NEGATIVE EFFECTS OF ENERGY-SAVING, NON-LINEAR LOADS ON LV SYSTEMS: CAUSES AND RECOMMENDATIONS

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Abstract: Pressure is being exerted on utilities and electrical energy customers to reduce energy consumption. There are two concerns: the effect that increasing greenhouse gasses have on global warming and the dwindling non-renewable resources currently used for the production of electrical power. The use of modern energy-efficient appliances such as Compact Fluorescent Lamps and micro-wave ovens is a widely promoted solution. These types of devices are recommended not only in affluent areas but also in developing countries (such as South Africa) where the use of computers and television sets are also being encouraged as devices for increasing the level of information and education. However, the use of these devices can introduce significant problems. This paper reviews a range of published material on the various aspects of this topic. It also includes the results from experimental measurements. Finally, the paper discusses some recommendations that are intended to bridge the gap between theoretical analyses and the practical implementation of mitigating steps, as they apply to low voltage distribution systems.

Key words:
Non-linear loads; harmonics; measurement and verification; wiring installations

1. INTRODUCTION

There is global concern over the current levels of greenhouse gas emissions, to which the generation of electricity from fossil fuels is a major contributor. Efforts to reduce emissions fall into two main categories – (a) make more use of renewable energy sources such as wind power, photovoltaic power and power from bio-mass, and (b) reduce energy consumption by using more efficient appliances. The second of these mitigation categories invariably employs devices with non-linear electrical characteristics. In this text these loads are referred to as Non-Linear Loads (NLLs). Their use is increasingly evident in the domestic as well as the commercial sectors.

In South Africa, the social, political and economic impact of the extensive electrification programme has been significant during the past 10 years. Yet, approximately 3 million households still need to be electrified, mostly in rural and so-called 'deep-rural' areas. These customers largely fall into the poorest class where unemployment is high and the level of education is low. In addition, the peak demand is growing and the national utility, Eskom, is facing a serious capacity problem, which is expected to become critical in 2007.

More efficient use of the available power is essential. A seeming logical option is to encourage the use of energy-efficient lighting in the form of Compact Fluorescent Lamps (CFLs) and the use of micro-wave cooking. Traditional food preparation and relatively high capital costs would influence the effectiveness of the latter. Demand side intervention may also be facilitated through education and training in the use of electrical energy. The most effective way of achieving this is via the television network, which obviously requires the use of television sets. These devices also have the disadvantage of distorting the load current. It should be understood that most of the rural customers cannot afford to purchase and operate high-energy appliances such as water heaters, electric ranges and air-conditioners. Consequently, the composite rural customer load may have a lower proportion of linear loads than the higher income groups in urban locations.

The occurrence of non-linear loads is equally prevalent in the commercial sector, particularly in the urban setting. Modern commercial loads are comprised of ever increasing numbers of computers, fluorescent light fittings (including CFLs) and air-conditioning units. Variable speed drives are now being used to operate the air-conditioning equipment in, ostensibly, the most efficient manner.

This paper attempts to highlight the negative effects of modern non-linear loads on low voltage (LV) systems based on the calculations and measured results derived by the authors and previously published literature. It will show what steps could be taken to bridge the gap between knowledge and technology, particularly in the South African context.

The problem has practical implications. These essentially arise from the gap between the theoretical analyses of the phenomena and a practical guideline to combat the problems. Operators and contractors at the LV distribution level require binding, lucid directives that will ensure the lowest penalty to the system and the customer.

So, while it is desirable to use 'energy-efficient' appliances to reduce energy and maximum demand, the electrical characteristics of these devices inevitably lead to the generation of unwanted harmonic currents. A large volume of literature has been published during the past two decades on the theoretical assessment of these harmonic generating devices. Some of the findings from the published articles will be reviewed in this paper. Results obtained from experimentation are also discussed. From these results recommendations to remedy the problems are proposed and discussed.

2. LITERATURE SURVEY

The material reviewed in this section is illustrative rather than exhaustive. It serves to identify the main issues relating to the generation of current harmonics by modern NLLs and the consequent impact on the LV network to which they are connected.

2.1 *Power definitions and relationships*

In current distribution practice almost all the calculations used in the sizing of electrical equipment are based on phasor quantities. These fundamental relationships have come under greater scrutiny with the increase in the incidence of NLLs. This topic is discussed at some length in the paper prepared by the *IEEE Working Group on Non-sinusoidal Situations* [1].

Under the assumption of ideal sinusoidal conditions the traditional approach to power relationships in a-c networks yields the following:

$$v = \sqrt{2}.V\sin(\omega t)$$
$$i = \sqrt{2}.I\sin(\omega t - \varphi) \tag{1}$$

where, v and i are instantaneous values, and V and I are RMS values, of voltage and current. The relationships in Equation1 assume constant angular velocity,ω [rad/sec] of the voltage and current phasors. The quantity φ represents the phase angle between the voltage and current phasors.

Then:

$$P = VI\cos\varphi$$
$$S = VI$$
$$Q = VI\sin\varphi \tag{2}$$
$$S = \sqrt{P^2 + Q^2}$$

Where, P is the active power [W], S the apparent power [VA] and Q the non-active (often called reactive) power [VAr]. The power factor is then given alternatively as:

$$PF = \cos\theta$$
$$PF = \frac{P}{S} \tag{3}$$

The quantity P is the rate at which energy is transferred to the load. It is further to be noted that energy in electrical terms can only be measured by an energy or revenue meter in energy units – Joule-sec, Watt-hours, MWh etc. In simple terms, energy is the quantity that does work and is uniquely associated with the active power, P.

Equations 1 to 3 lose their validity when either, or both, of the voltage and current waveforms depart from their sinusoidal shape. Under these conditions one cannot refer to a phase angle, because ω and φ are no longer constant. Hence, power factor varies in time throughout the fundamental period, T. We then have to use expressions with greater generality, such as those given by Sharon [2]:

$$P = \frac{1}{T}\int_0^T vi.dt$$
$$S = \frac{1}{T}\sqrt{\int_0^T v^2 dt.\int_0^T i^2 dt} \tag{4}$$

The power factor, the ratio of power to apparent power, is still an indicator of the effectiveness of the delivery of energy.

Non-sinusoidal, periodic voltages or currents may be expressed as a sum of sinusoidal harmonics, for example:

$$i = i_1 + i_2 + i_3 + ... + i_n \tag{5}$$

$$i_1 = I_1 sin(\omega t\text{-}\varphi_1);\quad i_n = I_n\, sin(n.\omega t\text{-}\varphi_n)\ \ etc.$$

Where the subscripts refer to the harmonic order and I_1 to I_n are the magnitudes of the harmonic currents. To facilitate the algebra we can simplify Equations 4 and 5 by letting $\theta = \omega t$, $dt = 1/\omega.d\theta$ and $T = 2\pi$.

If the LV distribution is 'stiff' enough (i.e. it has low Thevinin impedance), we can assume that the supply voltage at the point of a single-phase, non-linear load (NLL) is sinusoidal and free of harmonics. The current drawn by the NLL will be given by an expression similar to Equation 5 above. Then upon substitution into Equation 4 we obtain in general terms for any number of harmonic current components:

$$P = \frac{V_1 I_1 \cos\varphi}{2}$$
$$S = \frac{V_1 \left(\sum_{h=1}^{n} I_h^2\right)^{\frac{1}{2}}}{2} \qquad (6)$$

Using the relationship *P/S* for the power factor, PF, we obtain:

$$PF = P/S = \cos\varphi . \frac{I_1}{\left(\sum_{h=1}^{n} I_h^2\right)^{\frac{1}{2}}} \qquad (7)$$

It is clear from Equation 7 that the power factor reduces as the size and number of the harmonic components increases.

To illustrate the effects on power factor and thermal losses in conductors, consider a NLL with current component magnitudes: I_1 = 10A; I_3 = 7A; I_5 = 4A and I_7 = 4A. Take the phase angle of the fundamental component as 26^0. Assume further that the NLL is supplied from a 230V sinusoidal voltage source and that the total conductor resistance to the load is 0.5 ohms. The results given in Table I are then obtained.

Table I: Sample Calculations

Active Power	[W]	2071
Apparent Power	[VA]	3094
Cos(φ)		0.9
Power Factor	P/S	0.67
Conductor Losses	[W]	45.25
Losses due to I_1	[W]	25

The results suggest that under the given conditions, the power factor has worsened from 0.9 to 0.67 and the conductor losses have increased by 80%. Conductor losses are likely to be even higher because, due to 'skin-effect', the effective resistance of the conductor increases as the frequency of the current increases. The increase in resistance for the higher order harmonics will increase the estimated 'copper-losses'.

2.2 *Quality of supply*

Quality of supply (QOS) embraces a wide variety of aspects and these will not be considered in detail in this paper. However, one of the definitions, the total harmonic distortion of the current (THD_I), is helpful in describing and analysing the effects of NLLs:

$$I_H = \sqrt{\sum_{h=2}^{\infty} I_h^2}$$
$$THD_I = \frac{I_H}{I_1} \times 100\% \qquad (8)$$

In these expressions I_h is the RMS value of the h^{th} harmonic current component and I_1 is the RMS value of the fundamental current component. Typical measured values for domestic and commercial appliances are discussed in Section 3.

2.3 *Compact fluorescent lamps (CFLs)*

During the past two decades, various authors have reported on the current harmonic production of CFLs and its deleterious effects on distribution systems. For example, Mielczarski has drawn attention to a variety of side effects resulting from the use of CFLs [3]. These include accelerated equipment aging and interference with communication systems. Pileggi et al. performed simulations to investigate the effect of CFL loads on voltage distortion on a typical distribution feeder [4]. Within the context of the current trend to shift more generation into the renewable sector, it would be well to take note of the observations documented by Korovesis et al. [5]. Their paper investigates the influence of a large-scale installation of CFLs on line voltage distortion of a weak network supplied by a photovoltaic station.

2.4 *Personal computers (PCs)*

The personal computer (PC) made its appearance in the early 1980's. Their proliferation since then has been exponential and they presently represent a significant load component, particularly in commercial and academic institutions. These devices are fed from switch-mode power supplies and inherently draw distorted load current. A number of researchers have investigated the generation of this current harmonic distortion and the resultant impact on the networks. Moore [6] reports on his investigation into the influence of PC processing modes on line current harmonics. In an extensive survey of more than 370 PCs his research shows that hard-drive access causes the highest level of 3^{rd} and 5^{th} harmonic load currents. He notes that the degree of harmonic attenuation depends on the number of PCs connected to the same supply. But the diversity effects due to variation in loading level showed an increase in harmonic generation with line current RMS level. Diversity effects are also investigated by Grady et al. [7]. Aintablian and Hill [8] draw attention to the increase in neutral current in three-phase, 4-wire systems that arises from loads with triplen harmonics (3^{rd}, 9^{th} etc.). This phenomenon will be addressed in more detail later in this paper.

2.5 *Switch-mode power supplies*

Switch-mode power supplies are not only confined to PCs, but may be found in uninterruptible power supplies (UPS), printers, photocopiers, battery chargers etc. All these devices draw highly distorted load current. Further reports on the harmonics of switch-mode power supplies are found in literature [8, 9].

2.6 *Adjustable speed drives (ASDs)*

The speed of induction motors may be controlled by varying the supply frequency. This is commonly achieved by using pulse-width modulation (PWM), a process that leads to the generation of odd current harmonics, particularly the 5th, 7th, 11th and 13th. ASD applications are common in HVAC systems (heating, ventilating and air-conditioning), industrial processes and uninterruptible power supplies (UPSs). Modern energy-efficient equipment often use ASDs. Typical of the research done in this field are the papers by Dell'Aqila [10] and Capasso [11].

2.7 *Energy metering*

Customers have the right to accurate metering of their electrical consumption. However, the current distortion introduced by some of the energy-saving loads can, under certain conditions, cause the energy metering to be erroneous. Some utilities apply a tariff penalty for so-called 'reactive energy'; exactly what the term means and how it is to be measured when the current waveform is distorted is not defined. A number of research papers have been published on the theme of energy metering loads with distorted currents. Czarnecki comments on the effect of distorted current waveforms on active power flow and energy accounts [12]. He concludes that customers with polluted loads, when billed for energy measured as the integral of active power, cause a loss of revenue to the utility. Arseneau [13] supports this view and examines the performance of revenue meters based on existing (2004) definitions in comparison with one that measures the energy using only the fundamental waveform. In another paper [14] he examines the IEEE Standard 1459-2000 for revenue meters and concludes that it is inadequate for the measurement of NLLs.

2.8 *Demand side measurement and verification*

Related to the previous section is the measurement and verification of demand side management (DSM) interventions. There are many programmes worldwide that encourage the use of DSM strategies. Customers often receive financial incentives from the utilities, based on the measured performance of the DSM initiatives. Common programmes often include the replacement of incandescent lighting with CFLs and retrofitting of HVAC systems with compressors using ASDs. As mentioned, these devices draw distorted currents. Therefore, such post-installation loads will have a high component of polluted load current and, as indicated above, the measurement and verification of these interventions are subject to errors. Traditional induction disc meters under-estimate the revenue payable to the utility. These issues are mostly ignored in related operational standards, such as the American document: *M & V Guidelines: Measurement and Verification for Federal Energy Projects, Version 2.2* [15]. Practice in South Africa uses this document as a basic guide but also ignores the harmonic distortion of load currents.

3. EXPERIMENTAL RESULTS

The material presented and discussed in this section was derived from experimental measurement. These measurements show the extent of current distortion in the loads commonly associated with energy saving exercises.

The table in each of the following sub-sections 3.1 to 3.4 presents the RMS values of voltage and load current, the apparent power as recorded on a digital power analyser, the total harmonic distortion (THD), and the power factor obtained from the power analyser. Typical waveforms and the harmonic content as a percentage of the fundamental are illustrated graphically. In all cases, the 3rd harmonic content of the waveform is significant.

3.1 *Compact fluorescent lamps (CFLs)*

Measurements in this section refer to a 21W Compact Fluorescent Lamp.

Table II: CFL Measurements

V rms	I rms	S VA	THD %	PF
216	0.142	30.672	106.4	0.58

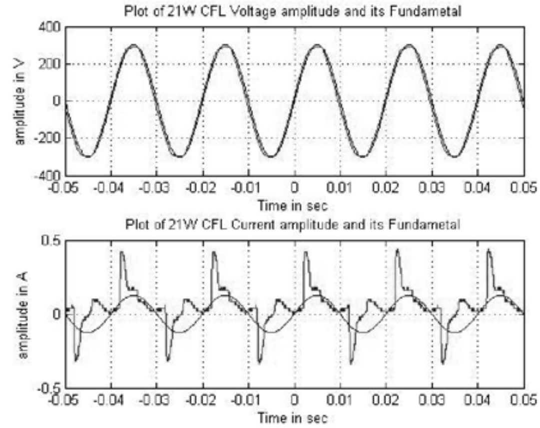

Figure 1: CFL Voltage and Current Waveforms

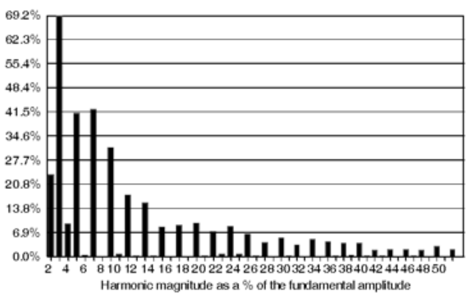

Figure 2: CFL Current Harmonics

3.2 *Personal computers (PCs)*

Table III PC Measurements

V rms	I rms	S VA	THD %	PF
225	1.26	283.5	121.17	0.63

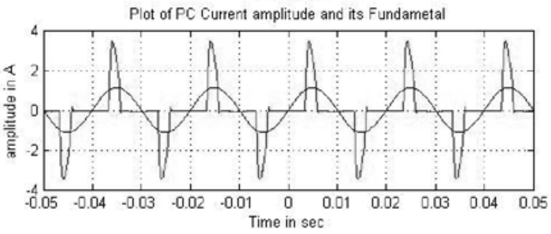

Figure 3: PC Current Waveform

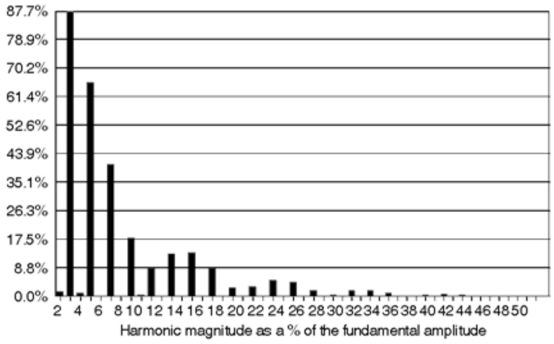

Figure 4: PC Current Harmonics

3.3 Television sets (TVs)

Table IV: TV Measurements

V rms	I rms	S VA	THD %	PF
225	0.563	126.675	155.47	0.441

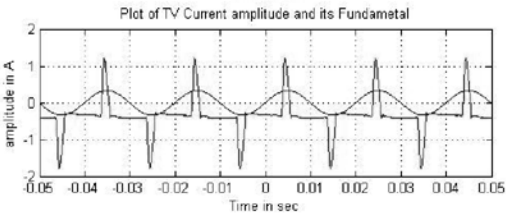

Figure 5: TV Current Waveform

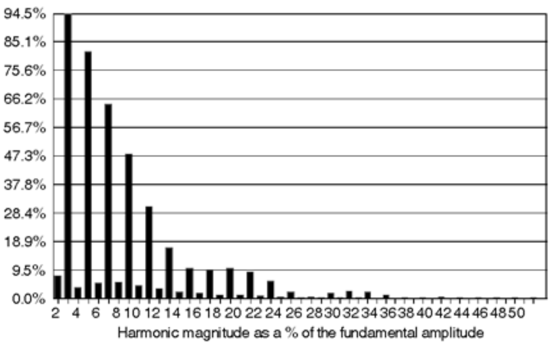

Figure 6: TV Current Harmonics

3.4 Microwave oven

Table V: Microwave Oven Measurements

V rms	I rms	S VA	THD %	PF
227	4.98	1130.46	38.47	0.871

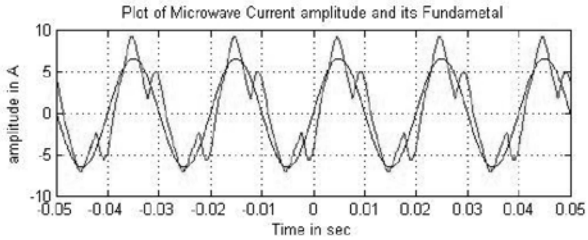

Figure 7: Microwave Current Waveform

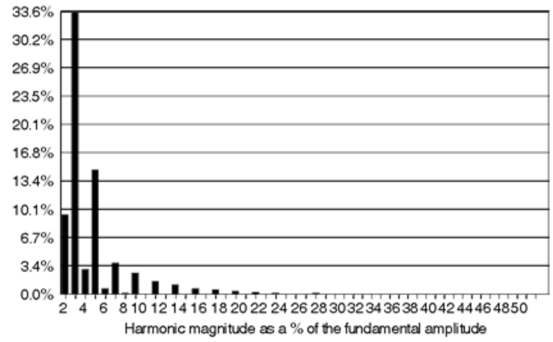

Figure 8: Microwave Oven Current Harmonics

3.5 Energy metering

The energy consumption of various appliances was measured with a traditional Ferraris type energy meter and the results compared with a true-reading digital energy meter. The percentage errors are summarised in Table VI.

Table IV: Energy Measurement Errors

Appliance	Error %
9W CFL	24.82
PC	7.59
TV	25.62
Microwave	3.9

The measurements indicate a loss of revenue to the utility for these loads when they are measured with conventional kWh metering.

3.6 Effect of neutral current from PC loads

The use of personal computers (PCs) is increasing at phenomenal rate. Because of their value as aids to education, they are often foremost in donations to the poor in developing countries, such as to schools in these communities. The impact on the loading of a network feeding a large number of computers presents real problems to the distribution systems.

The load illustrated in Figures 8 and 9 was recorded at a computer lab (larger than one in a typical school) in which a large number of PCs were supplied.

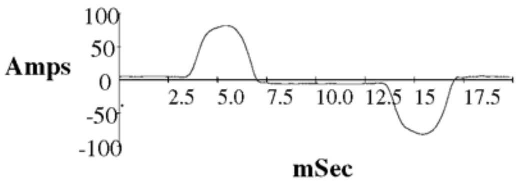

Figure 8: Current Waveform Blue-phase

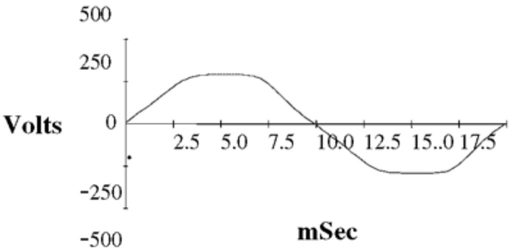

Figure 9: Voltage Waveform Blue-phase

The 3rd harmonic current was 27% of the fundamental. The large distortion in current causes voltage drops in the phase conductors feeding the PCs that result in a serious distortion of the voltage supply waveform, as shown in Figure 9. In a three-phase supply network the largest concern is the summation of the co-phasor triplen current components (3rd and 9th harmonics) in the neutral conductor. In measured cases in our study some neutral currents were found to be approximately 25% larger than the phase current.

4. IMPLICATIONS

Some of the many implications of NLLs are summarised here to indicate the remedial actions required.

Power factor definition and evaluation: In traditional network calculations the power factor is usually conceived and referred to as the cosine of the angle between the voltage and current phasors. It was shown in Section 2.1 that this is not valid when the load current has harmonics. Definitions of real and apparent power must be modified under these conditions.

Conductor heating losses: The sample calculations in Section 2.1 show how harmonics can increase ohmic losses in conductors for a given transfer of active power. These increased losses are largely ignored in network calculations.

Non-active (reactive) power compensation: Capacitors are often used in to correct power factor in networks with low 'lagging' power factors. The presence of NLLs has two negative implications: the higher frequencies can damage the capacitors and low power factor that varies instantaneously within each cycle is difficult to compensate with static filters.

Load modelling: Traditional Z, I, P models may no longer be valid when the loads are comprised of a significant NLL component, because the load characteristics change even within the normal range of voltage variation.

Load data sampling: Load data is usually monitored and stored with the use of digital logging equipment. Load parameters are sampled at a fixed sample rate. The Nyquist criterion is usually applied in these cases, which requires sampling at twice the fundamental frequency. Obviously, when measuring currents (and powers) with high harmonic content a faster sampling rate is required, e.g. 300 Hz for the 3rd harmonic of a 50 Hz system.

Network parameter calculations and models: Network parameters are traditionally calculated as resistance, inductive- and capacitive-reactance at fundamental frequency. Inductive reactance is directly proportional and capacitive reactance indirectly proportional to the frequency. The network parameters might have to be modified to include the effects of the third harmonics (and possibly the higher order ones as well) [16].

Voltage distortion: As shown in the example of the computer laboratory the voltage drop with its distorted waveform can modify the supply voltage, typically giving it a flattened peak. This could lead to quality of supply problems in sensitive areas. In domestic installations, where NLLs comprise a significant component of the total load, and where induction motors (e.g. refrigerator motors) are connected, the motors could experience over-heating.

Errors in revenue metering: The metering error discussed in Section 3.5 could lead to a significant loss of revenue in the case of NLLs. This could include domestic and commercial loads. Larger industrial loads using ASDs and power electronic equipment would have similar effects.

DSM intervention measurement: As discussed in Section 2.8, the measurement of pre- and post installation demand becomes suspect in the presence of NLLs. Erroneous measurement during verification will misrepresent the effects of DSM interventions that focus on replacement with energy-efficient appliances.

Triplen currents in the neutral: One of the most severe implications occurs in four-wire three-phase systems, common in distribution networks and wiring installations. Distorted currents with 3rd and 9th harmonic components give rise to triplen currents that are co-phasor in the neutral, as reported in Section 3.6. These can cause overheating and damage in a neutral conductor, which is often smaller in cross-sectional area, and therefore of higher resistance than the phase conductors. This could lead to degradation of insulation, short circuit currents and fire damage. These conditions are not covered in standard wiring regulations.

Transformer over-heating: The presence of harmonic components increases the eddy current losses in the core of a supply transformer. Triplen harmonic currents circulate in the delta windings of transformers, increasing conductor losses. At the higher frequency of the harmonic components of current, the leakage flux is deformed leading to an increase in losses. These increased losses raise the temperature of a transformer supplying significant NLLs, increasing the insulation degradation and reducing the lifetime, which may require de-rating of a transformer.

Auxiliary relays: Harmonic components can exceed the withstand capacity of small switching devices. For example, a photo-sensitive switch rated for loads up to 100 W failed in a few days when used to control three CFLs with a total power of only half the apparent rating of the switch. The switch, shown in Figure 10, over-heated and in the 'right' circumstances could have initiated a fire.

5. RECOMMENDATIONS

5.1 Harmonic mitigation

The obvious mitigation action would be to eliminate the generation of harmonics at the load. This would require cooperation from the manufacturers of appliances to ensure the suppression of harmonics, and national and international standards to guarantee compliance. Research will be needed to establish suitable limits for THD and 3rd harmonic content, which, it is proposed, would be displayed on the nameplates of all electrical equipment. A specification for NLLs would need to be harmonised with quality of supply specifications, such as NRS 048. Such an approach to mitigating NLL effects would require time (years) for implementation and would not eliminate the problem from existing equipment.

5.2 Wiring code

Existing wiring codes in South Africa do not adequately address the issues related to the use of NLLs. Three aspects need attention:

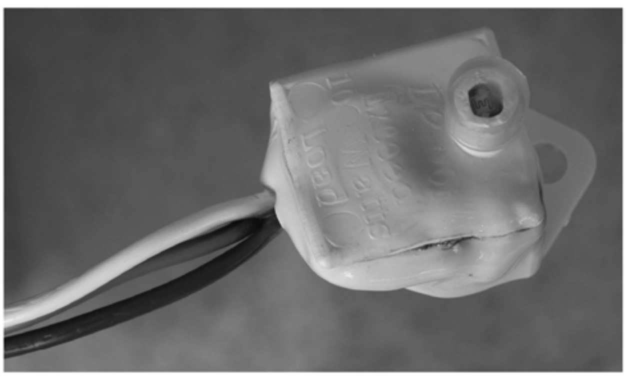

Figure 10: Switch Overheated by CFL Load

- The wiring code should give guidance in assessing the level of NLLs. For example, contractors would need to know how to assess a circuit when a significant proportion of the load consists of PCs, CFLs, ASDs or other NLLs.

- Triplen components cause large current magnitudes in the neutral of a 4-wire, three-phase system. Therefore the neutral conductor of all 4-wire circuits to NLLs should have an equivalent thermal rating at least equal to, and preferably 1.5 times higher than, the rated phase current.

- It might be difficult and costly to replace neutral wiring in existing installations. An alternative would be to employ a protection device that trips all three phases when (a) the phase current limit is reached and/or (b) when the neutral current exceeds the conductor current rating. In such a case the neutral conductor is not opened by the protection device. This may be accomplished practically by using four mechanically ganged MCBs and a short circuit across auxiliary contacts of the 4th (neutral) MCB.

5.3 Appliance and device labelling

In addition to the proposals for reducing harmonic generation discussed in Section 5.1, the following requirements for appliance and device labelling should be introduced as quickly as possible:

- Relays and switches should be specified to operate with NLLs, or should otherwise be clearly identified as being suitable only for resistive loads.

- Appliance ratings and labels should be expressed in both real and apparent power to reduce the risk that circuits will be under-sized because of inadequate allowance for the low power factor of appliances and equipment incorrectly assumed to be resistive.

5.4 DSM measurement & verification

It is recommended that DSM measurement and verification guidelines be thoroughly examined and rewritten. The areas that require particular attention are:

- *Electrical power definitions in the presence of non-sinusoidal voltages and/or currents:* The definitions must have universal acceptance. These definitions must include active, non-active and apparent power as well as power factor.
- *Measurement of active, non-active and apparent power and power factor:* Specifications must include standard revenue metering as well as logging equipment for verification.
- *Sampling interval for measurement equipment:* It is assumed that electrical power measurements will in future be done using static electronic functional

circuit elements (chips). The sampling rate for the measuring devices must be fast enough to ensure accuracy when the waveforms are non-sinusoidal.

5.5 Tariffs

The comments in Section 5.3 largely refer to DSM interventions but may also be applied to tariff assessment and development. It is important to structure tariffs that penalise customers whose load currents are distorted in such a way that verification and correction are possible. For this purpose both the true power factor (using a revised definition from Section 5.2) and the THD of the load current should be used.

5.6 Replacement of Ferraris meters

It is clear from the discussion that the conventional Ferraris meter is inadequate for measuring energy when the current is distorted. These should be replaced with static meters that measure true power.

5.7 Transformer rating

Transformer over-heating may be prevented by de-rating the transformer by a suitable amount. Other precautions include specifying and designing the transformer to limit the increased losses caused by NLLs.

6. CONCLUSION

The widespread adoption of appliances and equipment with non-linear electrical characteristics, as a way of increasing energy efficiency, has the potential to significantly and negatively affect supply systems. The use of appliances and control systems (ASDs) that distort the fundamental sine wave of the power supply system affects not only the quality of supply parameters, but has practical implications for the design and operation of supply systems. Urgent attention must be given to developing new definitions, specifications and practical procedures; to labelling appliances appropriately; to metering supplies accurately; and to maintaining the integrity and safety of electrical installations.

ACKNOWLEDGEMENTS

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