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Investigating the Power Quality of an Electrical Distribution System Stressed by Non-Linear Domestic Appliances

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Abstract: Power quality has become a matter of growing concern in recent years owing to a daily rise in use of non-linear loads at domestic level. In addition, fast growing technologies like distributed generation and electric vehicles are emerging as part of modern distribution systems. Therefore, it is necessary to evaluate and analyze the power quality issues due to various non-linear home appliances to give a clear picture of the current scenario. So that future technologies can be accommodated in the distribution systems while coping with existing power quality issues. The experimentally developed harmonic models, of various commonly deployed domestic appliances, are used for the simulation of a practical distribution system in Electrical Transient Analyzer Program (ETAP). Experimental results combined with simulation results show an alarmingly high level of harmonic distortion, breaching the recommended standard practices, in both current and voltage at not only point of common coupling (PCC) but also at the consumer's end. In addition to increase in losses, this also degrades power factor giving rise to distortion power. While discussing other impacts of harmonic distortion, true power factor (PF_{true}) and distortion power (D) has also been evaluated at PCC.

Keywords: Power Quality, Harmonic Distortion, Distortion Power, PF_{true}, Non-linear Loads

1. Introduction

There is an ever increasing interest in power quality due to the increasing use of computers and electronics equipments. Generally speaking power quality of a power supply is defined by a set of parameters which ensures the normal operation of equipment being supplied [1]. The ultimate reason for this high level of interest in power quality is economics associated with it, as any interruption of service caused by any disturbance can trigger a loss of millions of dollars in lost production [2]. There are several issues regarding the power quality including voltage dips, voltage swells, transients, harmonic distortion, flickers, voltage imbalances, transient interruptions and outages [3]. This research work focuses on harmonic distortion caused by various non-linear domestic appliances. The proliferation of non-linear electronic loads, which draw non sinusoidal current, is increasing day by day [4]. Harmonic distortion can be defined as the steady state deviation from an ideal sine wave of fundamental frequency due to the presence of sinusoidal components having frequencies as integer multiples of the fundamental frequency [5].

The entity usually used to quantify harmonic distortion is THD i.e. total harmonic distortion [6] which can be defined as "The ratio of the rms of the harmonic content to the rms value of the fundamental quantity, expressed as a percentage of the fundamental".

$$(\%)\ \mathrm{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} M_{h,rms}^2}}{M_{1,rms}} \times 100 \qquad (1)$$

Where $M_{1,rms}$ is the rms value of fundamental component of voltage/current and $M_{h,rms}$ represents the rms value for h^{th} harmonic component of voltage/current. Keeping in view the anticipated influx of newer technologies, in distribution systems, in future [7, 8, 9], it is necessary to investigate the impacts of various non-linear home appliances on the power quality of electrical distribution system. The research work presented in [10, 11] was carried out to evaluate the impacts of compact fluorescent lamps (CFL) and personal computers (PC) but operating in an isolated mode. However, this work analyzes the power quality issues rising due to various home appliances including microwave ovens, compact fluorescent lamps, personal computers, laptops and refrigerators operating together. For this study, an experimental arrangement was devised in Smart-Grid Lab of Glasgow Caledonian University, UK to identify the major harmonics in the current waveforms drawn by each of the mentioned loads. Then, these developed harmonic models were inserted in ETAP harmonic library for the simulation of a practical distribution system in order to analyze the impacts on power quality. Increased system losses are discussed in section 2, section 3 represents the experimental setup and results, section 4 explains the distribution system simulated in ETAP, sections 5 discusses the results obtained by harmonic analysis, distortion power is evaluated in section 6 followed by computation of PF_{true} in section 7 and conclusion in section 8.

2. Impacts of Harmonic Distortion

Any such distortion has several adverse effects on the power systems, like overheating and damage to neutral conductors and panel board feeders, unexpected tripping of circuit breakers and overheating and premature failure of distribution transformers, to name a few [12].

A. Increase in line losses

In the presence of harmonic distortion the true rms value of current (I_{rms}) flowing through a transmission line is given as:

$$I_{rms} = I_{1,rms}\sqrt{1 + THD_i^{\,2}} \qquad (2)$$

Where $I_{1,rms}$ is the rms value of current flowing at fundamental frequency. Higher the value of THD_i (total harmonic distortion in current), higher will be the value of I_{rms}. Consequently, increasing the line losses as line losses are directly proportional to the square of the current (I^2_{rms}) flowing through conductors.

Moreover skin effect becomes more profound at higher frequencies forcing the higher order current components to flow closer to the surface of the conductors decreasing the effective cross-sectional area of the conductors. Subsequently, there is an increase in the resistance of the transmission lines which will further increase the transmission line losses.

B. Increase in transformer losses

Harmonic currents reach the distribution transformer and cause extra heating in the transformer increasing the system losses. This could be devastating for indoor transformers and during the hot summers.

1) *Increase in Copper losses:* Copper losses are directly proportional to the load current and resistance of the windings. As discussed in section 2.A load current will increase due to harmonic distortion and resistance of windings will also increase because of skin effect. As a result copper losses will increase causing extra heating in transformers.

2) *Increase in core losses:* Eddy current losses (W_e) in the core of transformer are directly proportional to the square of the frequency. So at higher frequency harmonics, the eddy current losses will also be higher.

$$W_e \,\alpha\, f^2 \qquad (3)$$

Hysteresis losses (W_h) will also increase with higher order harmonic currents owing to the fact that these are directly proportional to the frequency.

$$W_h \,\alpha\, f \qquad (4)$$

3. Experimental Setup

An experimental setup based upon National Instruments data acquisition (NI DAQ) module and a virtual instrument developed in LabView was employed for the harmonic modelling of home appliances. The experimental arrangement is shown in Fig. 1. NI DAQ module interfaced to the live conductor using a current probe, captures the current waveform for each load. The waveform is then analyzed in LabView to obtain the harmonic model. Power analyzer gives the real power and displacement power factor (PF_{disp}). PF_{disp} is then used to compute the real power factor (PF_{true}) for each of the appliances.

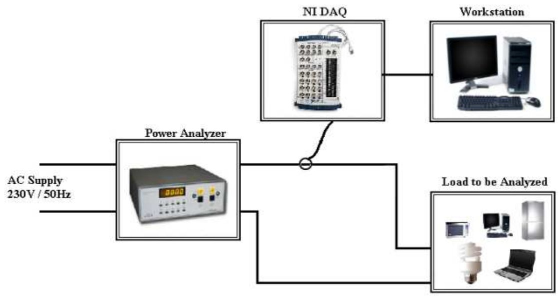

Fig. 1 Experimental arrangement

The current waveform drawn by a laptop operating on AC power is shown in Fig. 2 and its amplitude spectrum depicting the dominant harmonics is shown in Fig. 3.

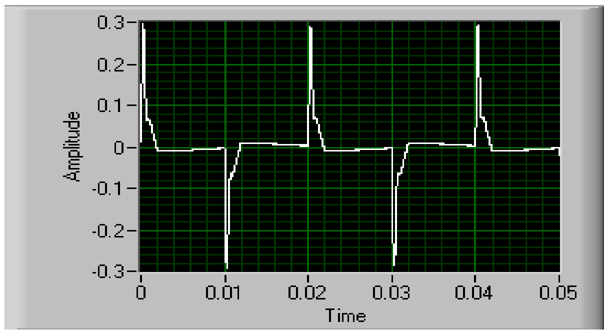

Fig. 2 Current waveform drawn by Laptop

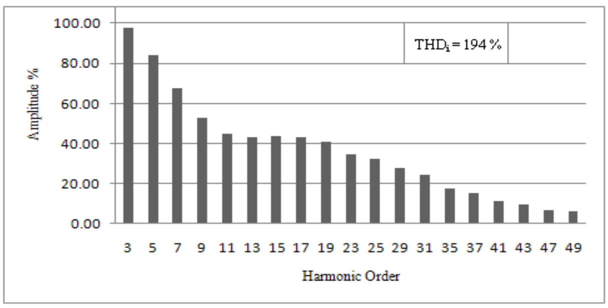

Fig. 3 Amplitude Spectrum of Current drawn by Laptop

The total harmonic distortion in the current waveform (THD_i) for Laptop is found to be 194 % according to IEEE and EN50160 standards.

True power factor (PF_{true}) is defined as the ratio of total actual power (P) to total apparent power (S), whereas, displacement power factor (PF_{disp}) is defined as cosine of angle between fundamental components of voltage and current [13]. PF_{disp} given by power analyzer for the laptop is equal to 0.454. PF_{true} is computed using the findings of Grady and Gillespie as given in Equations 5 and 6 [14].

Distortion power factor (PF_{dist}) is defined as follows:

$$PF_{dist} = 1/\sqrt{1 + THD_i^{2}} \tag{5}$$

Using Equation 5, PF_{dist} for laptop is equal to 0.479.

$$PF_{true} = PF_{disp} * PF_{dist} \tag{6}$$

PF_{true} is equal to 0.217 using Equation 6.

Similarly, amplitude spectrum, phase spectrum, THD_i and PF_{true} is computed for PC, CFL, fridge, and microwave oven as summarized in Table 1.

Table1. Non-Linear load Parameters

Appliance	PC		Laptop		CFL		Microwave		Fridge	
Harmonic order	Amp (%)	Phase (Deg)	Amp (%)	Phase (Deg)	Amp (%)	Phase (Deg)	Amp (%)	Phase (Deg)	Amp (%)	Phase (Deg)
3	46.49	90.70	97.58	-25.68	122.02	-28.01	26.68	-158.65	15.09	-26.47
5	20.93	139.88	84.22	-44.53	82.85	-50.18	13.62	-59.00	13.43	149.32
7	13.94	-165.48	67.45	-58.84	74.10	-58.66	5.21	12.12	22.96	-112.63
9	8.88	-133.71	52.64	-65.72	63.14	-82.61	3.14	135.13	6.66	29.45
11	3.95	-17.74	44.80	-65.79	36.50	-102.68	1.88	-115.41	1.72	-173.76
13	6.71	97.50	43.28	-66.60	19.93	-92.14	1.19	-9.72		
15	3.20	176.83	43.48	-70.97	14.42	-79.75				
17	4.63	-103.10	43.01	-79.17	13.27	-42.01				
19	3.52	-22.19	40.72	-88.22	21.71	-43.50				
THD_i (%)	54.57		194		189		30.64		31.34	
PF_{true}	0.88		0.21		0.30		0.86		0.86	

4. Distribution System Simulation

The distribution system considered for this research work is based upon a practical system located in Eimanabad sub-division maintained by Gujranwala Electric Power Company, Pakistan (GEPCO). The impacts have been analyzed for a 100 kVA distribution transformer supplying 18 homes. Single line diagram of the under study distribution system modelled and simulated in ETAP as per actual parameters is shown is Fig. 4.

ETAP is well acclaimed software which has the capability to perform harmonic analysis, load flow analysis, short circuit analysis, transient stability analysis to name a few. The detail of loading at each node/ bus is given in Table 2 where non-linear appliances represent 10.88 % of total loading.

Table 2. Loading Details

Load Type	Bus 4 supplying 6 homes (kW)	Bus 5 supplying 4 homes (kW)	Bus 6 supplying 3 homes (kW)	Bus 7 supplying 2 homes (kW)	Bus 8 supplying 3 homes (kW)
PC	0.12	0.24	0.00	0.12	0.24
Laptop	0.15	0.22	0.08	0.00	0.15
CFL	0.63	0.37	0.31	0.19	0.34
Microwave oven	3.00	1.50	1.50	3.00	1.50
Fridge	0.57	0.38	0.28	0.19	0.28
Miscellaneous loads	14.82	10.92	8.36	3.04	7.51

5. Harmonic Analysis

Harmonic analysis is performed in ETAP to acquire the voltage and current waveforms along with their respective amplitude spectrums at all the nodes/ bus bars of the distribution systems. According to IEEE standards 5 % is maximum allowable total harmonic distortion in voltage (THD_v) for voltage levels up to 69 kV with 3 % being the maximum allowed individual harmonic distortion in voltage (IHD_v).

For the same voltage level, the limits for individual harmonic distortion in current (IHD_i), for a system having short circuit ratio (I_{sc}/I_L) between 20 and 50, are given in Table 3 [15].

Table 3. IHD_i Limits

Harmonic Order	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$h \geq 35$
% Mag	4.00	2.00	1.50	0.60	0.30

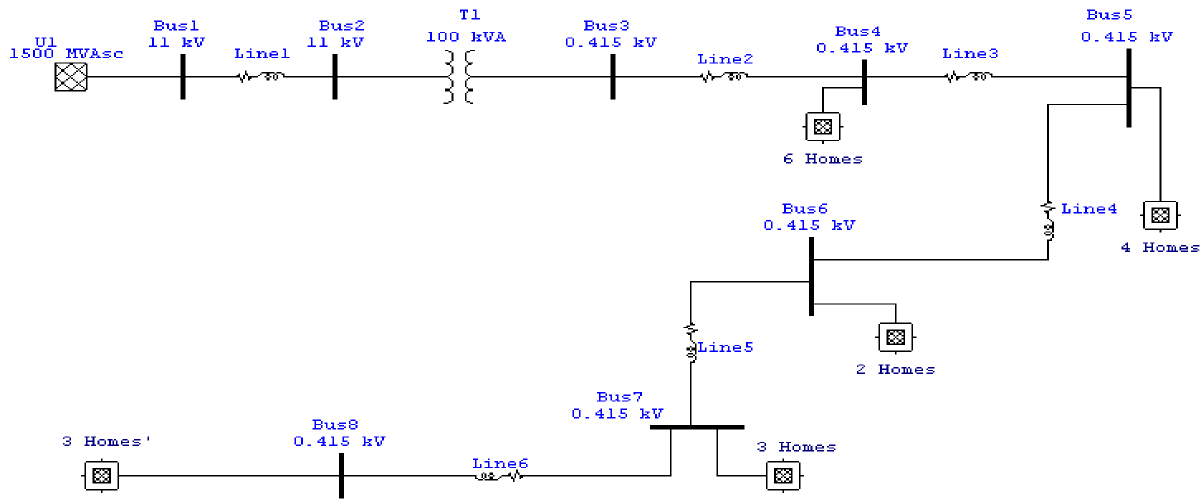

Fig. 4 Single Line Diagram of System Under Study

A. Current and voltage waveform at Point of Common Coupling

Current waveform at bus bar 4; point of common coupling (PCC) for all the homes; is shown in Fig. 5 and its amplitude spectrum, showing dominant harmonics, is presented in Fig. 6.

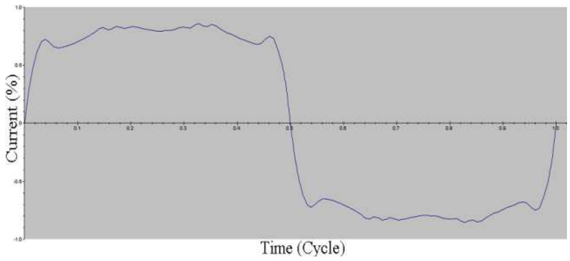

Fig. 5 Current waveform at Point of Common Coupling

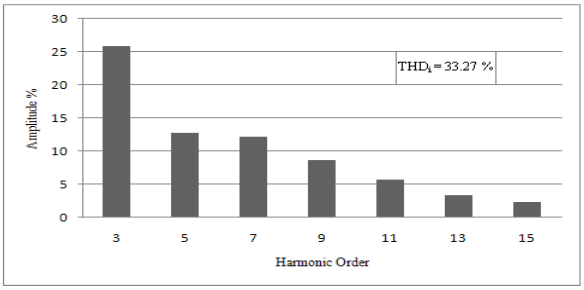

Fig. 6 Amplitude spectrum of current at Point of Common Coupling

The current waveform is highly distorted as compared to ideal sine wave due to high penetration of non-linear loads and has a THD_i value of 33.27 %. The 3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th} and 15^{th} harmonics, having an IHD_i of 25.89 %, 12.81 %, 12.13 %, 8.62 %, 5.67 %, 3.29 %, 2.32 % respectively as shown in Fig. 6, have values higher than the maximum standard values.

When this highly distorted current flows through system impedance it also causes voltage distortion. The voltage waveform at PCC is shown in Fig. 7 and its amplitude spectrum is illustrated in Fig. 8.

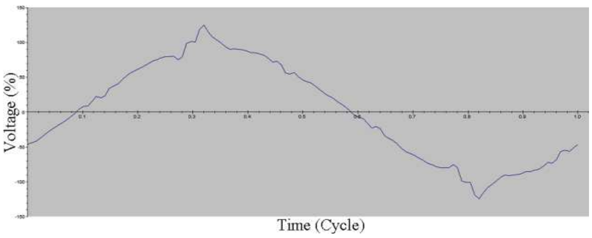

Fig. 7 Voltage waveform at Point of Common Coupling

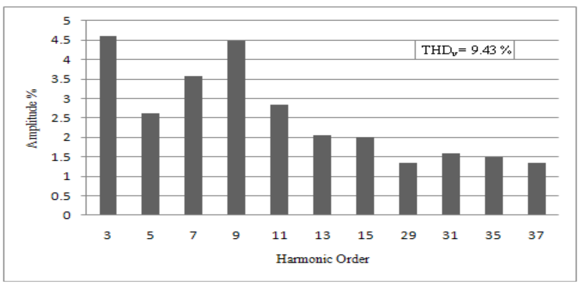

Fig. 8 Amplitude spectrum of voltage at Point of Common Coupling

The voltage waveform is also highly distorted due to the distorted waveform drawn by non-linear domestic loads. The THD_v for the waveform i.e. 9.43 % is violating the recommended standard practices along with 3^{rd}, 7^{th} and 9^{th} harmonics having IHD_v of 4.60 %, 3.57 % and 4.49 % respectively.

B. Current and voltage waveform at Bus Bar 8:

Because of the increasing system impedance, longer the distance from the distribution transformer higher will be the harmonic distortion. Current waveform at bus bar 8 i.e. PCC for 3 homes and also the furthest bus bar from the distribution transformer is shown in Fig. 9 along with its amplitude spectrum, showing dominant harmonics, presented in Fig. 10.

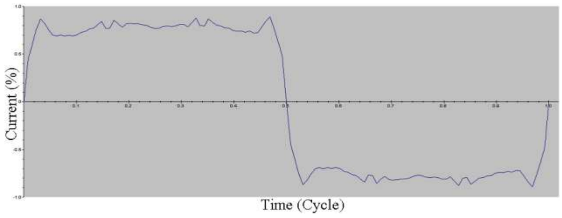

Fig. 9 Current waveform at Bus Bar 8

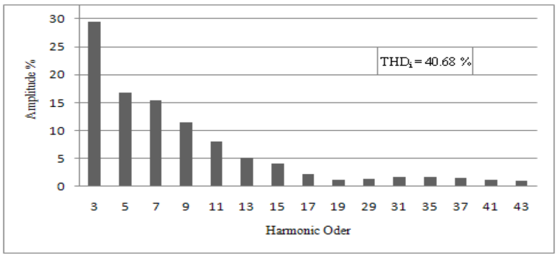

Fig. 10 Amplitude spectrum of current at Bus Bar 8

THD_i has an alarmingly high value equal to 40.68 % with 3^{rd}, 5^{th}, 7^{th}, 11^{th}, 37^{th}, 41^{st} and 43^{rd} harmonic breaching the IHD_i standard limits. This increased harmonic distortion will have an equally increased devastating effect on voltage distortion. The voltage waveform and its amplitude spectrum are shown in Fig. 11 and Fig. 12 respectively.

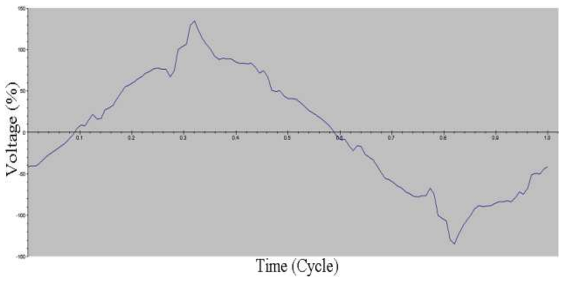

Fig. 11 Voltage waveform at Bus Bar 8

THD_v has a value of 14.50 % at bus bar 8 which is fairly high as compared to the THD_v (9.43 %) at PCC. In addition to THD_v, 3^{rd}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics also fail to satisfy the standard values set for THD_v (5 %) and IHD_v (3 %) respectively.

This increase in harmonic distortion with the increasing distance from the transformer is very critical for rural areas where distribution systems are widely spread over large distances with homes distant apart.

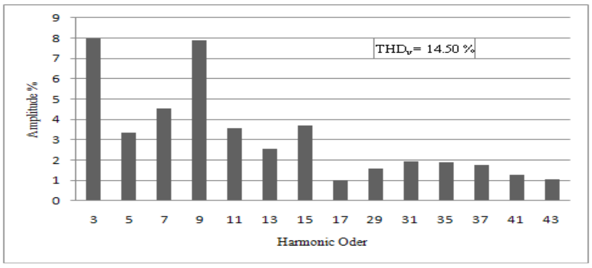

Fig. 12 Amplitude spectrum of voltage at Bus Bar 8

6. Distortion power at PCC

Distortion power (D) which flows in the system because of harmonic pollution is related to apparent power (S) or total power supplied by the utility, the actual power (P) and reactive power (Q) as [16]:

$$D = \sqrt{S^2 - P^2 - Q^2} \quad (7)$$

In the presence of non-linear loads producing harmonic distortion, apparent power can be computed as [17]:

$$S = S_1 \sqrt{1 + THD_v^{\ 2}} \sqrt{1 + THD_i^{\ 2}} \quad (8)$$

Combining Equations 7 and 8 yields:

$$D = \sqrt{S_1^{\ 2}\left(1 + THD_v^{\ 2}\right)(1 + THD_i^{\ 2}) - P^2 - Q^2} \quad (9)$$

Where, S_1 represents the apparent power at fundamental frequency. The values for S_1, P and Q at PCC are found to be equal to 86 kVA, 78 kW and 36 kVAr by performing load flow analysis. Substituting these values and values of THD_v and THD_i at PCC from section 5 into Equation 9 will yield:

$$D = 29.80 \text{ kVA}$$

7. True Power Factor at PCC

PF_{disp} obtained at PCC by load flow analysis is 0.91. PF_{true} at PCC can be calculated using actual power P and real apparent S obtained from Equation 8.

$$S = 90.93 \text{ kVA}$$

$$PF_{true} = P/S = 0.86 \quad (10)$$

PF_{true} can also be computed using Equations 5 and 6 producing the same result.

8. Conclusions

Based upon experimental and simulation results, this research work highlights the impacts of various non-linear home appliances on the power quality. The results reveal the high level of THD_v, IHD_v, THD_i and IHD_i beyond the acceptable standard values at PCC. The voltage and current at the consumer's end is also highly distorted which may result in the malfunction of electronic devices. Harmonic pollution forces the apparent power flowing in the system to increase. This increase accounts for distortion power in the distribution system. Harmonic distortion also degrades the power factor. System losses comprising of line losses, eddy current losses and hysteresis losses also increase owing to the presence of high frequency harmonic components of current flowing in the distribution system. The situation may become even more critical with the emergence of newer technologies like distributed generation and electric vehicles which are expected to be part of distribution systems at a massive scale. Therefore, steps are required to mitigate harmonic currents produced by domestic appliances. This will enable the electrical distribution system to embrace a greener future more potently.

Acknowledgment

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