INSTITUTE FOR SUSTAINABLE ENERGY, UNIVERSITY OF MALTA

SUSTAINABLE ENERGY 2013:
THE ISE ANNUAL CONFERENCE

Thursday 21st March 2013, Dolmen Hotel, Qawra, Malta

TESTING THE POTENTIAL OF VOLTAGE REGULATION FOR ACHIEVING HIGHER ENERGY EFFICIENCY

Cedric Caruana[1], Charles Yousif[2] and Martin Debono[3]
[1]Faculty of Engineering, University of Malta
[2]Institute for Sustainable Energy, University of Malta, Triq il-Barrakki, Marsaxlokk MXK 1531, Malta,
[3]CD Power Saving Co. Ltd., Ciancio House, Cannon Road, Qormi, QRM 9030, Malta
Tel: (+356) 21480500
Corresponding Author E-mail: mdebono@powersaving.com.mt

ABSTRACT: This paper focuses on energy efficiency of household electrical loads. It concerns a commercial product that aims to lower consumption by decreasing the supply voltage. In practice, the utility voltage is variable and at certain locations it might be consistently on the high side. The potential energy saving of the VO4Home unit is experimentally tested with a real voltage profile. The VO4Home has three settings that correspond to constant voltage reductions of 13V, 16V and 24V. A mix of loads was selected to reflect a typical household load. For the load mix and operating pattern, a minimum energy saving of 7.3% increasing up to circa 8.7% was recorded. The VO4Home is supplied in Malta by CD Power Saving Ltd.

Keywords: VO4Home, Voltage drop, energy saving, appliances.

1 INTRODUCTION

The limited supply of conventional fuels and the resulting increase in energy rates has led to considerable research efforts aimed towards alternative sources of energy and increased energy efficiency. Increased energy efficiency incorporates the use of new technology or establishing new practice in the use of the traditional technology. Energy efficiency measures generally result in shorter payback periods. There are different approaches for increasing the energy efficiency of electrical loads. Some devices are specifically targeted for particular applications, like Motor Energy Controllers [1]. This paper concerns a more general approach for increasing the energy efficiency as it targets to lower the supply voltage magnitude to lower the consumption of the diverse loads that may be connected.

The voltage level in Malta is regulated by the Malta Network Code [2] at 400V ± 10%, which translates to a phase voltage of 230V ±23V. Measurement of the voltage magnitude at different sites identified that the voltage varies throughout the day and can be consistently on the high side. This is especially true for consumers that are connected at points near to the substation or have their own substation. It is argued that operating electrical loads at high voltage might lead to an increase in the power consumption that will translate into a higher energy bill. Voltage regulation is proposed to reduce the energy consumption. Operation at lower voltage, within a specified limit, might also contribute to prolonging the lifetime of electrical equipment.

This paper concerns a specific unit under the trade name of VO4Home. This is a device that reduces the incoming low voltage supply, with the intent of reducing the energy consumption and reducing the voltage stresses on household electrical equipment. The VO4Home is designed and manufactured in the UK [3]. The paper examines the potential change in electrical energy consumption following the installation of a VO4Home in a typical household. It is not intended in any way to test the compliance of the VO4Home with any applicable standards. Nor does this consider the possible damage to electrical equipment due to voltage variation.

2 THE DEVICE

The VO4Home unit is basically a transformer housed in a rigid steel housing with a plastic cover to maximise the safety of the product, as shown in Figure 1. The unit can be configured to give one of three fixed ratios. The output voltage level is selected through a rotary switch that would reduce the voltage by 12, 18 or 25 V. The unit also includes a miniature circuit breaker to facilitate switching ON and OFF.

Figure 1: VO4Home unit showing the three voltage tapings.

Table 1 shows the technical specifications for the specific model under test. It is to be noted that the company manufactures different types of units, to suit the different needs in single and three phase systems.

Table 1: VO4 Home Technical Specifications

Rating (Amps)	**60 Amps**
Rating (kVA)	45 kVA
Phases	1
Frequency (Hz)	50/60
Primary Voltage	230 Volts (±10%)
Secondary Voltage / Phase	5, 10, 15 or 12,18,24
Ambient Temperature Range	-10 to +40C
Humidity	90%
Insulation Class	F
Varnish Class (Vacuum Impregnation)	H
Voltage Withstand (1 Min)	3,000V
Insulation Resistance at 500V DC	>1000MΩ
Temperature Rise	<100K
Efficiency typical	>99.9%
Primary Neutral Terminal	Din rail 16mm cable terminal
Secondary Terminals	Din rail 16mm cable terminal
VO4HOME Supplied in an Enclosure	
Style	All welded Mild Steel case
Size (LxDxH) mm	316x269x173
IP Rating	22
Weight	18.5kg

The VO4Home is intended to be installed directly after the incoming supply such that all/most of the in house circuits operate at the lower voltage. Selection of the setting depends on the incoming voltage level at the premises and is hence site specific. Monitoring of the voltage at the premises will identify the trend of the voltage at the site. The monitoring exercise should cover at least a diurnal variation for both weekdays and weekends. The voltage at the furthest point within the circuit of the building should also be considered, such that when the VO4Home is installed, it will not fall below the minimum voltage level.

Within the operation of the system, monitoring can also be made periodically to ensure that the voltage limits are still within the allowable limits. The tapping can then be changed accordingly, bearing in mind that this can only be made with the mains power switched off.

3 Test Procedure

The objective of the test was to examine the change in energy consumption when a typical set of loads that are found within a typical household are operated with and without the VO4Home apparatus.

The potential savings resulting from the reduction of the voltage level vary for the different types of domestic load. Typical domestic loads can be generally into four general types [4] i.e. Resistive, Inductive, Lighting and Electronic.

Resistive loads have a prime function to produce light and heat. Inductive loads are generally those with some form of electric motor. Lighting load comprises a number of different lighting technologies which have evolved from the conventional incandescent to the compact fluorescent lamps that are gradually being replaced by light emitting diodes (led) based lamps. Electronic loads cover the types of loads that include some form of power conversion stage to supply the internal electronics.

Despite the general classification, loads of the same general type can still exhibit different behaviour as regards to the change in consumption with voltage level. Resistive loads possibly include some form of thermostat control, where the load would be disconnected once a set temperature is reached. Inductive loads and also lighting loads are nowadays featuring increasing amounts of electronic control making them more energy efficient [4]. The diverse range of possible responses to voltage variations makes it difficult to predict the potential savings.

A mix of common appliances was therefore selected to reflect a typical household. Different type loads were connected to different circuits. The operating times of the different appliances were selected to reflect typical usage, however the operation of low consuming loads, like compact fluorescent lighting was extended to facilitate measurement. The loading was designed to minimize the effect of ambient temperature variation. For this purpose, water heaters and air conditioners were not included in the tests. Also, the room where the experimental tests were carried out was kept at constant temperature by means of an air conditioner.

The load mix, agreed upon with the local distributor of the VO4 and approved by the manufacturer, was established as follows:

1. Resistive loads:
   a. Electric kettle: An electric kettle was used to boil a total of 10 litres of water each day. The 10 litres of water were previously cooled for a day in a refrigerator such that the water is at the same initial temperature. The electric kettle used was rated at 2kW and could hold approximately 1.8 litres of water.
   b. Sandwich toaster: A sandwich toaster was switched on for 2 hours per day to emulate loads like toasters, electric cookers, stoves etc. The sandwich toaster in use was rated at 230V, 700W.

2. Inductive loads:
   a. Refrigerator: A refrigerator was loaded with 20 litres of water and set at a constant thermostat setting. The first 10 litres of water were left in the refrigerator continuously, while the second 10 litres were replaced with warmer water once daily. Before introducing this interchangeable 10 litres of water into the refrigerator, it was kept in the testing room in order to attain the same air-conditioned temperature every time. The temperature setting of the air-conditioner was 25°C. The refrigerator was rated at 0.8A, 220-240V. Tests showed an instantaneous power of circa 118W.
   b. Desk fan: A desk fan was switched on for 2 hours per day. The desk fan was rated at 48W, 240V.
   c. Small motor: A 0.25hp motor was switched on for 2 hours per day, which would simulate a water pump. The motor was run unloaded. Tests showed an instantaneous power of circa 188W.
   d. Dehumidifier: A dehumidifier was set at maximum setting and left to operate continuously throughout the test. The dehumidifier was rated at 240W, 240V.

3. Lighting loads:
   a. Compact fluorescent lamp: 1x 20W compact fluorescent lamp was switched on continuously throughout the test. The lamp had an electronic ballast.
   b. Fluorescent tubes: 2x 60W fluorescent tubes with magnetic ballast were switched on continuously throughout the test.
   c. PL lamps: 4x fluorescent PL lamps were switched on for 2 hours per day. Each lamp was rated at 26W. The lamps had inductive ballasts with a loss of 8W each.

4. Electronic loads:
   a. PC: A personal computer was left on for the duration of the test. The personal computer was left in idle mode. Tests showed an instantaneous power of circa 111W.
   b. TV set and DVD player: Both the TV set and the DVD player were left on continuously with the volume muted. The DVD was stopped. The TV was a conventional tube unit rated at 95 W. The DVD player was rated at 20W. Tests showed a total instantaneous power of circa 96W.

A schematic of the test setup is shown in Figure 2. Actual photos of the equipment under test are shown in Figure 3 – Figure 5.

Tests were run for the different settings of the VO4 Home as shown in Table 2. Test 5 was intended to check that the consumption with the VO4Home bypassed remains the same as previously hence mitigating against possible changes due to external factors. Each test was run for a period of forty eight (48) hours. The lux output from the continuously operated lighting loads was checked for the different VO4 Home settings. Data was logged using an Elite Pro meter. One channel was connected to the input supply while a second channel was connected to the output of the VO4 Home output. A third channel monitored the refrigerator consumption. For all channels, a 50A current probe was used. The tests were conducted at M'Xlokk where the premises are very near to a substation. No attempt was done to stabilize the voltage such that the tests are done in a real environment.

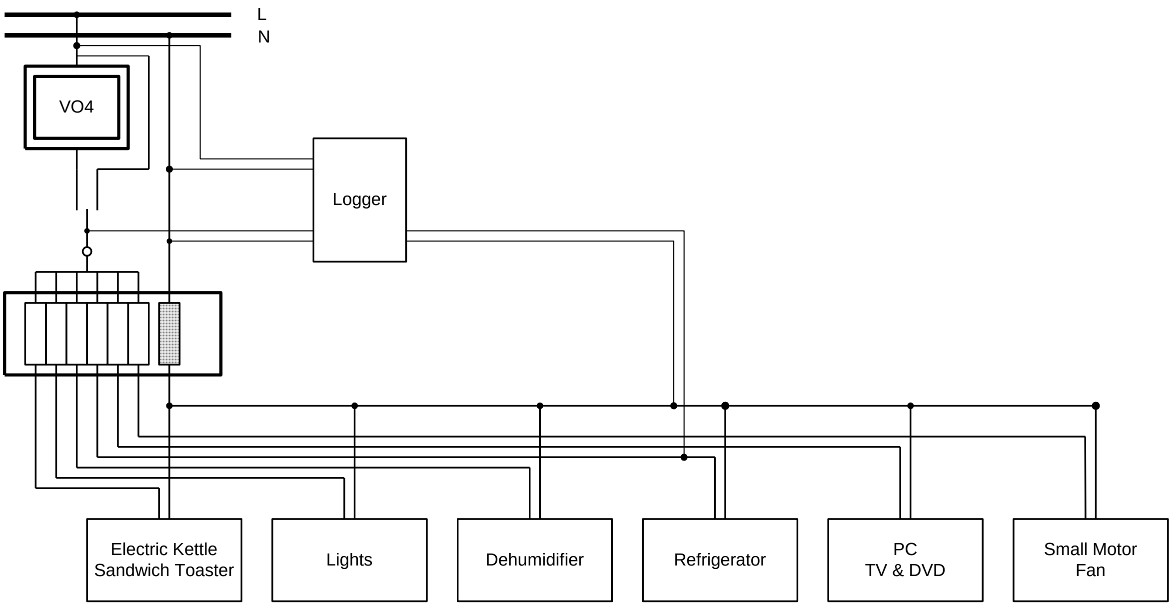

Figure 2: Schematic of the test setup


Figure 3: Actual test photo showing the PL lamps (in a case), desk fan, pc and monitor, TV and DVD player, the cfl lamp (behind TV) and the kettle at the far right. The fluorescent tubes can be seen behind the monitor.


Figure 4: Actual test photo showing the dehumidifier and the small motor.


Figure 5: Actual test photo showing the refrigerator and the sandwich toaster.

Table 2: Sequence of tests

Test	Conditions
1	V04 bypassed
2	V04 setting 2
3	V04 setting 3
4	V04 setting 1
5	V04 bypassed

4 TEST RESULTS

Data at the input and output of the VO4Home unit and at the refrigerator circuit was captured every minute. Plots of the variation of the voltage, current, average power and refrigerator average power for the different cases are shown. For each case, the average power is shown at the input of the VO4Home unit, as that reflects the monitored consumption by the typical household's energy (kWh) meter. The refrigerator average power is necessarily measured at the output of the VO4Home. However it is only intended to facilitate explanation of the events in the average power plot.

3.1 VO4Home Bypassed

As mentioned previously, the test with the VO4Home bypassed was run two times, once at the beginning and once at the end. The second test run showed a similar trend to the first run. Data from the second run is used in the following analysis. Figure 6 shows the variation of the supply voltage at the test site over a period of 48 hours. It can be seen that the input voltage is on the high side with an average of circa 241V. It can also be seen that the voltage is not constant but varied during the test period. The variation is not significant though reaching minimum and maximum input voltages of circa 234V and 246V respectively.

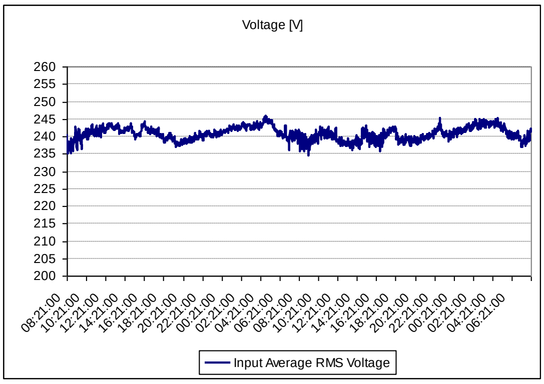

Figure 6: Voltage variation for test with VO4 Home bypassed

Figure 8 shows the current variation. The loading reached a total current of circa 17A for short durations. The current was then at a lower level of circa 4A for most of the time. The unit maximum loading is just above 25% of its rating.

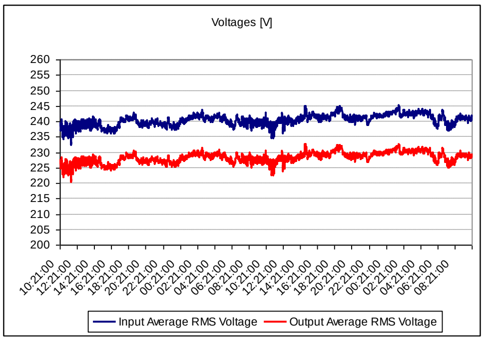

Figure 7: Voltage variation for VO4 Home setting 1

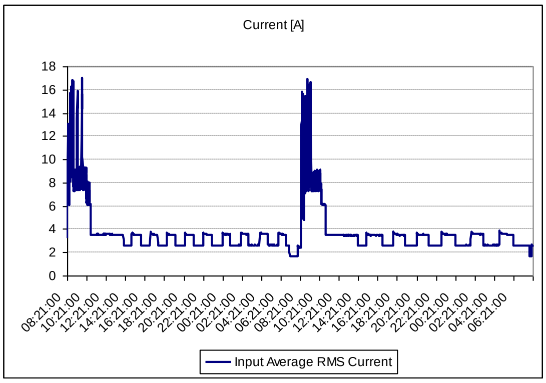

Figure 8: Current variation for test with VO4 Home bypassed

Figure 9 shows the input average power and the refrigerator average power variation. The refrigerator average power variation clearly shows the two instants when it was loaded with warm water. Also, the refrigerator controller switches the unit on and off according to the set level, which was left constant throughout all the tests. The input average power shows a number of events that reflect the loads that were not left on continuously.

The variations between circa 1.75kW and 3.75kW starting at around 08:21hrs for the two days reflect the operation of the kettle used for boiling the water. The variations between circa 1kW and 1.75kW starting at the same times, for duration of approximately 2 hours each, reflect the operation of the sandwich toaster. The rise in power at the same time and for the same duration between circa 0.6kW to 1kW reflects the switching on of the PL lamps and the motor. The remaining regular switching, as can be verified from the refrigerator average power plot, reflects the operation of the refrigerator's controller.

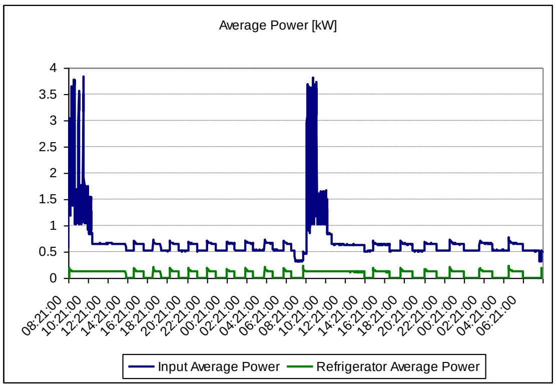

Figure 9: Average Power variation for test with VO4 Home bypassed.

3.2 VO4Home Setting 1

Figure 7 shows the input and output voltage variations for the VO4Home Setting 1. As can be seen, this setting establishes a constant difference of 12V between the respective voltages.

It can be seen that, as before, the voltage is not constant during the test period. The input voltage had an average of circa 240V and reached minimum and maximum values of circa 232V and 245V respectively. The output voltage had an average of circa 228V. Figure 10 shows the input and output current variation. As can be seen, there is a slight variation in the currents due to the transformer action. A similar variation to Figure 8 is observed for the input average rms current.

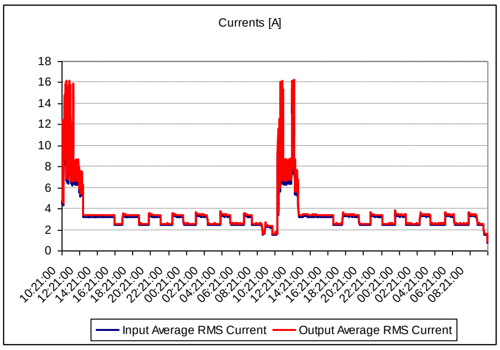

Figure 10: Current variation for VO4Home Setting 1

Figure 11 shows the input average power and the refrigerator average power variation for the VO4Home setting 1.

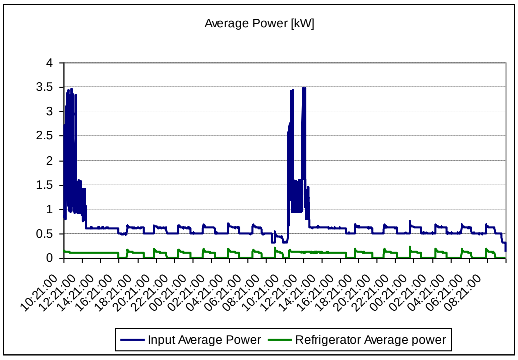

Figure 11: Average power variation for VO4 Home setting 1

As mentioned previously, refrigerator average power was measured at the output of the VO4Home hence an allowance must be made for the efficiency of the VO4 Home. However the purpose of the inclusion of the trace is only to explain the variation of the input average power waveform. The refrigerator loading and its controller operation can be clearly seen. It can be observed that the refrigerator switching on day 1 of the test was less frequent with the refrigerator remaining on for longer durations, possibly due to the lower instantaneous power. It is to be remembered that the ambient temperature was controlled through the air conditioner. The operation of the kettle, sandwich toaster, PL lamps and motor can also be seen starting at circa 10:21hrs on both test days.

3.3 VO4 Home Setting 2

Figure 12 shows the input and output voltage variation for the VO4Home Setting 2, which establishes a constant difference of 18V. As for the two cases before, the voltage was not constant through the test period and showed a sudden dip of circa 6V at around 1500hrs on the first day of the test. The voltage recovered at around 2200hrs. The input voltage averaged circa 243V and reached minimum and maximum values of circa 237V and 248V respectively. The output voltage averaged circa 225V.

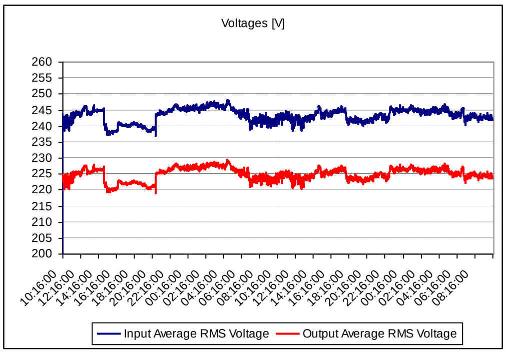

Figure 12: Voltage variation for VO4 setting 2

Figure 13 shows the input and output current variation. A similar variation to Figure 8 and Figure 10 is observed.

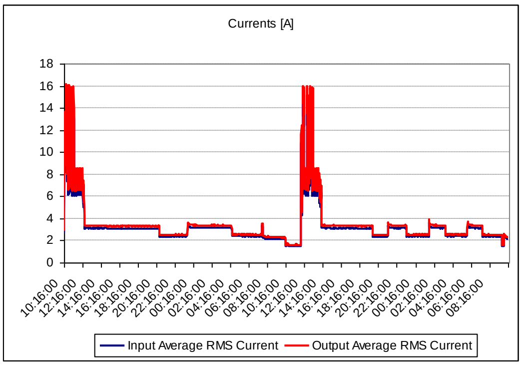

Figure 13: Current variation for VO4 setting 2

Figure 14 shows the input average power and the refrigerator average power variation for the VO4 Home Setting 2. As before, the refrigerator loading and its controller operation can be clearly seen. It can be observed that the refrigerator switching was even less frequent with the unit operating for longer contiguous durations. The operation of the kettle, sandwich toaster, PL lamps and motor can also be clearly seen starting at circa 10:16hrs and 12:16 hrs for test days 1 and 2 respectively.

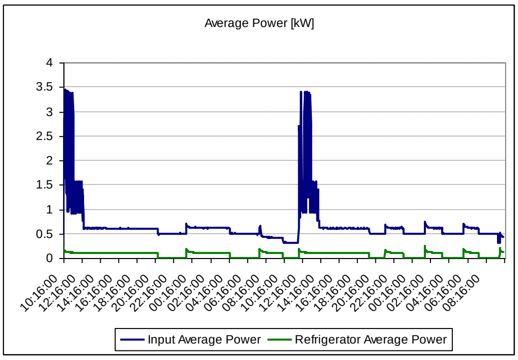

Figure 14: Average power variation for VO4 Home setting 2

3.4 V04 Home Setting 3

Figure 15 shows the input and output voltage variation for the VO4Home setting 3. This setting establishes the maximum difference of 25V between the respective voltages. The voltage also showed a variation through this test, showing a sharp drop at circa 22:46hrs on the first day. The input voltage had an average of circa 242V and reached minimum and maximum values of circa 235V and 248V respectively. The output voltage had an average of circa 217V.

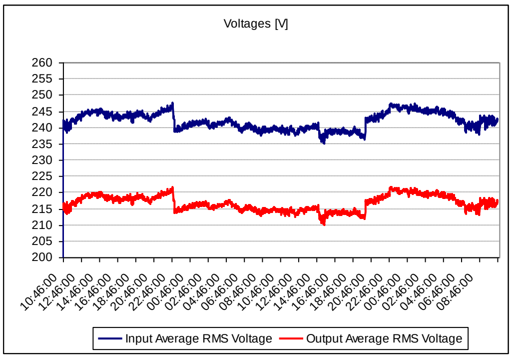

Figure 15: Voltage variation for VO4 setting 3

Figure 16 shows the input and output current variation. A similar variation to the previous tests is shown for day 1 of the test. Day 2 shows a slightly different picture that will be explained through the average power graph.

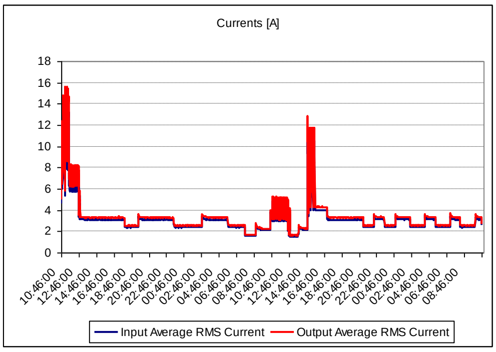

Figure 16: Current variation for VO4 Setting 3

Figure 17 shows the input average power and the refrigerator average power variation for the VO4 Home Setting 3. As before, the refrigerator loading and its controller operation can be clearly seen. It can be observed that even for this case, the refrigerator switching was less frequent with the unit operating for longer contiguous durations for the first day of the test. The operation of the kettle, sandwich toaster, PL lamps and motor can also be clearly seen starting at circa 10:46hrs on the first day of the test. On the second day, the sandwich toaster and the motor were switched on, for duration of two hours, at circa 10:46hrs. The kettle and the PL lamps were switched on, the latter also for two hours, at circa 14:46hrs. This difference leads to a drop in the maximum instantaneous power seen by the VO4. It is not expected to affect the power consumption readings as the VO4 Home's quoted efficiency varies only by circa 0.2% between half load and low load operation. The efficiency was experimentally verified to be at the quoted level.

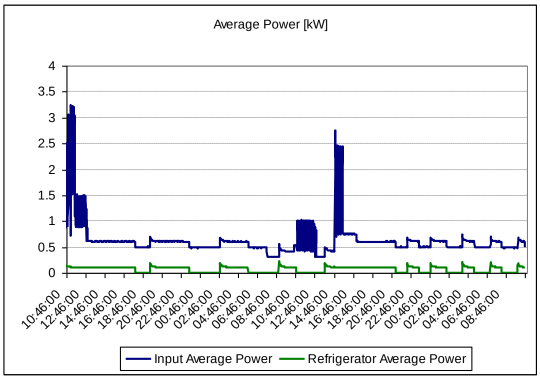

Figure 17: Average power variation for VO4 Setting 3

The total energy consumption for each case was also logged. The figures are shown in **Error! Reference source not found.**.

Table 3: Logged consumption for the different settings

VO4 Home Setting	Volt Difference [V]	Log Consumption [kWh]
Bypassed	0	34.166
1	12	31.351
2	18	31.051
3	25	30.181

5 ANALYSIS OF RESULTS

Analysis of the results confirms that the operation of the desk fan, small motor, lighting and electronic loads were as intended. The operating time of the kettle and the sandwich toaster varied for the different tests but this was expected due to the lower resulting instantaneous power at the different VO4Home settings. Both devices were thermostatically controlled. It was observed that the kettle operating time increased by circa 14% from the case of VO4Home bypassed, to the case at setting 3. The respective time increase for the sandwich toaster was of circa 21%.

The dehumidifier also showed different operating times. This was set at its maximum setting for the duration of all the tests. However its tank has a limited capacity and it stopped operating when the tank was full. The humidity content of the room was not fully controlled, even though the air-conditioning unit was always on to control the temperature, which lead to some changes in the operating duration of the dehumidifer. As the dehumidifier accounts for a significant percentage of the total load, as will be seen later, the consumption readings in **Error! Reference source not found.** were normalised to reflect constant dehumidifier operation. Close examination of Figure 9, Figure **11**, Figure **14** andFigure **17** revealed the periods when the dehumidifier stopped operating.

Figure 9 had showed a drop in the input average power just before the second kettle cycle that does not correspond to the refrigerator switching. A similar drop was seen at the end of the test. The dehumidifier was not operating for circa 1.5 hours.

Figure 11 had showed similar drops in input average power that did not correspond to the refrigerator switching. The drop also occurred before the second kettle cycle and at the end of the test. The dehumidifier was not operating for circa 2 hours. Figure 14 had showed similar drops but of longer duration. The drops occurred also before the second kettle cycle and at the end of the test. The dehumidifier was not operating for circa 5 hrs.

Figure 17 also showed a drop of long duration starting at circa the first 07:46 hrs till the second kettle cycle. The dehumidifier was not operating for circa 6.75 hrs. The calculated durations were used to determine the rectification required for the consumption values shown in **Error! Reference source not found.**. Tests at the different VO4Home settings were repeated to confirm the average power for each setting. The normalised consumption readings and the resulting savings, expressed as a percentage of the consumption with the VO4Home bypassed, are tabulated in

Table **4**.

Table 4: Normalised consumption for the different settings

VO4 Home Setting	Log Consumption [kWh]	Normalised Consumption [kWh]	Consumption [%]	Saving [%]
Bypassed	34.166	34.456	100.0	0.0
1	31.351	31.729	92.1	7.9
2	31.051	31.926	92.7	7.3
3	30.181	31.443	91.3	8.7

Table **4** showed that the introduction of the VO4Home unit at setting 1, i.e. a constant voltage drop of 12V, led to a reduction in the energy consumption of circa 7.9%. The saving increased slightly to circa 8.7% for the maximum VO4 setting. The lower value of circa 7.3% obtained for setting 2 can be partly attributed to the longer operating times of the kettle, toaster and the refrigerator. The saving figure for setting 2 is expected to be close to that of setting 1 as the average voltage drop between the two cases was of only 3V as compared to the 13V drop resulting from setting 1. Another factor is the margin of error in the readings. However the proximity of the saving figures indicates repeatable performance. Setting 3 led to a voltage reduction of 11V compared to setting 1, yielding an additional saving of slightly less than 1%. These specific percentages are valid for this load mix under test and with the specified timings and will vary for a different load mix and/or operating times.

It can be concluded that, for this particular load mix and operating times, the introduction of the VO4Home led to a minimum energy saving of circa 7.3%. Further reduction of the voltage through the different settings led to an additional saving of circa 1.4%. It is noticed that the saving figure is less than that quoted in [5] for tests on a similar device.

Plug-in meters were used to calculate the percentage contribution of each device to the total consumption. These values should be treated as approximate due to the lower accuracy of the plug-in meters. The percentage values, based on the normalised consumption data with the VO4Home bypassed, are tabulated in Table 5.

Table 5: Approximate percentage loading contributions.

Load Type	**Sub Total [%]**	**Total [%]**
Resistive Loads		
Electric kettle	7.1	
Sandwich toaster	3.7	**10.8**
Inductive loads		
Refrigerator	9.6	
Desk fan	0.4	
Small motor	2.2	
Dehumidifier	26.2	**38.4**
Lighting loads		
Compact fluorescent lamp	3.3	
Fluorescent tubes	16.4	
PL lamps	2.1	**21.8**
Electronic loads		
PC	15.6	
TV and DVD player	13.4	**29.0**

It can be seen that the dehumidifier established the highest percentage loading at circa 26% followed by the fluorescent tubes and the personal computer, both at circa 16%. The highest load category was the inductive load, mostly due to the dehumidifier, at circa 38%.

Table 6: VO4 Home efficiency at the different settings with the test load

VO4 Home Setting	Efficiency [%]
1	99.8
2	99.8
3	99.5

VO4 Home Efficiency

The efficiency of the VO4 Home unit, measured at the different settings for the test load, is shown in Table 6. It can be seen that the unit efficiency is very high averaging 99.7%. This corresponds to the efficiency levels quoted in the product literature [VO4 brochure].

Lux Measurement

It was expected that the lux output from the different lamps used in this test drops as a result of the voltage reduction. The lux output at the different VO4Home settings was therefore examined to check that the performance of the various lamps was still acceptable. The variation in the lux outputs are specified in Table 7 as percentages of the original.

Table 7: Variation of the lux outputs with the VO4Home settings

	Lux Level [%]			
Lighting Load	VO4 Home bypassed	Setting 1	Setting 2	Setting 3
Compact fluorescent lamp	100	95.7	91.1	82.4
Fluorescent tubes	100.0	96.2	90.6	83.0

The two forms of fluorescent lights showed a similar behaviour dropping the lux level with voltage down to circa 83% of the original output. This would be equivalent to replacing the 23W CFL with a 19W lamp. Such reduction in the output will be noticeable but might be acceptable to the user.

6 CONCLUSIONS

From the analysis of the normalised consumption data it can be concluded that, for this particular load mix and operating times, the VO4Home unit under test led to a minimum energy saving of circa 7.3%. Further reduction of the voltage through the different settings yielded an additional saving of circa 1.4%. The consumption data was normalised to rectify for the different operating times of the dehumidifier that resulted from the uncontrolled humidity content of the test room. The resulting saving percentages are valid for this particular load mix under test and will vary for different loads and/or operating times.

The VO4 Home unit loading was established by a mix of devices reflecting a typical household. Devices whose consumption depends on ambient temperature like water heaters and air conditioners were not included in the test. The highest percentage contribution to the load was a dehumidifier at circa 26% followed by two fluorescent tubes and a personal computer, both left on continuously, each establishing circa 16% of the load. It follows that inductive loads such as air-conditioners, pumps, refrigeration units and washing machines would be the category that would see most savings.

The effect of the voltage reduction on the lighting loads was also measured. For the cases of the compact fluorescent lamp and the fluorescent tubes, the lux levels dropped down to circa 83% of the original. This was equivalent to replacing the lights with a lower power-rated lamp.

REFERENCES

[1] P. Spiteri, C. Spiteri Staines and C. Caruana, “Increasing the electric motors efficiency in industrial applications”, Sustainable Energy 2012: The ISE Annual Conference, Qawra, Malta, 2012.

[2] “The Network Code”, Enemalta Corporation, Available online at www.enemalta.com

[3] VO4 Technical Information, VO4Home Ltd. Available online at: www.vo4home.com.

[4] G.K. Hood, “The effects of voltage variation on the power consumption and running cost of domestic appliances”, Australian Universities Power Engineering Conference AUPEC, Brisbane, Australia, 2004

[5] “Research Report for the Voltage Optimisation Home Study at RWE npower”, HurleyPalmerFlatt, June 2010. Available online at: www. vo4**home**.com/_literature_38090/**RWE**_Npower_**trial**_report.