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Dual–voltage micro-electricity grids

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Abstract

Most developing countries are facing energy shortage and this impacts the social and economic development. Reliable electrical networks are absolutely necessary for energy supply. Unfortunately, the energy access has become a major problem in developing countries. When electricity is available, in large cities for instance, the grid is not reliable. Additionally, power cuts, power interruptions and electricity rationing are frequent, causing social tensions. This work focuses on a solution for lighting during electricity rationing. The use of a dual-voltage LED lamp can be an alternative solution to expensive kerosene and candles. A dual-voltage LED lamp can give the same light output at 240 VAC, 20 VAC or 24 VDC. Here is proposed a design of a small electrical grid encompassing dual voltage lamps and energy storage. This solution can be implemented in single family homes and in renewable energy mini-grids, and as well as in whole cities. Successful trials have been carried out at the Open University and in Cambridge, UK and results are presented in this paper.

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Keywords: Energy access; unreliable electrical network; energy efficiency; dual voltage; variable voltage; developing countries; minigrid; grid stability.

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1. Introduction

Africa is known to be blessed with abundant natural resources, but the majority of its inhabitants live with low purchasing power, without adequate energy supply, and in a context of poor sanitation, poor infrastructure and poor healthcare systems.

The electrification rate varies across the continent, over 90 % in the Maghreb region, 85 % in South Africa [1] but only 24 % in Sub-Sahara [2]. Bringing electricity to 1 billion inhabitants will be a real challenge as it requires massive investments. The World Bank estimates this at US$ 50-80 billion per year [3].

National governments are striving to electrify homes and provide electricity to industries. However, many places remain without electricity, and where grid electricity is available, it is not reliable. In rural areas, the electrification rate is usually very low, below 20% despite attempts to electrify through electrification programs, managed by rural electrification agencies created in many countries. In urban areas, the grid does not supply all households. Reliability of electricity supply is a major issue. High population density in large cities exacerbates the situation as populations that have found enormous advantages of being able to rely on electricity find themselves denied it. Demonstrations have been recorded in many countries, for example Ghana [4], Cameroon, and Guinea.

It has become urgent for governments to supply electricity to populations to alleviate poverty, sustain economic growth and insure social and political stability. Expectations and electricity demand have massively overtaken supply, and most African countries find themselves having to enforce Load Shedding, cutting off large sections of the community completely for significant periods. Clearly this is undesirable, and various more discriminating load management techniques have been developed. However, they are all expensive.

Table 1 contrasts discriminating and indiscriminate ways of reducing electricity demand.

Smart meters are the new idea. They can be highly discriminating, and can be programmed to turn off/on specific consumers or even individual loads, on request from the electricity supplier. However, they are an expensive solution:

- The hardware itself is expensive
- Installation is expensive
- In a democratic society, users will only accept restrictions in return for tariff reductions, which reduce revenue
- A bureaucratic and communications infrastructure has to be built

Furthermore, in locations where electricity theft is widespread, any demand management technique that leaves 240 V on the line is unlikely to be effective [5].

So believing that smart meters may not necessarily be the best solution for Africa, in our research at the Open University, we set out to answer two key questions about Load Shedding:

- Can we find an indiscriminate approach to load shedding that has less impact on society than just cutting users off?
- Can we find a discriminating approach to load shedding that is less costly to implement than smart meters?

Table 1. Indiscriminate versus Discriminating Reduction of Electricity Demand.

	Indiscriminate	Discriminating
Regime	Cut off every user and appliance EXCEPT where additional investment has been made	Cut off ONLY users or appliances where additional investment has been made
Example	Blackouts	Smart meters, intelligent appliances
Effect	Immediate large savings, but with high impact on society and economy	Gradual incremental effect proportional to the investment made
Finance	Users pay to restore utility (e.g. by buying a generator)	Equipment cost, installation cost, tariff concessions

In this paper, we present a possible answer to the first of these questions. It is based on dual-voltage LED lamps which can give the same light output at 240 VAC, 20 VAC or 24 VDC. We review experimental work undertaken in the UK on dual-voltage (Low-Voltage (LV) 240 VAC and Extra-Low Voltage, (ELV) 20-30 VAC) electricity grids, and LED lamps able to take advantage of them. A number of open issues that are the subject of ongoing research are raised.

2. Methods

Conventional wisdom says that an electricity supply must as far as possible be at a constant voltage [6,7]. However, the advent of LED-based lighting for the first time calls this into question – at the Open University we have developed an LED lamp that can give a constant light output all the way from 24 VAC/DC to 240 VAC (and probably with a little more development, down to 12 VDC). This leads to a very simple idea: With lamps that give the same light whatever the voltage, keep them on all the time, by installing a dual-voltage supply that provides 220-240 VAC when energy is plentiful, and a much lower voltage (perhaps 20-30 VAC) when it is not.

At 20 VAC, demand from conventional loads will be reduced by 99% (resistive loads) or 100% (discharge lamps), but these constant-brightness LED lamps will continue to provide the same amount of light.

Switching an electricity distribution grid to a much lower AC voltage can be implemented very quickly and inexpensively, when compared to other electricity demand management methods – just select a different tapping on the transformer. The process is essentially the same, whether for a small mini-grid, or for a whole country. There is no need to make any other changes to the grid equipment or household wiring. Naturally, power-hungry appliances will not function at the lower voltage, but at 20-30 VAC, they should not suffer any lasting harm.

There are several potential benefits of providing a variable voltage:

- Lights will stay on when even when electricity supply cannot meet the demand.
- Although they do not yet exist, it will also be possible to make mobile phone and laptop chargers that will work over this voltage range [8,9].
- As LED lamps can work from DC or AC, households will have the option to switch their LED lighting between batteries (without an inverter) and the mains as required (but note that appliances should not be connected to DC at any voltage) [10,11,12].

There are also several potential difficulties that must be addressed, and if necessary circumvented. Among the challenges that have been identified are:

- Can a dual-voltage LED lamp be built cost-effectively, and can retrofit-able voltage boosters for other essential loads be made cost-effectively?
- Will enough energy be saved?
- Will standard kWh meters charge for the electricity (and does it matter if they do not)?
- Will standard protection devices (fuses, MCBs) operate correctly at ELV?
- Will any appliances be damaged? What is the highest voltage that can be used without (for example) causing stalled motors to overheat?
- Will the grid be stable at low voltage? How stable will the voltage be?
- How practical will it be to run a whole city at low voltage? (For example, we know we will need to defeat automatic On-Load Tap Changers (OLTCs) used to stabilise voltage).

We are addressing some of these challenges with research in the academic literature and laboratory experiments. However, some (for example, running a whole city at low voltage) have so far proved resistant to attempts to model them – owing to a lack of defined characteristics for loads below their minimum operating voltage.

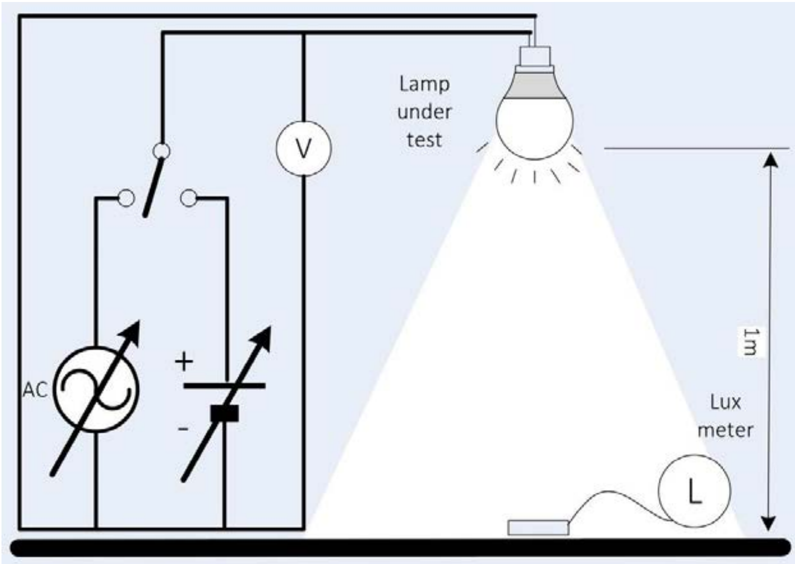

Fig. 1. Experimental arrangement.

3. Results and Discussion

3.1. Cost-effective LED lamps

A prototype variable-voltage LED lamp has been constructed using a patented two-stage approach, and performance characterised (Fig.1). The designed LED lamp can work at any voltage from 250 VAC down to below 20 VAC, or 24 V DC from a battery. Fig.2 shows that the lamp gives the same amount of light across the full voltage range

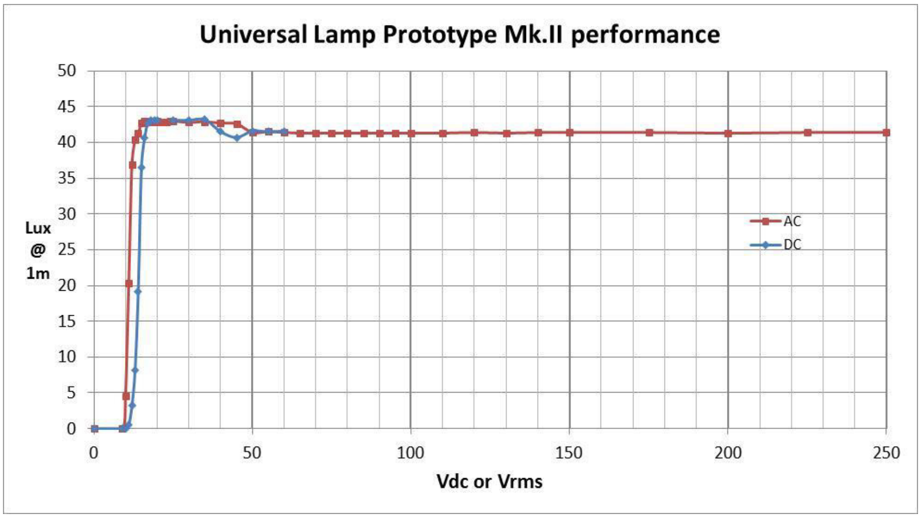

Fig. 2. Performance of prototype LED lamp.

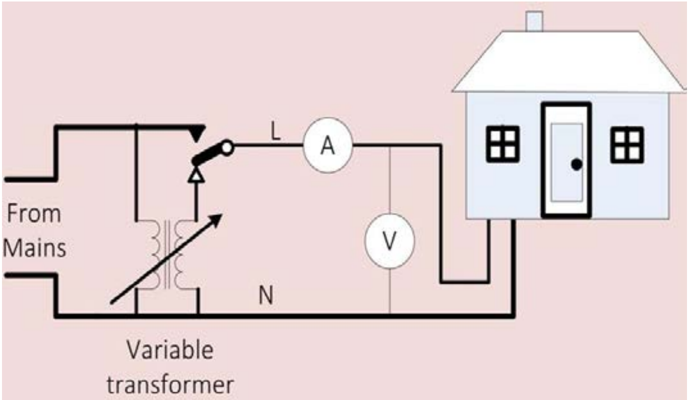

Fig. 3. Test arrangement.

3.2. Energy savings, possible damage to appliances

Fortunately, most Switched Mode Power Supplies (SMPS) units designed for mains voltage shut down above the voltage we are proposing to use. Fluorescent lamps, including Compact Fluorescent (CF) lamps, will not strike at 20-30 V (nor will their starters), so these may be treated as essentially open-circuits at ELV. That just leaves truly resistive loads, where the power is proportional to V^2/R – so reducing the voltage to a tenth reduces the power dissipated to a hundredth.

As it has proved too difficult to measure and aggregate the V-I characteristics of all the individual appliances in a house, we measured the load characteristics at ELV of an entire house containing many electrical appliances (Figures 3,4).

Fig.4 shows the load current for a large house with many appliances turned on (tungsten and compact fluorescent lamps, refrigerator and freezer, and several TV/audio devices and domestic appliances on standby – but no uninterruptible power supplies), when connected to ELV. It will be noted that the current measured is not stable, and fluctuates randomly between the limits shown, over a period of a few seconds. This will need to be repeated for several different types of buildings, to provide a representative sample and a forecast of the energy savings to be achieved. Note that after this experiment, no problems were reported with any appliance or load when full voltage was restored.

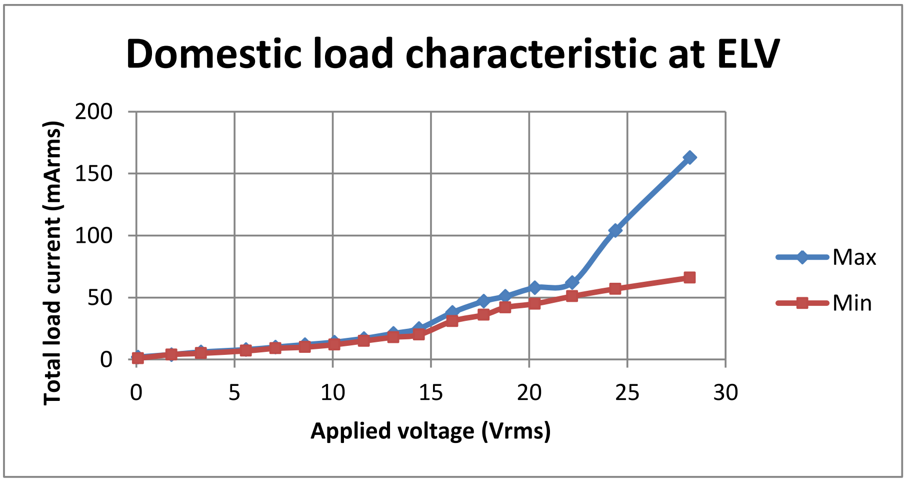

Fig.4. ELV load characteristic of large house with many appliances turned on.

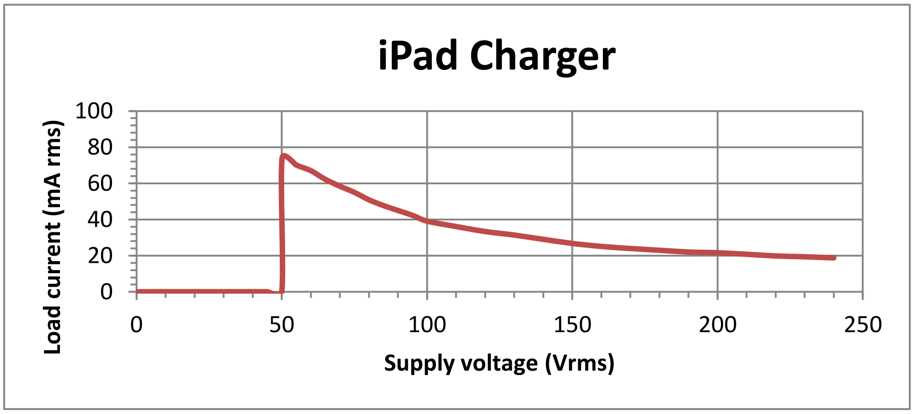

Fig. 5. SMPS Load characteristic (Apple 10W USB Adapter model A1357, rated 100-240 V, output 4.8V 340mA at all inputs over 50 V).

3.3. Grid stability

The question of grid stability arises because an increasing percentage of electrical loads are switched mode power supplies (SMPS) that exhibit a constant-power characteristic with varying input voltage. To keep the power constant as voltage falls, the current they draw from the supply must increase. Typically, increasing the current drawn from the supply further lowers the voltage. Without corrective action (disconnection), this downward spiral can end in 'voltage collapse', where the voltage falls and falls and the current increases and increases, to a point at which SMPSs start to shut down. When they shut down, the current falls to almost zero, allowing the voltage to rise – eventually to a point where the SMPS can start up again. This cycle can take from milliseconds to seconds, and is extremely irritating to users.

A typical SMPS characteristic for a power supply with an input rated 100-240 VAC is shown in Fig.5. This issue becomes more acute as voltage falls, and it is clear from our work that the load characteristic of loads intended for dual-voltage operation will need to be designed with some care.

4. Conclusions

The technology and technical feasibility of a dual-voltage electricity grid has been researched and established, albeit on a limited scale. A number of practical implementation and regulatory issues remain to be resolved, but it is thought that this will best be done by a number of small-scale pilots.

Technical work is being undertaken, in particular (a) to determine the most practical methods for providing ELV to large numbers of properties and to investigate voltage variability issues, (b) to establish and circumvent potential safety hazards inherent in providing ELV over extended periods, and (c) to design cost-effective step-up systems to retrofit to essential services that cannot be modified to run from ELV.

Pilot trials are proposed at three scales:

- Individual houses will be equipped with batteries to provide 24 VDC to lighting circuits during power cuts, to demonstrate the practicality of using the same lamps and wiring at LV and ELV.
- Isolated solar- or wind-based mini-grids will be equipped with transformers to reduce the voltage supplied during times of shortage. Savings on required battery capacity will be demonstrated.
- With the full co-operation of an electricity supply company, a neighbourhood will be connected to 20-30 VAC at times when other neighbourhoods are experiencing power cuts, via tappings on a substation transformer. Energy savings will be demonstrated and measured.

Acknowledgements

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