POWER QUALITY LOSSES IN DISTRIBUTION TRANSFORMERS ORIGINATED FROM ELECTRONIC LOADS – A REVIEW

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ABSTRACT

To increase energy efficiency, manufacturers have introduced appliances with lower energy consumption, such as lamps based on LED and fluorescent light technology, electronic transformers, dimmers, power electronic controlled heat pumps, etc. These technologies significantly reduces the energy consumption, however, as these technologies is based on fast switching, harmonics are introduced. Harmonics from each appliance in the households are added and emitted to the distribution grid where the distribution transformer is the first receptor. The harmonics causes increased losses in the distribution transformer which gives temperature rise and reduced life. This paper assembles the results of earlier works and estimates the costs in the distribution grid for electronic loads.

INTRODUCTION

EU and other authorities along with customers are putting higher demand for increased energy efficiency on the manufacturers of appliances. To fulfil these demands, the manufacturers have introduced appliances with lower energy consumption. These low energy consuming appliances are based on fast switching technologies, which we refer to as electronic loads as opposed to resistive loads. The main difference between electronic (non-linear) loads and resistive (linear) loads are that resistive loads a) do not generate harmonics, b) reduces power (and current) consumption as voltage drops, and c) do not use reactive power. Electronic loads generate harmonics and uses constant power, which means increased current as voltage reduces. Some examples of electronic loads are:

- Lamps based on light-emitting diodes (LED) and fluorescent light technology,
- Electronic transformers used by for instance computers, low voltage halogen lamps, and mobile phone chargers.
- Switches with dimmer to control the lights.
- Power electronic controlled heat pumps, air conditioners, fans, etc.
- Electric vehicle chargers.
- Induction cooker

Harmonics and reactive power from appliances in the households are added by superposition and emitted to the distribution grid where the distribution transformer is the first receptor. Cables and overhead lines are of course affected as well, however not to the same extent. The harmonics and reactive power causes increased losses in the distribution transformer which gives temperature rise and reduced lifetime. There are of course other problems as well with harmonics for transformers, for instance resonance and mechanical stresses; however these issues are not part of this work.

GRID LOSSES

The annual losses in the electrical grid in Sweden are about 10 TWh, which is about 7% of transmitted energy (150 TWh). Of these losses about 3 TWh are in the transmission grid (400 – 220 kV), 2 TWh in the sub-transmission grid (130 – 20 kV), and 4,5 TWh in the distribution grid (10 – 0,4 kV). In the distribution grid there are about 170 000 distribution transformers, and as the sum of the power rating of the transformers is 45 GW, the mean power rating for distribution transformers is

$$\frac{45\,\text{GW}}{170000} = 265\,\text{kW}\,. \tag{1}$$

That is quite high since peak demand in Sweden is about 25 - 30 GW. The consumption varies quite much in Sweden, see Figure 1. The annual transmitted energy through the distribution grid is about 95 TWh, which gives the mean power of about 11 GW. So, the average power is about 25%, which is quite low compared to generator and power transformers. The seasonal variation has been calculated and is as a mean during 1995 – 2008 for winter 29%, spring 26%, summer 21%, and autumn 25%.

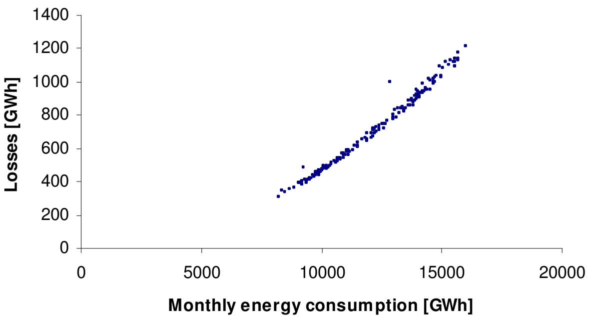

Figure 1: Monthly losses in Sweden 1995 – 2008 as function of energy consumption.

HARMONICS GENERATED BY ELECTRONIC LOADS - REVIEW

There are some papers on the topic electronic loads in [1], [2], [3], [4], [8], however there are more papers on more specific appliances, such as computers. Overall, most electronic loads produce harmonics, and it is the third harmonic (150 Hz) that is the dominant harmonic. However, the fifth (250 Hz) and the seventh (350 Hz) harmonic are in many cases contributing to quite much as well to the total harmonic distortion (THD). There have been some studies on harmonics and its relation to the distribution grid, and in particular the increased heating of the transformers and its related costs. Customers are of course also affected of these harmonics, which may lead to increased losses in the customers' appliances and malfunction. In general there are very few publications about the cost of power quality related problems.

- Computers are the most studied electronic load which includes the harmonics of individual computers and computer intensive work places [5] - [8]. The power supply (electronic transformer) of the computer generates some third harmonics, but also the fifth and the seventh harmonic exist. The total harmonic distortion in the current (THD_I) could be above 100% and power factor down to 80%, however the total harmonic distortion in the voltage (THD_V) is only about 5%.
- There are a few research articles on heat pumps and air conditioners, especially its relation to power quality problems [9]. There is an essay [10] available on the internet that deal with impact on distribution transformers from heat pumps, which show that the third harmonic is the largest of the harmonics, and that the harmonics will vary depending on the speed of the pump. There is also a suggestion on how much distribution transformers should be down rated. The smoothening effects of harmonics from several air conditioners have been studied in [11].
- There are many research articles on compact fluorescent lamps (CFLs) [12], [13], [14], [15], [16]. In particular, the compact fluorescent lamps emit third harmonics, but also the fifth and the seventh harmonic exist to quite large extent. There is a lot of difference between different brands regarding both the amount of emitted harmonics and the amount of each harmonic. There are also some articles about how to make models of CFLs [17]. Main conclusion is that THD_V could be up to 10%, THD_I above 100%, and power factor down to 60% for large installations.
- Lamps that have a switch with dimmer function causes harmonics [18] [19], [20]. Dimmers are a kind of direct converters. There are two types, trailing edge and leading edge, that is based on technologies with transistor respectively thyristor. The paper [18] shows the harmonic content in the grid when there are many switches with dimmer function in the same place in the grid. The harmonic amplitude can be partially reduced due to the smoothening effect from several switches with dimmer function set to different angles, that is if the light is dimmed (reduced) to different extent at different customers.
- As electric vehicles (EV) and Plug-in hybrids (PHEV) will consume much power, harmonic levels could be high. There are some articles [21], [22], [23]. The third harmonic is the dominant harmonic, however not as high compared to computers and compact fluorescent lamps. This is because the amount of power needed for charging is much higher, so the fundamental is dominant. However, the harmonic content is depending on the charging state of the battery, which means that there is a big difference between trickle charge (THD_I < 30%) and fast charge (THD_I < 5%). Down rating of distribution transformer due to harmonics from electric vehicles has been studied in [24], and conclusion is that with 100% penetration, the transformer should be down rated to about 80% to not reduce lifetime.

TRANSFORMER LOSSES

With increased reactive power and harmonics in the grid, the losses in the distribution transformer will increase [26], [27]. The temperature will rise [26] and as the paper insulation in the transformer age with increased temperature, the transformer lifetime will reduce. The amount of increased losses in distribution transformers have been studied in [28], [29]. These added losses in the transformers lead of course to energy costs, which have been studied in [30]. And finally, the higher loading (due to harmonics or reactive power) of the distribution transformer leads to reduced lifetime [31]. The load (copper) and no-load (iron/core) losses for typical distribution transformers are assembled in Table 1.

Table 1: Typical load & no-load losses in transformers.

Type		100	160	250	315	kVA
CENELEC dry	P_0	440	610	820	1150	W
	P_k	2000	2700	3500	4900	W
CENELEC oil	P_0	210	300	425	610	W
	P_k	1475	2000	2750	3850	W
Hexaformer oil	P_0	170	240	290	310	W
	P_k	1580	1960	2400	2600	W
Amorphous oil	P_0	70	100	140	200	W
	P_k	1500	2000	2800	3900	W

The losses can be evaluated by using the seasonal loading of a typical distribution transformer, which was found out in the introduction section, and if we assume that the transformers are oil insulated and since the mean power is 265 kW, we could use the loss numbers from the 315 kVA transformer in Table 1, since most of the transformers are very old and hence do not have as low losses as in the table.

Assuming that all distribution transformers are online all hours during the year (8760 h), that would give annual distribution loading losses at about

$$P_k = 170000 \cdot 3850 \cdot \frac{0,29^2 + 0,26^2 + 0,21^2 + 0,25^2}{4} \cdot 8760 = 0,4\,\text{TWh} \quad (2)$$

The no-load losses could be estimated to

$$P_0 = 170000 \cdot 610\,\text{W} \cdot 8760\,\text{h} = 0,9\,\text{TWh}\,. \quad (3)$$

With energy costs at 40 €/MWh, the annual cost for distribution transformer losses at 1,3 TWh is about 50 M€ in Sweden if we assume no harmonics and unity power factor. The average transformer has losses at 8 MWh at cost €300. This ideal case is of course not the case today, however serves as a reference on what extra it costs with bad power quality. These costs can of course also be reduced by selecting transformers with a lower loss construction as the Hexaformer or choosing other core material such as amorphous material. That would also reduce the impact of low power quality – at least in costs for losses, however investment is about 50% more expensive.

COSTS – REACTIVE POWER

Transfer of reactive power causes additional losses in the transformer since the current increases. If the power factor is for example 0,8 or 0,9 instead of 1 means that the current is about 25% respectively 11% larger. When the current increases, the load losses increases with the square, giving about 55% respectively 23%. The annual cost is shown in Table 2, and a power factor at 0,8 could cost 4 M€ annually.

Table 2: Load losses in 315 KVA transformers.

Power factor:	1,0	0,9	0,8	0,5	
Annual losses	400	440	500	800	GWh
Annual cost	16	17	20	32	M€

COSTS – HARMONICS

Increased harmonic content in the current (THD_I) will increase both the load losses and the no-load losses. The load losses will increase due to the increased skin effect. The no-load loss will increase due to increased eddy current losses. If we assume a perfectly balanced system, the third harmonic will be cancelled. Then there is only fifth left to be interesting, as the seventh and above are too small and hence neglected. If we then consider a 10% increase of the fifth-harmonic in the current the no-load losses increase by 25%. As seen from Table 3, the losses and costs increase quite much, for instance THD_I = 10% costs 10 M€.

Table 3: No-load losses in 315 KVA transformers.

THDI	0%	10%	15%	20%	
Annual losses	900	1125	1400	1800	GWh
Annual cost	36	44	56	72	M€

CONCLUSIONS

This paper has gone through many publications regarding harmonics and reactive power from electronic loads. It is clear that the harmonics and reactive power will increase with increased use of electronic loads. This will lead to increased losses and ageing of transformers, which will cost money for the distribution company.

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