THE EFFECTS OF VOLTAGE VARIATION ON THE POWER CONSUMPTION AND RUNNING COST OF DOMESTIC APPLIANCES

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Abstract

The aim of this paper is to quantify the answer to the question "How does voltage variation affect the power consumption and energy cost of a domestic household". Over 20 typical domestic appliances were subjected to normal voltage variations and their power and energy measured and analysed. The results reveal that although supply voltage variations may affect power consumption, the use of certain modern appliances will ensure that the overall change in energy cost can be minimal.

1. INTRODUCTION

The nominal system voltage in Australia is now 230/400 volts bringing all 220/380 volt and 240/415 volt systems to a common standard. [1] Under normal service conditions a variation of +10%, -6% is allowed. However the distribution of electricity at the 240/415 volt level with a tolerance of +/-6% still falls within the Australian standards. Electricity supply authorities are required to comply with a nominal supply voltage of 240 volts. [2] Therefore it is necessary to ask whether continuing to operate at the higher 240 volts rather than at 230 volts will eventually cost the consumer more. In a submission to the 2001 Electricity Price Distribution review it was argued that tight controls should be placed on voltage variation above and below the specified value, to maintain adequate supply quality and to discourage energy waste and unfair cost increases for customers. [3]

When analysing the effects of supply voltage variation on power consumption and ultimately cost to the consumer it is found that domestic appliances can be divided into 3 general types i.e. Resistive, Inductive and Electronic. Resistive devices have a prime function to produce light and heat and make up 60% to 80% of most household energy usage.[4] The inductive devices are often those with some form of electric motor whose output is that of mechanical work albeit that work may be used to provide heating or cooling as in the case of refrigerators and air conditioners. These devices contribute between 10% to 40% of household energy use. The electronic devices form part of entertainment systems in the home but are becoming more common in all appliances where some form of control is required. These are normally low power devices and rarely contribute more than 20% to the energy cost.

Various types of lighting fall within the three main categories, however for comparisons it is useful to identify them as a 4th group. The combination of these 4 groups, represent the appliances of a typical domestic installation.

2. SCOPE

As the use, type and treatment of appliances varies, the existence of a single typical domestic installation is unlikely. However the aim of this work was to measure and analyse a range of devices in order to ascertain a broad set of guidelines in which we could understand the true effects of supply voltage variations. Therefore the actual values of power, energy consumption, and the size of each appliance do not appear prominently in this paper since the objective is to consider relative changes. The use of the word appliance is to be regarded as generic and is assumed to mean any electrical device in a domestic installation.

Furthermore no consideration was made of the possible damage to appliances by voltage variation nor the effects of short term supply surges and sags. Electricity industry guidelines [4] allow for compensation for damage to an electrical installation due to unauthorised voltage variation. However this does not recognise any additional or reduced cost of electrical energy due to normal voltage changes.

This paper simply addresses the power and energy consumption of a domestic installation based on a relatively constant supply voltage which is greater or less than the recommended 240 volt level.

3. THE EXPERIMENT

Over 20 typical household appliances were subjected to tests under normal operation where the supply voltage was varied whilst measurements of voltage, current, active power, energy and time were taken. Calculations of reactive power, total power and power factor were also made. Data was placed in an Excel spreadsheet for analysis.

Voltage variation was achieved by adjusting the output voltage of a single 3kVA autotransformer. In order to gain higher voltage limits the input and output terminals of the autotransformer were reversed. All appliances were initially tested between 220 and 260 volts. In some cases the appliances were subjected to a wider range of voltage variations in order to get more accurate results. A standard household kilowatt hour meter was used to determine energy in cases such as the washing machine where the appliance had a changing power cycle as distinct from those which ran continuously. In some cases where the current waveform was high in harmonic content the kilowatt hour meter was used to compare to the energy calculations. Where an appliance such as an electric jug had a preset cycle, a stopwatch was used to get the time base for the energy calculations.

A photograph of the experimental layout is shown in figure .1 below. Digital instruments were chosen for their accuracy and minimal loading to the circuit. A kilowatt hour meter was used as a backup to the digital meters and also as a means of determining how a common household meter would handle the changes particularly since the waveforms for some of the devices were non sinusoidal and full of harmonics.

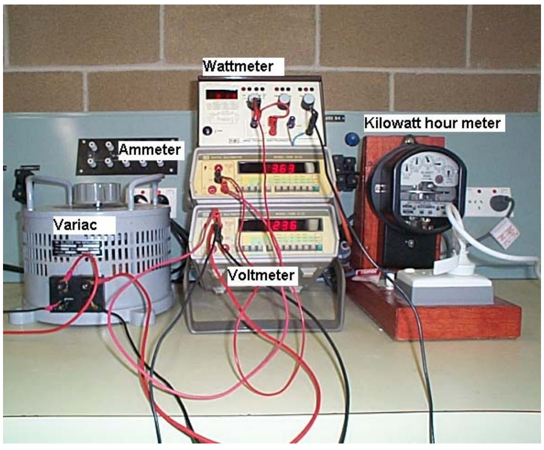

Figure.1 Experimental layout

During the course of this project it became obvious that the quantity of electronic control is increasing. Appliances such as washing machines and air conditioners with electronic controllers and inverters running electric motors are becoming more common. Whilst this is increasing the efficiency of the appliances it is also creating a problem for power quality with the generation of harmonics.

4. RESISTIVE APPLIANCES

From an analysis of the basic resistive appliance group it would appear from the outset that the heating devices would produce a predictable outcome. In this case the application of Ohms' law applied to power ($P=v^2/R$) where the change in voltage would produce a change in the power consumption of the square of the voltage change. The graph of figure.2 shows the relative power consumption versus per unit voltage based on a 240 volt supply.

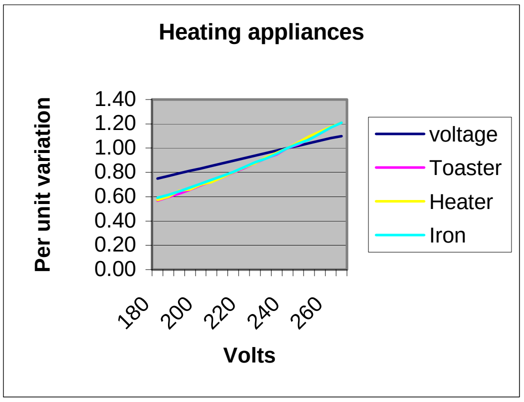

Figure.2 Relative variations of heating devices

All domestic appliances producing heat behaved predictably when it came to power dissipation, i.e. a rise of 10% in voltage produced slightly less than 21% increase in power. This was due to the higher resistance of the devices as the temperature increased.

However when tested for energy usage where the appliance had a thermostat it was found that the increased power could actually reduce the cycle time and in the case of the electric frypan, jug and iron the energy cost of voltage variation is practically zero. There was some erratic behaviour in the operation of the thermostats such as in the case of the iron there was a 5% variance in the cycle times at fixed voltage.

The testing of the electric jug over a very wide range of voltages showed this to also be the case. A change of approximately 80 degrees Celsius produced no measurable change from the expected value.

A further test included repetitively measuring the time taken to boil one litre of water in the jug. This test showed that regardless of the voltage applied the energy required for the application was approximately 390 kilojoules. In monetary terms boiling an electric jug costs no more or less regardless of the voltage. The table below in figure.3 shows the average calculated energy use for the electric jug over a wide range of voltages.

This table shows that a higher voltage does result in a slightly lower energy use. This change is too small to be significant. When this test was repeated many times at 240 volts the variation between tests was approximately +/-2 kilojoules. Other factors include heat loss and energy transfer rates but as measured are minimal.

Voltage in Volts	Power in Watts	Time in seconds	Energy in Joules
160	1080	366	395
216	1910	204	389
240	2350	164	385
264	2840	136	386

Figure.3 Energy vs Voltage for Electric Jug

Electric hot water services, heating and cooking appliances will behave in a manner similar to the electric jug, i.e. they may consume more or less power whilst running but will have similar energy usage and cost basically the same to run as long as they have a thermostat!

4.1 Summary of resistive appliances

Electric hot water, heating and cooking make up 60% to 80% of the average household electricity bill. The effects of voltage variation on this cost could be zero if all appliances were thermostatically controlled. Use of a heater without a thermostat would cost 21% extra for a 10% rise in voltage although the extra heat produced may cause a person to switch the heater off earlier than expected.

5. INDUCTIVE APPLIANCES

This product range contains the electric motors and has an output which is work based. The devices tested included a refrigerator, freezer, vacuum cleaner, washing machine, pedestal fan and an induction motor used in a power tool. In this group of appliances the most significant with respect to a household power bills are the refrigerator and freezer. These appliances typically make up 10% of domestic energy usage. From measurements of active power consumption in the refrigerator an increase of 10% of voltage resulted in a power increase of only 5% The freezer tested was significantly older and large and showed a variation of 10% in active power. This compares to the total power increase of 17% for the refrigerator and 26% for the freezer respectively. The comparative relative values for active power are shown in figure .4 and total power in figure .5 below.

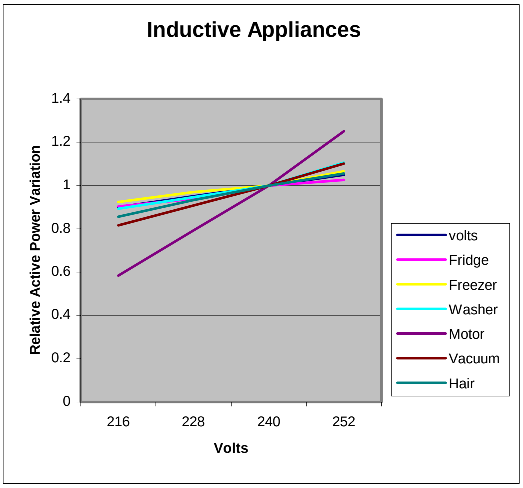

Figure.4 Inductive appliance active power

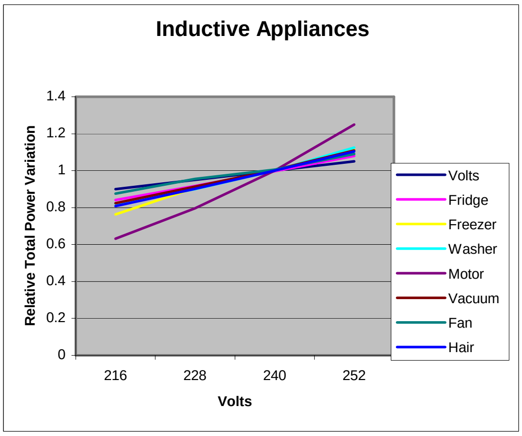

Figure .5 Inductive appliance total power

When tested for energy usage there was no significant variation regardless of voltage leading to the conclusion that the actual change in running cost due to higher voltage was virtually nil. Energy was initially measured using a kilowatt hour meter over periods of one week with the voltage set by a variac. A further refinement of the test using a stopwatch showed that there was a decrease in the cycle on time which counteracted the increased power.

No reverse cycle heating and cooling device was measured for this paper. However the cost of heating and cooling in domestic installations can be as high as 41% of the overall energy cost so some comment should be made.

Reverse cycle appliances operate on a similar principle to refrigerators and can be treated similarly with respect to power and energy usage. The popularity of reverse cycle cooling is leading to an increase in use of such appliances and is expected to cause power factor problems for electricity distributors in the future. A further factor is the increased efficiency of such devices by using electronic inverters for power supplies. Whilst this will reduce the power factor problem it is expected that it will contribute to a degradation of power supply quality by increasing the harmonics produced by the electronic switching.

Other appliances such as the washing machine, electric fan, power tools, etc. can be expected to have a change energy cost proportional to voltage change. Their relative value to the average electricity bill however is quite small.

5.1 Summary of inductive appliances

Whilst there is a change in active power for most of these appliances of between 3 and 12% for a 10% voltage increase, the larger energy users have thermostatic control and therefore have no real change in energy use and hence cost to the consumer. The most significant changes to voltage variation are that of the increase in reactive power.

6. THE ELECTRONIC DEVICES

The so called entertainment appliances are many and varied but consume very little of the overall power in a domestic installation. Tests were performed on a V.C.R. and Television, Computer and Microwave. The microwave oven although providing heating still falls into the electronic category, as the microwave power supply is generated by semiconductor switching.

By far the most interesting of these devices was the personal computer. Its switched mode power supply ensures that its energy use is almost impervious to supply voltage changes. A reasonably current Pentium II computer was subjected to a wide variation of voltages between 200 to 270 volts. The table below shows that the computer power varied only 3% over the entire 70 volt range. This can be seen in figure .6 below.

Voltage	Active Power	Total Power
0.83	0.98	0.98
0.88	0.99	0.97
0.92	0.99	0.98
0.96	0.99	0.98
1.00	1.00	1.00
1.04	1.01	1.00
1.08	1.00	1.01
1.13	1.01	1.00

Figure .6 Relative power use for computer.

In the case of the microwave, television and video cassette recorder the change in power usage was approximately half that of the voltage variation. A graph of the relative values is shown in figure .7 below.

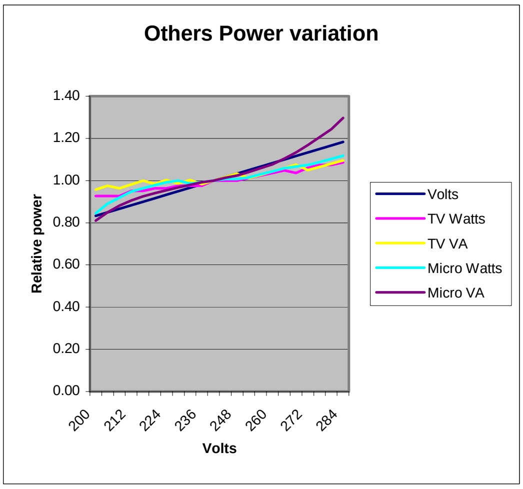

Figure .7 Microwave and T.V., V.C.R.

6.1 Summary of electronic devices

These devices can make up to 20% of a domestic power bill however changes in power consumption are less than half that that of the voltage variation. Because these devices tend to run on a time cycle rather than a work cycle they have the potential to cost more to run with higher voltage.

7. DOMESTIC LIGHTING

Home lighting accounts for approximately 10% of the average electricity bill. This is one area in which voltage variation does affect power use and energy costs. In this section 4 types of lamp were chosen to represent the majority of domestic lighting appliances. These were the incandescent lamp, fluorescent (uncorrected), compact fluorescent and Halogen.

The incandescent lamp is basically a resistive device which is sensitive to voltage variation and its temperature changes significantly. This tends to work toward protection of the lamp as tests show that a 5% variation produces only 8% power variation but a 10% voltage change produces a change in power of approximately 16%. As lamps tend to be switched on continuously the cost is unlikely to vary from the expected deviations due to any householder intervention. Therefore voltage changes are mirrored in energy costs. The significant change in temperature and light output of the incandescent lamp makes it the most affected domestic appliance of voltage variations.

The halogen lamp tests results were similar to that of the incandescent but slightly worse. The halogen lamp recorded a 17% increase in power for a 10% increase in voltage.

The Fluorescent lamp was tested both uncorrected and corrected however as the majority of fluorescent lamps in homes are uncorrected only those results are included in the summary. The fluorescent lamp faired worse than the incandescent in its power changes with a rise of 22% in active power for a 10% rise in voltage. The total power measured showed and increase in 38% for the same voltage rise. Fluorescent lights have the same problem as the inductive devices i.e. the increase in reactive power with over voltage. As the voltage is increased the fluorescent lamps power factor decreases.

The 21 watt compact fluorescent lamp tested could be placed into the category of electronic appliances. With a +/-20% variation the power change was directly proportional to the voltage i.e the current did not change and remained fairly constant regardless of the voltage.

7.1 Summary of Lighting

The tests show that lighting power consumption and its associated energy cost is affected by voltage variations. The compact fluorescent with its electronic ballast faired best and reflects its status in the electronic category. The incandescent and Halogen lamps fit into the resistive category but have a lower power change due to the increased resistance caused by large temperature change. The fluorescent fits into the range of inductive devices and causes the most problem with reactive power in response to over voltage.

A summary of lighting relative power and hence energy costs in response to voltage variation is shown in the graph of figure .8 below

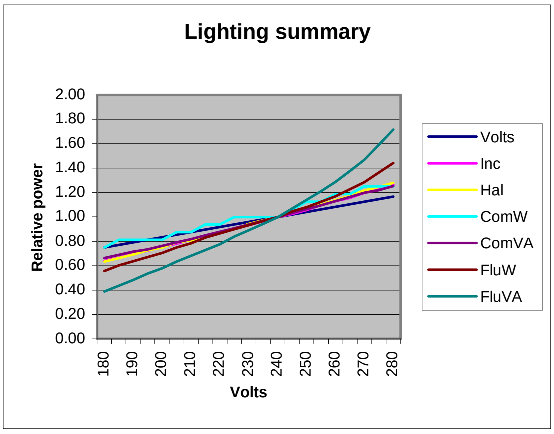

Figure .8 Summary of lighting power

8. MEASUREMENT OF DATA

Data was collected from two substations which are predominately domestic. A 10kVA transformer supplying 3 homes in rural Victoria was monitored over a period of one week and samples of voltage, current and power factor taken each minute. A second transformer which supplies approximately 40 customers in a Ballarat Housing estate was monitored similarly. The graph of figure.9 shows the per unit voltage variation over a 24 hour period for the regional transformer.

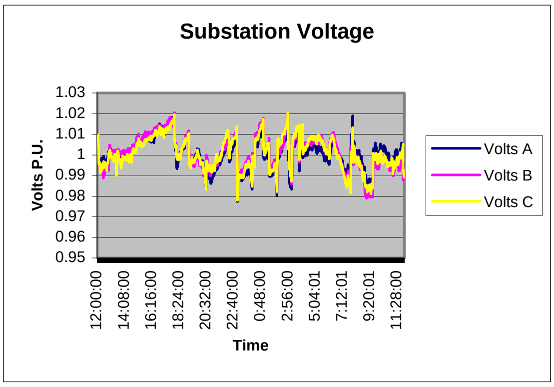

Figure.9 Substation voltage over 24 hours

From data collected for the week the worst case range of per unit voltage variations of all 3 phases varied from 0.976 to 1.024. This represents good voltage control considering a current variation range of 0.33 to 2.7 and a power factor varying from 0.63 to unity. The rural substation had a slightly larger 3 percent swing in voltages which is understandable considering its location.

9. CONCLUSION

In a domestic installation with electric hot water, cooking and reverse cycle air conditioning, a sustained 5% over voltage could be expected to have the following cost implications

Heating, cooking, and hot water would make up three quarters of energy used in this type of domestic installation and should cost no extra if thermostatically controlled. The exception to this is the electric radiator or heater without a thermostat. This device would use an extra 10% power and if not switched off earlier would add significantly to energy cost.

Refrigeration and reverse cycle air conditioning increase power consumption by approximately 8% but in energy and cost terms make no appreciable difference. They have a longer off cycle at higher voltages and for small voltage changes can expect to be close to cost neutral. Refrigeration could be expected to account for one tenth of energy cost but with air conditioning in the summer this could rise to forty percent of total household energy consumption.

Other appliances with electric motors, such as hair dryers, electric fans, washing machines, vacuum cleaners etc. have a 10% increase in power which is reflected in the energy cost. Many of these appliances have a short operation cycle or are low power devices and do not contribute significantly to overall cost.

The electronic home entertainment devices have a power change less than the relative voltage change and appear to be less affected by voltage variations. These devices may comprise up to twenty percent of total domestic electrical energy costs .

Lighting is the worst affected by voltage variation and can be expected to add an extra 8% to what would be ten percent of the energy cost overall. This is a problem that could be solved by using lighting dimmers which would reduce the power as required.

The substation measurements did not provide an adequate overview of a group of typical households. The comparatively small voltage variation compared to the wide apparent unrelated change of both active and reactive power in the substation data made it virtually impossible to gain a measured overview of the power and energy effects.

The data did show that domestic supply voltage tends to drop below the desired voltage more than it rises above it.

Up to one quarter of a typical modern domestic installation could be affected by voltage variation and in the case of a difference between a 240 volt and a 230 volt base this would translate to less than two percent of the overall energy cost.

This demonstrates that voltage variation from the consumers point of view has minimal effect on the cost of electrical energy.

10. REFERENCES

[1] Australian standards, “AS/NZS 60038-2000 “Standard Voltages”

[2] Office of the Regulator General Victoria, “Electricity Distribution code”

[3] Pears, A., ”Submission to Electricity Distribution Price Review”, 2001, pp 2-6.

[4] CountryEnergy, “Your guide to appliance energy sage”, www.countryenergy.com.au

11. ACKNOWLEDGEMENT

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