The Impact of Small and Medium Power Loads on Distribution Network Efficiency and Harmonic Propagation

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ABSTRACT

A substantial amount of loads connected to utility distribution network are small and medium power range loads, of which majority are from residential and commercial/shops customer sectors. As these loads are dispersed across the low voltage distribution network (overhead or underground cables), harmonic mitigation devices or power factor correction capacitors are rarely installed at the aggregate load bus (utility low voltage transformer bus) to improve performance of the network.
Harmonic measurements of these small and medium power loads indicate that a majority of them are highly nonlinear and/or have low power factor. As a result, there is a reduction in energy efficiency of distribution network, particularly in network components such as low voltage lines/cables and distribution transformers.
This paper investigates real power losses caused by small and medium power range loads of residential and commercial/shops sectors due to harmonic currents propagation and reactive power flow. Results of the investigation are based on harmonic measurements at sites and aggregate load modelling at low voltage bus of distribution transformer.

INTRODUCTION

Small and medium power single phase electrical loads such as fluorescent lights, personal computers, television sets, office electronic equipment, refrigerators, air-conditioners, etc, are commonly used in residential and commercial premises. Most of these loads operate with low power factor with a majority of them being nonlinear/power electronic loads that produce significant amount of harmonic current distortion. Hence, low voltage distribution network that supply power to residential and commercial areas are typically burden with high harmonic currents and reactive power flow which results in a reduction of the distribution network efficiency. Harmonic currents cause higher losses in transformers and as a result a need to de-rate transformers based on K-factor [1]. In the case of harmonic currents flowing through lines and cables, skin effect increases line resistance with frequency and therefore results in higher losses [2]. It is therefore necessary to assess the impact of small and power loads on the distribution networks efficiency before any mitigating measures are taken.
To assess the impact of small and medium power loads on distribution network, a comprehensive measurement exercise is carried out to obtain harmonic current spectrum and power factor of the individual loads. Aggregate load models derived from measurements of harmonic current spectrum and power factor of the individual loads are then used in simulation to estimate losses in the respective low voltage distribution network.
This paper investigates the impact of small and medium power loads on distribution network efficiency and harmonic propagation through measurement, load modeling and simulation studies. The approach is based on aggregate load models of typical small and medium power loads derived from harmonic current spectra and power factor obtained from measurements and harmonic power flow simulations.

CHARACTERISTICS OF SMALL AND MEDIUM POWER LOADS

Small and medium power loads consists of both linear and nonlinear/power electronic loads. Linear loads do not produce harmonics. Examples of linear loads of small and medium power range are incandescent lamps, fans, refrigerators, and air conditioners. Nonlinear/power electronic loads are loads that produce harmonics. Examples of nonlinear loads of small and medium power range are the compact fluorescent lamp (CFL), personal computer (PC), television (TV), and the magnetic ballast fluorescent lamp (MBFL).
Harmonic measurements taken at selected individual linear loads of small and medium power range indicates that most of these loads have low power factor (PF) and generate small amount of harmonics (total harmonic current distortion (THD_I) between 4 to 10%). Refer Table 1. Whereas, nonlinear/power electronic loads of small and medium power are characterized by highly distorted load current (THD_I between 80 to 130%, distorted current waveforms are shown in Fig. 1 – 3), and very low true power factor due to its high harmonic currents content. True power factor is approximated using the following [2],

$$\text{True power factor} \approx \frac{P_1}{V_1 I_1} \frac{1}{\sqrt{1+(THD_I/100)^2}} \qquad (1)$$

where P_1, V_1 and I_1 are the fundamental real power, voltage and current respectively.
Low power factor and high harmonic currents of the small

and medium range power loads contribute to the reduction in energy efficiency of distribution network.

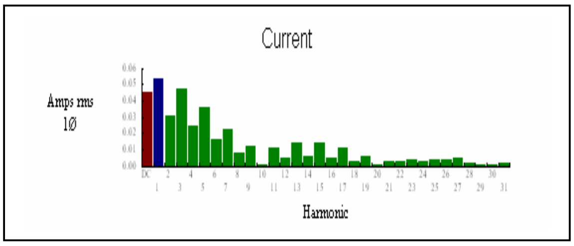

Fig. 1. Harmonic Current Spectrum of CFL

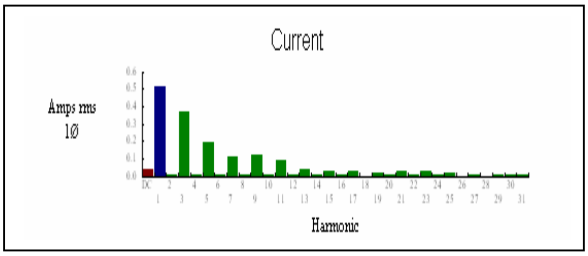

Fig. 2. Harmonic Current Spectrum of PC

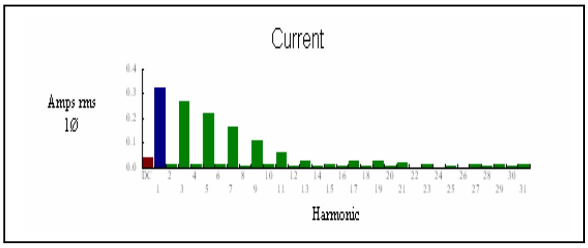

Fig. 3. Harmonic Current Spectrum of TV

Table 1 – Power Rating, Harmonic Current Distortion and Power Factor of Small and Medium Power Range Loads

LOAD	KVA	THD_I (%)	PF	TRUE PF
Air Conditioner	1.25	9.8	0.96	0.9
Refrigerator	0.23	4.1	0.58	0.58
Mag. Ballast FL	0.113	8.3	0.53	0.53
CFL	0.024	134	0.98	0.47
TV	0.13	115	0.96	0.59
PC	0.16	84	0.99	0.75

AGGREGATE LOAD AT LOW VOLTAGE BUS OF TRANSFORMER

Small and medium power range loads are typically used in residential and commercial/shops where it is connected to the low voltage (LV) bus of the distribution transformer through LV overhead lines and/or underground cables. Hence, at the LV bus of the distribution transformer there is a large number of different types of loads, both linear and nonlinear, which together form an aggregate load. A simulation model of aggregate small and medium power loads is shown in Fig. 4.

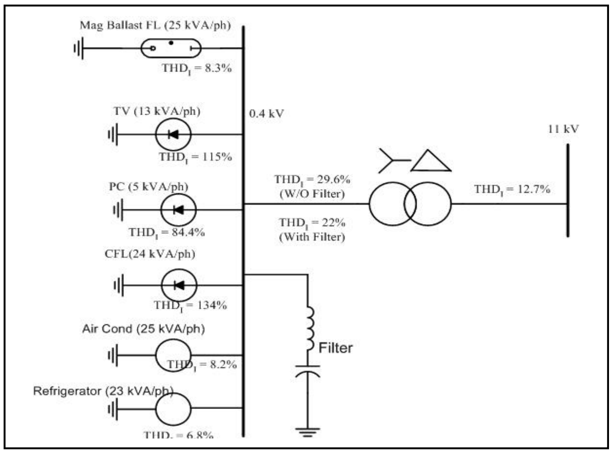

Fig. 4. Aggregate Load Model at LV Bus of Transformer

Net harmonic currents at the aggregate load bus is the vector sum of harmonic currents produced by the individual harmonic loads, and therefore is influenced by the phase angle components of the harmonic current spectra of the individual loads. Due to the diverse types of small and medium power loads, significant reduction in THD_I occurs at the LV bus of the distribution transformer due to phase cancellation [3, 4]. Simulation and field measurement results indicate that THD_I at aggregate small and medium power loads is between 10 to 20%.

Results of simulation are essentially dependent on the load composition and types of loads. Two case studies, i.e, a typical residential aggregate load type and a typical commercial aggregate load type are presented. The load compositions are modelled to approximately represent those of a residential and commercial/shops type. Demand for case of residential aggregate loads is at 40% transformer rating, whereas case of commercial aggregate loads is at 100% transformer rating. To verify the model, results of simulation are compared with those obtained from harmonic field measurement shown in Fig. 5 – 7. Simulation results are shown in Table 2.

It can be observed from the simulation results shown in Table 2 that THD_I of aggregate loads are significantly lower than that of individual nonlinear loads shown in Table 1. This is essentially due to phase cancellation and linear and nonlinear load composition ratio. Additionally, it can be observed that power factor of aggregate loads are less than 0.85 as shown in Table 3.

Table 2 – Harmonic Propagation of Aggregate Loads

LOAD TYPE	Harmonic (h)	I_h at LV Side (Amp)	I_h at HV Side (Amp)
Residential	Fundamental	479	18.4
	3rd	127	0
	5th	59	2.2
	7th	18	0.7
Commercial	Fundamental	1263	50
	3rd	140	0
	5th	42	1.6
	7th	18	0.7

Table 3 – THD_I and Power Factor at Aggregate Load Bus

LOAD TYPE	THDI (%)	PF	TRUE PF
Residential	29	0.843	0.811
Commercial	11.2	0.835	0.833

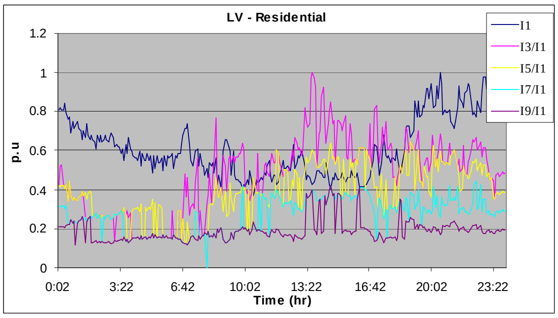

Fig. 5. Measured Harmonic Currents at LV bus of Transformer Supplying Residential Loads

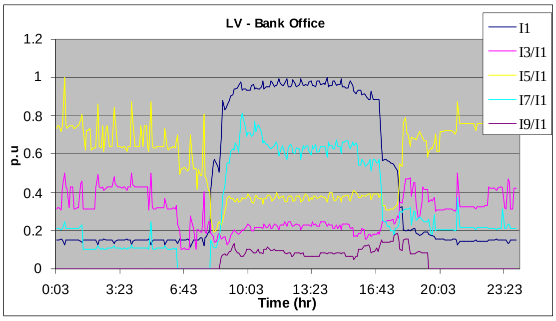

Fig. 6. Measured Harmonic Currents at LV bus of Transformer Supplying Commercial Loads

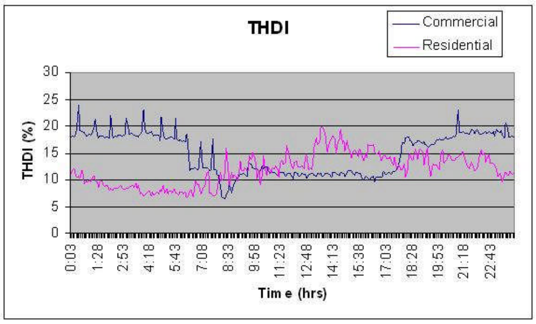

Fig. 7. Measured THD_I of a Residential and Commercial Aggregate Load

IMPACT OF HARMONIC CURRENTS ON DISTRIBUTION TRANSFORMER

In power transformers the main consequence of harmonic currents is an increase in losses. As a result, it is necessary to de-rate, i,e reduce the maximum power load on the transformer. To estimate the de-rating of the transformer, the load's K-factor is normally used. K-factor is calculated according to the harmonic spectrum of the load current and an indication of the additional eddy current load losses as shown below,

$$K = \sum_{h=2}^{h=h_{max}} h^2 I_h^2 \tag{2}$$

Where

K is the K-factor

h is harmonic number,

I_h is the fraction of total rms load current at harmonic number h

From (2), the K-factor calculated based on harmonic currents generated by aggregate loads of residential and commercial types is found to be between 1.1 and 2.1 as shown in Table 4.

Table 4 – K-factor of Transformer Supplying Residential and Commercial Loads

Aggregate Load Type	K-Factor
Residential	**2.1**
Commercial	**1.1**

Additionally, the effect of harmonic currents on the resistance value of the low voltage cables [2] is,

$$R_h = R_1(0.187 + 0.532h^{1/2}) \tag{3}$$

For the two case studies presented, it is assumed that the average cable length between loads and the LV bus of the transformer is 200m which results in additional losses of about 300 Watts, i.e, between 0.4 to 3% of the total losses at fundamental frequency.

PASSIVE FILTER AS REACTIVE POWER COMPENSATOR

Passive filters are an economical method in mitigating the propagation of harmonic currents in distribution network. In addition to filtering harmonic currents, passive filters can also be used as a reactive power source.
LV transformer buses supplying a group of small and medium residential and/or commercial customers are usually not fitted with any harmonic/reactive power mitigation device. However, in certain cases, particularly where load demand is close to 100% of transformer rating, it may be justified to install passive harmonic filter to function as harmonic mitigation device as well as reactive power compensator. This is shown in the case of commercial type load where the total power loss at fundamental frequency is 68 kW and reduces to 61 kW with reactive power compensation using detuned passive harmonic filter.
As indicated in the simulation study shown in Table 5, passive harmonic filter connected at the LV bus of transformer results in a reduction of about 10% in losses at fundamental frequency in the LV cables and transformer.

Table 5 – Effects of Passive Filter on Energy Efficiency of Transformer and LV Cables

LOAD TYPE	POWER FACTOR		LOSSES AT FUND. FREQ (KW)		LOSS REDUCT-ION WITH FILTER
	No Filter	Filter	No Filter	Filter	
Residential	0.843	0.996	9	8	11%
Commercial	0.835	0.902	68	61	10%

CONCLUSIONS

Aggregate effects of small and medium power range loads from residential and commercial customers' impact the performance of distribution network efficiency in terms of its net harmonic currents and reactive power flow. Based on measurement and simulation results, net total harmonic currents distortion of aggregate small and medium power loads may justify for a K-factor of between 1 and 2 on the transformer. However, reactive power compensation at low voltage of distribution transformer seems to be more crucial in improving distribution network supplying small and medium power. To avoid resonance caused by power factor correction capacitors, detuned passive harmonic filters are more effective and may be economically justified in cases of highly loaded distribution transformers, such as transformers that supply city center commercial loads of high load density.

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