage may make regulations to enforce a smoothing inductor or a filter placed within the devices to reduce or eliminate the impulse noise to have a better N-PLC communication in smart houses.

VI. REFERENCES

[1] A. Iagar, G. Nicolae, P. Corina, and M. Dinis, “The influence of home nonlinear electric equipment operating modes on power quality.”

[2] C. Venkatesh, D. S. Kumar, D. V. S. S. Sarma, and M. Sydulu, “Modelling of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System,” in *Fifteenth National Power Systems Conference (NPSC), IIT Bombay, December 2008*, 2008, pp. 592–597.

[3] A. Capasso, R. Lamedica, and A. Prudenzi, “Estimation of net harmonic currents due to dispersed nonlinear loads within residential areas,” in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.98EX227)*, vol. 2, pp. 700–705.

[4] Gabriel Nicolae Popa, A. Iagar, and C. M. Dinis, “Simulation and Experimental Analysis of Non-Linear Loads from Residential and Educational Buildings,” in *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2016.

[5] M. Andrejevic-Stosovic, M. Dimitrijevic, S. Bojanic, O. Nieto-Taladriz, and V. Litovski, “Characterization of nonlinear loads in power distribution grid,” *Facta Univ. - Ser. Electron. Energ.*, vol. 29, no. 2, pp. 159–175, 2016.

[6] G. Hallak and G. Bumiller, “PLC for Home and Industry Automation,” in *Power Line Communications*, Chichester, UK: John Wiley & Sons, Ltd, 2016, pp. 449–472.

[7] C. J. Kikkert, “Coupling,” in *Power Line Communications*, Chichester, UK: John Wiley & Sons, Ltd, 2016, pp. 223–260.

[8] T. E. Sung and A. Bojanczyk, “Power-Line Communications and Smart Grids,” in *Convergence of Mobile and Stationary Next-Generation Networks*, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2010, pp. 317–348.

[9] H.-T. Roh and J.-W. Lee, “Residential Demand Response Scheduling With Multiclass Appliances in the Smart Grid,” *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 94–104, Jan. 2016.

[10] A. Ricci, V. Aisa, V. Cascio, G. Matrella, and P. Ciampolini, “Connecting electrical appliances to a home network using low-cost power-line communication,” in *International Symposium on Power Line Communications and Its Applications, 2005.*, 2005, pp. 300–304.

[11] IEEE, “1901.2-2013 - IEEE Approved Draft Standard for Low Frequency (less than 500 kHz) Narrow Band Power Line Communications for Smart Grid Applications,” IEEE, 2013.

[12] D. Guezgouz, D. E. Chariag, Y. Raingeaud, and J.-C. Le Bunetel, “Modeling of Electromagnetic Interference and PLC Transmission for Loads Shedding in a Microgrid,” *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 747–754, Mar. 2011.

[13] M. Elgenedy, M. Sayed, M. Mokhtar, M. Abdallah, and N. Al-Dhahir, “Interference mitigation techniques for narrowband powerline smart grid communications,” in *2015 IEEE International Conference on Smart Grid Communications (SmartGridComm)*,

2015, pp. 368–373.

[14] J. Mišurec, P. Mrákava, and D. Adamko, “Interference in power lines and data communication over narrow-band PLC Jiří,” *Electrorevue*, vol. 2, no. 3, pp. 63–67, 2011.

[15] H. Gassara, F. Rouissi, and A. Ghazel, “Narrowband stationary noise characterization and modelling for power line communication,” in *2013 13th International Symposium on Communications and Information Technologies (ISCIT)*, 2013, pp. 148–153.

[16] M. Zimmermann and K. Dostert, “An Analysis of the Broadband Noise Scenario in Powerline Networks.” 2006.

[17] C. Soltanpur, K. M. Rabie, B. Adebisi, and A. Wells, “Masreliez-Equalized VOFDM in Non-Gaussian Channels: Power Line Communication Systems,” *IEEE Syst. J.*, vol. 12, no. 3, pp. 2803–2811, Sep. 2018.

[18] Y. Wang *et al.*, “Comparison of Differential-Mode and Mixed-Mode Conducted Emission for Household Appliances in Power-Line Communication System,” *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 6, pp. 2023–2028, Dec. 2017.

[19] M. Girotto and A. M. Tonello, “EMC Regulations and Spectral Constraints for Multicarrier Modulation in PLC,” *IEEE Access*, vol. 5, pp. 4954–4966, 2017.

[20] F. Fang and Z. Yang, “Time domain suppression scheme of narrowband interference based on narrowband OFDM power line communications,” in *2016 International Conference on Communication and Electronics Systems (ICCES)*, 2016, pp. 1–6.

[21] I. H. Cavdar, “Performance Analysis of FSK Power Line Communications Systems Over the Time-Varying Channels: Measurements and Modeling,” *IEEE Trans. Power Deliv.*, vol. 19, no. 1, pp. 111–117, Jan. 2004.

[22] H. Meng, Y. L. Guan, and S. Chen, “Modeling and Analysis of Noise Effects on Broadband Power-Line Communications,” *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 630–637, Apr. 2005.

[23] “Narrowband PLC and the power line medium | eeNews Power.” [Online]. Available: http://www.eenewspower.com/content/narrowband-plc-and-power-line-medium/page/0/2. [Accessed: 22-Jan-2019].

[24] J. C. Rosas-Caro *et al.*, “A review of AC choppers,” in *2010 20th International Conference on Electronics Communications and Computers (CONIELECOMP)*, 2010, pp. 252–259.

[25] K. Mino, M. L. Heldwein, and J. W. Kolar, “Ultra compact three-phase rectifier with electronic smoothing inductor,” in *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005.*, vol. 1, pp. 522–528.

[26] A. F. Zobaa and S. H. E. A. Aleem, “A New Approach for Harmonic Distortion Minimization in Power Systems Supplying Nonlinear Loads,” *IEEE Trans. Ind. Informatics*, vol. 10, no. 2, pp. 1401–1412, May 2014.