Power Quality Analysis using Harmonic Heating factor by Multiple Energy Efficient Appliances in Smart Building

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Abstract: Harmonic distortion is usually not taken into account within domestic installations and the associated wiring systems, as its potential is considered sufficiently small to be neglected. Standards to limit harmonic manifestations in the low voltage (LV) network are available, but these can be breached as a consequence of advancements in power electronics in some modern household devices contributing higher levels of harmonic distortion than permitted. While these devices *individually* might not be considered serious in terms of systemmatic harmonic distortion manifestations, electrical equipment failures and insulation failures - increasingly being derived from harmonic cable heating - suggest a different story. Recently, attempts have been made to offer harmonic derating factors for building electrical circuit design, but this approach currently prioritizes large power devices. This article explores the need for harmonic considerations during the design stage of electrical services engineering projects. Best practice suggestions, in the context of the dissemination of heat caused by harmonics related to household load deployments/configurations, are also provided using some practical household data.

1. Introduction

The maintenance of standard operating voltage and current profiles is addressed as a power quality (PQ) problem. The PQ problem is further exasperated with the introduction of smart devices or smart loads in the distribution network most of which being non-linear in nature. In this regard, the presence of harmonics in the electrical network may be the cause of increased losses within transformers, overloading in neutral conductors, disturbances in the torque of motors, etc. (Watson & Arrillaga, 2003). “Smart distribution-grids” or distribution networks with smart devices claim the potential to improve the performance of the electric power system, as well as to offer the same performance as existing technologies, but in a more cost-effective way. However, these smart devices also need a proper harmonics mitigation technology, otherwise these also have some adverse consequences on PQ (Farhoodnea *et al*, 2013). To add to the problem, the inclusion of distributed energy resources, which employ power electronic converters/inverters, are also affecting power quality in the system (Khadem *et al.,* 2010). The interaction between distributed generators and electrical vehicles with the grid is discussed by Gil-de-Castro, Rönnberg and Bollen (Gil-de-Castro *et al.*, 2014). Their work suggests that the harmonics from individual domestic devices can flow to the grid and can cause an impact on other grid-connected devices. However, the study was limited to the harmonic interactions between grid connected devices and domestic devices and did not consider the interaction between individual appliances in the (domestic) household environment. The interactions between grid connected devices at harmonic frequencies can also introduce a harmonic resonance mode in the system (Watson & Arrillaga, 2003).

Harmonic heating effects are examined by Palmer et al. (Palmer *et al*., 1993) employing pipe type cable modelling through finite element analysis that utilizes the Nehar McGrath harmonic heating

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model. Cable heating effect in the presence of harmonic distortion is analysed and experimentally verified by Blackledge et al. (Blackledge *et al*., 2012). The authors briefly explain the cable heat transfer method and also discuss the harmonic rating factor introduced in BS 7671 (IEE, 2008), the national standard in the United Kingdom for electrical installations. The paper also contains a comprehensive discussion pertaining to the harmonic heating effect caused by harmonics in a building. In (Yong *et al*., 2010), the authors considered the losses in audio visual devices. The paper utilized time of use survey data concerning the audio-visual device to quantify the amount of power that can be saved. It was observed that *THD* reduction (by a factor of 10) could reduce the energy loss significantly and inculcate a saving of seven million of euros.

Inverters associated with Distributed Generation (DG), are one of the primary sources of harmonics in a building environment. Furthermore, inaccurate filter design could also lead to voltage distortion which can severely affect the consumer appliances. A harmonic resistance damping method is developed by Munir, Li and Tian to dampen the DG inverter harmonics (Munir *et al*. 2016).

The work presented here is based on simulation of the harmonic heating effects caused by devices that induce harmonic frequencies in the house/building and will evaluate the possible threat derived from the cumulative contributions created by such devices in different scenarios. An aim of the work is to find a relationship between the harmonics induced and the heating effect, caused. Current (i) waveforms consumed by these devices are simulated. Mitigation of the manifested distortion (THD,i|v) is explored through Fourier analysis and quantitative methods and subsequently characterised on terms of best practice considerations. The inclusion of renewable energy sources in smart network also injects harmonics in the network. In that context, this work, is also relevant to the smarter networks, where consumers are also potentially prosumers (customers that both consume and produce electricity).

1.1 Harmonics and Loss(es) due to harmonic manifested heat

In order to analyse the effect of harmonics in a building energy systems, simple methods are utilised to represent the harmonic heating. In any conductor when sinusoidal currents are introduced the geometry associated with the conductors introduces a complex electromagnetics problem. The sinusoidal varying magnetic flux induces a time varying magnetic flux density which induces eddy currents and as a consequence of the skin effect, higher losses relatively, in comparison to a DC context, are created. The ratio of AC to DC resistance is the parameter that varies for each harmonic frequency. The inductive element of the cable is not considered here as the associated value is sufficiently small and it does not cause an active power loss contribution to heat. However, the same is not true if the voltage waveform is considered, but this does not feature in this study. The ratio of AC to DC resistance is described generally in (1),

$$\frac{R_{AC}}{R_{DC}} = \frac{\int \frac{(i(x,y))^2}{\sigma} ds}{i^2 r_{dc}} \tag{1}$$

The integral is in respect to the cross-sectional area of all conductors in the system (cognisant of conductivity, σ). The effective resistance ratio is weighted sum of resistance ratios calculated at each frequency and provided by (Palmer *et al*., 1993)

$$\left(\frac{r_{ac}}{r_{dc}}\right)_{eff} = \sum_{n=1}^{\infty} \gamma_n^2 \left(\frac{r_{ac}}{r_{dc}}\right)_n \tag{2}$$

where γ_n is the ratio of n^{th} harmonic to the magnitude of total harmonic current. Considering only non-sinusoidal load current, and in consideration of a Fourier transform application, multiples of fundamental frequency, which themselves are sinusoidal, can be determined. The total heating caused by each component and in the context of a low voltage distribution network, the ratio of AC/DC resistance approximately equals 1.02 (Gobeirna De Espana, 2003), the total power loss can be obtained as follows:

$$P_L = I^2 r_{AC}$$

$$P_L = 1.02. r_{DC}. i^2 (1 + THD_i^2) \tag{3}$$

where I is the total current consumed by the harmonic load, including the *THDi* (i.e. the current THD) factor in the equation to quantify the harmonics as

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{4}$$

where, I_1 is the fundamental current, I_n is the harmonic current component for each harmonic order and *n* is the order of harmonics. Power loss without harmonics or AC resistance considered is:

$$P_{L\_normal} = I^2 r_{DC} \tag{5}$$

This paper will offer a comparison of the mismatch between the normal power loss and the loss incurred through *THD* (considering harmonics) to understand the amount of harmonic rating factor that may be required for the sub-circuit cable rating. The authors acknowledge that harmonic power factor, displacement power factor, etc. play an important role in the heating manifestations of harmonics. These characteristics however, are not considered in this study as their respective contributions are almost insignificant in terms of the building environment.

2. System Configuration

A typical residential environment contains a variety of electrical equipment, most of which can be classified as non-linear loads. The proliferation of non-linear load in the residential sector is due to the application of electronic switching devices commonly known as switch mode power supplies contained within power supplies. The first step in performing harmonic analysis is to obtain the magnitude of current consumed by these non-linear harmonic loads in the domestic household.

Various literatures discuss the PQ issues of the energy efficient harmonic loads but the performance during the operating conditions of said load is often neglected. Furthermore, the PQ studies for the most common and often highest power consuming appliances such as washing machines and vacuum cleaners are not widely disseminated. During the power quality analysis of the energy efficient appliances of a building, it is often found that some of the harmonic loads change their active and reactive power consumption or harmonic current injection characteristics depending on their operating mode from the pre-specified values. Non-linear devices such smart multi-media devices, desktop PCs, laptops, etc. are representative of the most typical single phase converter based loads, with similar current and voltage characteristics.

Modelling of these nonlinear loads is achievable in any simulation platform such as MATLAB^{TM}. For instance, non-linear load design based on single phase diode-bridge converter is considered using a Norton equivalent circuit are described in (Yong et al., 2010). These models are developed for single loads, and performance has been tested with single load representations only. Mazin et al. (Mazin et al. 2011) describe the harmonic contribution of residential loads by studying the characteristics of load side and source side harmonic impedances. It is also common knowledge that in residential buildings individual loads always consume reactive current and produces harmonic currents at the same phase angle with respect to its supply voltage in the same operating condition. Therefore Salles et al. (Salles et al, 2012), in this regard, suggest that typical spectrum can be used to model a harmonic-producing load. In this paper, the linear and non-linear harmonic load models have been developed by controlled current source in simulink power system (SPS), based on the available harmonic information (% of THD and phase angle) of domestic load data. A Simulink developed load model was subsequently verified with the experimentally collected data for which more than 200 measurements have been taken randomly for the harmonic appliances in a residential building where the variation of voltage THD is found from 1.2 to 1.7%. In most readings considered, the magnitude of the harmonic current order above 21st is found to be less than 5% of the fundamental. Modelling and verification details are not presented here owing to page restriction.

3. Results

To analyse the combined effect of these harmonic loads, a household network wiring is considered which is in accordance with the British wiring standards, BS7671 (IEE/BSI. 2008), Power is distributed through radial circuits, with varying current carrying capacities (I_z). In a domestic context, lighting circuits are facilitated through a 1.5 mm^2 (I_z = 6A capacity) wiring system with general services (socket) circuits are facilitated through a 2.5 mm^2 wiring system (I_z = 20A capacity). The daily power consumption of lighting/general service load may vary depending on various factors. In this study the power quality analysis of the appliances during their operation mode is considered and hence does not relay on the manufacture pre-specified values.

The worst case harmonic scenarios in a domestic environment happens when multiple harmonic loads are connected to a single sub circuit as the harmonics are generally cumulative in nature. Hence to understand this environment, various probable combinations of harmonic loads are combined together to form different case studies. A total of six harmonic loads were considered along with two linear heating loads forming 255 combinations. Exemplar cases are provided in Table 1 with their corresponding current *THD* calculated. While the harmonics are generally cumulative, in some cases, they tend to cancel out depending upon the harmonic phase angle and hence in the practical consideration the *THD* may reduce with certain combinations. However, to understand the worst possible scenario in a domestic environment, five combinations that accumulated the highest losses are considered and presented in Table 1 and Fig. 1. In this regard, the exemplar scenarios are analysed for the harmonic power loss and then compared with standard power loss calculated by the RMS value of current. It is evident that the actual power loss occurring in the conductor is much more than the loss during the normal operating condition. To put it in perspective, a 2.5 mm^2 cable, with maximum rated current carrying capacity, the loss is 3.8 W/unit length but in case 2 the loss is close to 5 W/unit length even when the RMS current is much less than the rated current. This therefore implies, that relatively speaking, a circuit operating at near to its rated current would incur enhanced deterioration in the cable, which could eventually lead to cable failure or in the worst case a fire incident.

Table 1: Harmonic Devices different combinations and their resultant *THD* percentage

	Lights	Microwave Oven	Fridge	Vacuum Cleaner	Washing Machine	Laptop	Current THD (%)
Ratings (W)	*40*	*1350*	*160*	*1400*	*1200*	*250*	
CASE 1	ON	ON	OFF	OFF	ON	ON	44.65
CASE 2	ON	ON	ON	OFF	ON	ON	42.12
CASE 3	ON	ON	ON	OFF	ON	OFF	41.31
CASE 4	OFF	ON	ON	OFF	ON	ON	40.73
CASE 5	OFF	ON	ON	OFF	ON	OFF	39.74

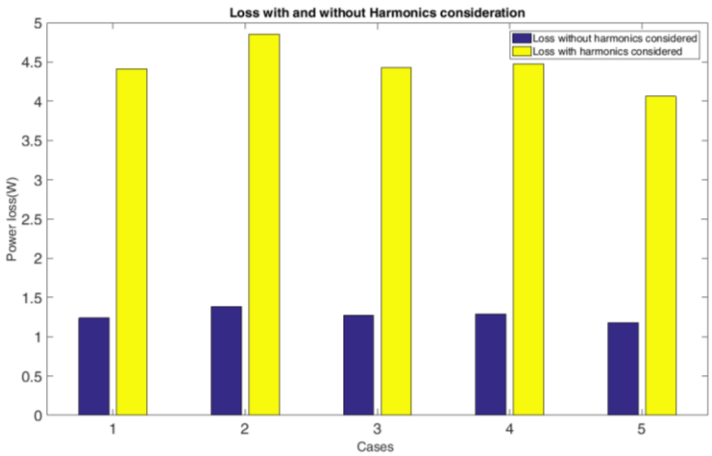

Fig. 1: Loss with and without Harmonic consideration

To understand the relationship between the *THD* and heating effect a *THD* vs P_{loss} curve is plotted in Fig. 2 which shows an exponential increase in the power loss with an increase in *THD*. This is apparent when equation (2) is employed to calculate the power loss in terms of *THD*. As the harmonic pollution increases in an electrical network the heating in the cable increases and may eventually be higher than the rated value for a particular conductor. This situation may not be recognised by standard protection equipment as it relies on the RMS value of current. However, modern protection circuits with thermal overheat protection may detect if the increase in temperature is in the same circuit as of the protection unit. It is normal practice in the domestic environment for consumers to employ extension cords to connect multiple devices and may not have such type of protection locally. Such possibilities in the domestic environment are the primary motivation for this study with consumer awareness and best practice awareness in respect to harmonic loads as the goal. To understand the adversity of the situation, the initial point depicted in Fig. 1 at *THD* of 1% represents a loss of only 3.83×10^{-5} pu, whereas at 100 % *THD* it reaches close to 0.4 pu and it reaches 1pu when *THD* is 160 %.

Fig. 3 illustrates that in consideration of the harmonic profile associated with CFL (Case A) and CFL with resistive load (Case B), that the *THD* is not always the optimal measure of harmonic content in the system, or to even understand the harmonic pollution in a system. Since the *THD* is a ratio of fundamental to the vector sum of harmonics, when a purely resistive load like a heater is connected to a circuit containing harmonic load, the *THD* may appear to be lower; even though the harmonic profile does not change. Hence the harmonic pollution will be still observed in the system, which is evident from the harmonic spectra illustrated in Case A and Case B of Fig. 3. This scenario could be intolerable for many sensitive consumer equipment and could eventually lead to premature failure of such devices. This is because sensitive consumer equipment containing electronic circuitry could form a lower impedance in the context of certain harmonic frequencies. Reliability studies such as mean time failure studies need to be conducted to completely understand and quantify the direct effect of harmonics in the context of consumer equipment.

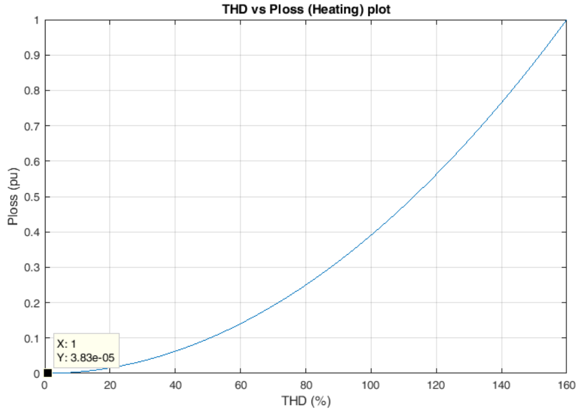

Fig. 2: *THD* <u>vs</u> P_{loss} Plot

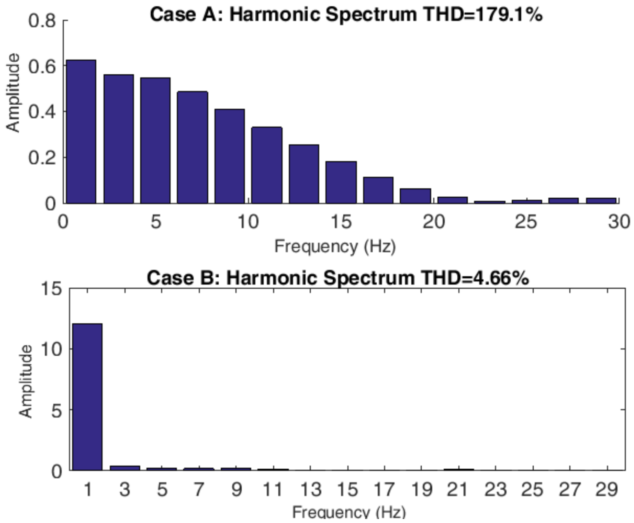

Fig. 3: Harmonic spectrum of different cases considered

3.1 <u>Scenario with inverter based DG such as solar PV as source</u>

The above case was analysed using a stiff source such as the electrical grid, which may still provide a close to the sinusoidal voltage input even with significant harmonic pollution from a building energy system. However, with a source like solar PV generator or a battery storage system, the situation is entirely different. The source voltage may not be exactly sinusoidal with the harmonics present and even with filters installed in the inverter system. This would further lead to distortion in the power quality and adversely impact on equipment operation in a building. With impure power, the performance and expected life time of equipment is affected. Fig. 4 illustrates a voltage waveform without a stiff source where the harmonic pollution causing voltage distortion is clearly visible. The voltage *THD* is approximately 12 percent in Fig. 4. However, the regulation states a 2-5 % limit to the harmonic voltage connected to the electrical system depending on the power rating. That said however, a 2 % tolerance in the context of a high power piece of equipment would itself represent a high value and could lead to consumer equipment damage. Furthermore, in the context of power loss in cables with non-linear loads connected to distorted voltage increases in the losses incurable will also be observed relative to linear load considerations.

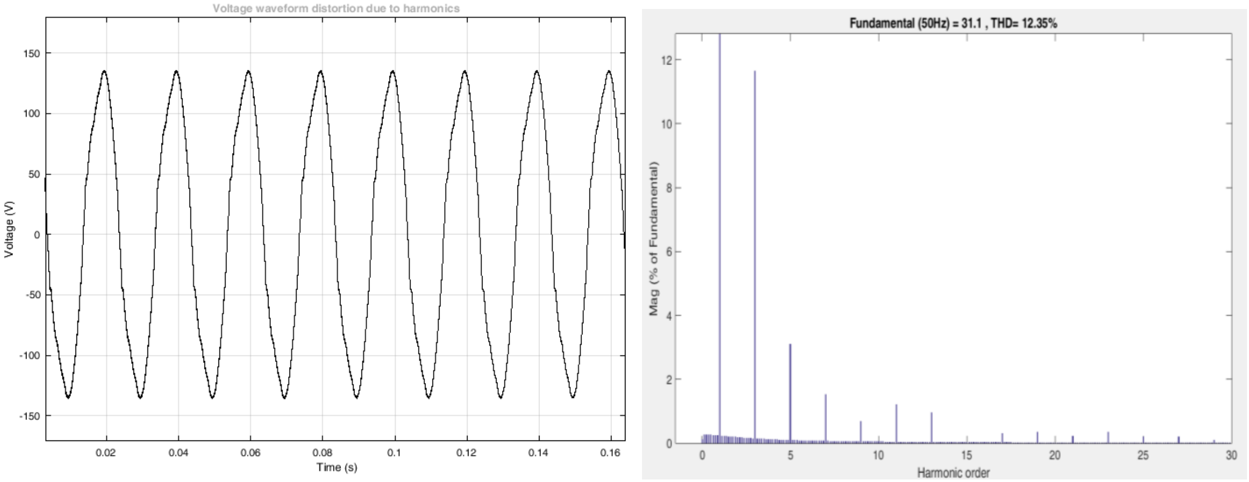

Fig. 4: Voltage waveform distortion due to harmonics with an isolated source and its harmonic spectrum

3.2 Recommendations and Best Practices

The following are the recommendations based on the analysis and observation in this work, which can be followed in domestic/building environments to safeguard the equipment involved and reduce the harmful effects of harmonics. These are only simple solutions to the much-understated problem and would need further detailed study and theoretical explanations based on field data to prepare for future penetration of harmonic load.

1. Separate circuit supplying harmonic loads based on the power rating
2. Anticipate for potential load growth during electrical circuit design phase
3. Consider a harmonic rating factor while deciding conductor size
4. Install a generous number of general service outlets,; mitigate against the use of extension cords/leads
5. Use loads with harmonic filters facilitated
6. Prioritize a DC supply, in the context of DG, for loads in the house would help to bypass the issues with harmonics
7. Implement strict regulation for limiting harmonics in the domestic environment.
8. Consider tariffs that incentivise consumers against higher harmonic pollutants
9. Create consumer awareness of the harmful effects of harmonics and sensitive equipment
10. Create a harmonic tolerance rating with to understand the withstand capability of devices to a harmonic environment.

4. Conclusion

Harmonic distortion and its associated problems is not a new concept. However, the issue has heretofore not been afforded sufficient importance within the domestic environment. The analysis presented in this paper indicates the need to consider the same in a building system to preserve and maintain the stable long term operation of building electrical services in the context of modern smart environment scenario. The cable heating effect associated with harmonic current should be carried out during the design phase of the building itself. This calls for much more accurate anticipation of loads and consumer behaviour as well. The BS7671 wiring standards have provided a harmonic derating factor which should be considered at the design phase with 3 phase systems. However, in the context of single phase, the presented analysis may also be used to de-rate the associated conductors. While this may lead to use of oversized cable, safety of equipment and human life will be justifiably enhanced as a consequence. The situation would deteriorate if a low impedance source like solar photovoltaic generator is used as they inherently have waveform distortion characteristics, and the harmonics would lead to further voltage distortion. This scenario was not initially anticipated and would be further exasperated with larger harmonic loads such as electric vehicles (EV). In terms of future work, the effect of harmonics on domestic equipment needs to be quantified. This could serve to introduce a device rating standard, which would provide a tolerance within a harmonic environment metric.

5. References

Watson, N. and Arrillaga, J., Power systems electromagnetic transients' simulation (Vol. 39). IET, 2003

Farhoodnea, M., Mohamed, A., Shareef, H. and Zayandehroodi, H., Power quality impact of renewable energy based generators and electric vehicles on distribution systems. Procedia Technology; 2013; 11; 11-17.

Khadem, S.K., Basu, M. and Conlon, M., Power quality in grid connected renewable energy systems: role of custom power devices, 2013; ICREPQ.

Gil-de-Castro A., Rönnberg S. K. and Bollen M. H. J., A study about harmonic interaction between devices, 2014; 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest; 728-732

Palmer, J.A., Degeneff, R.C., McKernan, T.M. and Halleran, T.M., Determination of the effect of harmonics on pipe-type power cable AC/DC resistance ratios 1993; IEEE transactions on magnetics, 29(2); 1427-1433.

Blackledge, J., O'Connell, K., Barrett, M., Sung, A., Cable heating effects due to harmonic distortion in electrical installations. 2012; International Association of Engineers: ICEEE12, London

IEE/BSI, BS 7671:2008, Requirements For Electrical Installations, IEE Wiring Regulations, 2008; The Institution of Engineering and Technology; 17th Edition

Yong J., Chen L., Chen S., Modeling of Home Appliances for Power Distribution System Harmonic Analysis, 2010; Power Delivery, IEEE Transactions on; 25(4); 3147-3155.

Munir M.S., Li Y.W. and Tian H., Improved Residential Distribution System Harmonic Compensation Scheme Using Power Electronics Interfaced DGs, 2016; IEEE Transactions on Smart Grid; 7(3), 1191-1203

Gobeirna De Espana, Guía técnica de aplicación en BT, anexo 2: cálculo de las caidas de tension (Technical Guide for application to the Low Voltage Electrotechnical Regulation), 2003

Mazin, H.E., Nino, E.E., Xu, W. and Yong, J., A study on the harmonic contributions of residential loads, 2011; IEEE Transactions on Power Delivery; 26(3); 1592-1599

Salles, D., Jiang, C., Xu, W., Freitas, W. and Mazin, H.E., Assessing the collective harmonic impact of modern residential loads—Part I: Methodology 2012; IEEE Transactions on Power Delivery; 27(4); 1937-1946.