A NOVEL NATURE-INSPIRED PICOGRID FOR FLEXIBLE PV APPLICATION IN RURAL ELECTRIFICATION SYSTEMS

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Abstract

The Picogrid is a response to the need for electrification in off-grid rural areas in Sub-Saharan Africa. The concept lends itself to the inclusion of renewable energy technologies such as solar photovoltaics and allows for a robust, resilient solution for rural applications. The biomimetic or nature-inspired design allows for uncomplicated scaling of the operational core system. Additionally, the system is fault tolerant and exhibits self-healing properties.

Keywords: Picogrid, Rural Electrification, Biomimetic, Distributed Generation.

1. Introduction

There are vast rural areas un-serviced by electrical utility-grids in Sub-Saharan Africa and its inhabitants have to resort to other means of electricity generation in order to make use of electrical appliances/apparatus. This is usually in the form of liquid-fuelled generator sets etc. Solar photovoltaic (PV) is rapidly growing in popularity due to decreased costs, improved reliability and capability to generate electricity using sunlight. PV technology is therefore a natural fit for the distributed generation required in rural and other off-grid scenarios but limitations such as complexity, lack of flexibility and scalability with existing platforms have inhibited its widespread implementation. The proposed Picogrid concept is a response to the need for off-grid electrification in rural areas and is intended to provide a resilient, reconfigurable, expandable and plug-and-play solution which can suitably exploit Solar PV technology. In addition to these benefits, the open-architecture of this system will not only interest researchers, government departments, and Non-governmental Organisations (NGOs), but also manufacturers in the solar industry sector. This paper is organised as follows. Firstly, the necessity for creating a platform on which sustainable decentralised energy systems can be implemented is discussed. Thereafter, the details of Picogrid concept are presented.

2. Decentralised Renewable Energy Systems

The emergence of renewable energy technologies such as solar PV has brought about a paradigm shift in power generation from centralised to distributed schemes. Grid-connected Decentralised Renewable Energy Systems (DRESs) offer improved reliability and power quality by integrating distributed generation and providing islanding capability. DRESs can also be implemented as stand-alone systems for remote, rural and other specialized applications where no grid connection is available [1]. Hence, there is a growing interest in using these systems as a means to alleviating the electrification deficit in Sub-Saharan Africa.

2.1. Energy Landscape in Sub-Saharan Africa

The vast majority of energy generated and consumed in Africa is concentrated in North African countries and South Africa as shown in Fig. 1.

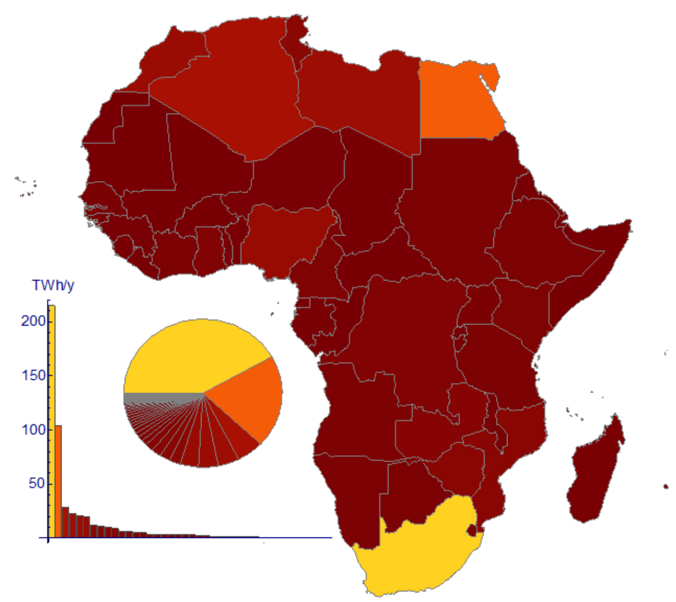

Fig. 1. Electricity usage in Africa (data sourced from [2])

Sub-Saharan Africa is considered to be the epicentre of the global challenge to overcome energy poverty with rural electrification rates at low as 16% [2]. Although this region has immense renewable energy potential, particularly solar energy, as shown in Fig. 2, these resources remain largely untapped. Figure 3 shows the development trend in non-fossil fuel based infrastructure in Africa which does indicate recent growth in solar energy amongst the predominant levels of hydropower dependency. Although many program/initiatives are underway to improve electrification in Sub-Saharan Africa progress is hindered by many challenges particularly with the uptake of DRESs.

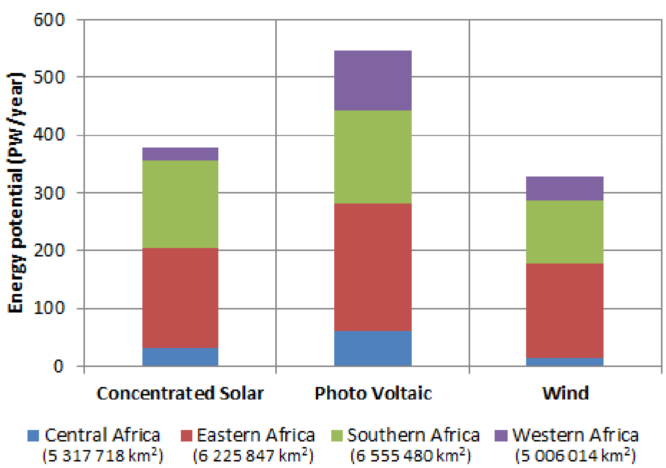

Fig. 2. Total installed renewable power generation capacity in Sub-Saharan Africa from 2000 to 2014 (data sourced from [3])

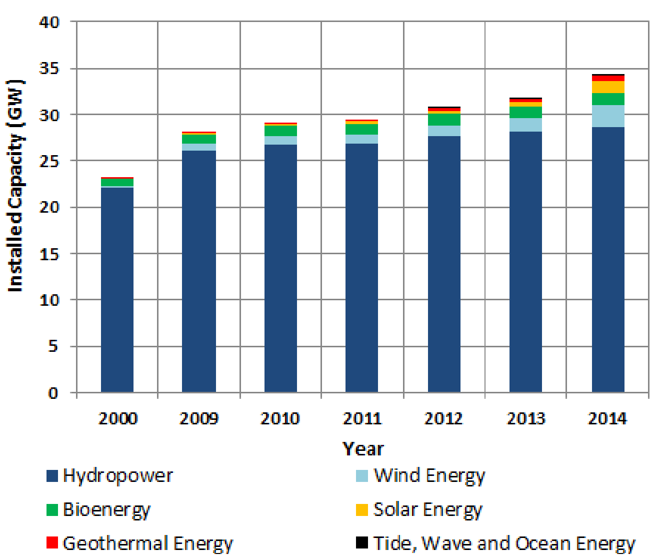

Fig. 3. Total theoretical renewable energy potentials in Sub-Saharan Africa (data sourced from [4]).

2.2. Challenges and Opportunities

The electrification challenge in Sub-Saharan Africa has tremendous social and economic impacts. However, there are some positive aspects that can be taken from the lack of existing energy infrastructure as highlighted in [5]. The power systems in advanced industrial countries are built around the century-old paradigm of large-scale centralised generation and depend primarily on fossil and nuclear sources. Furthermore, these systems are supported by massive technological and regulatory infrastructures. The absence of the regulatory apparatus and existing infrastructures in developing countries offers the possibility of introducing renewable technologies at a fundamental level and the opportunity to lead the way for microgrid technology. An example of this is the mobile telecommunications boom in the absence of older landline systems and accompanying infrastructure.

Figure 4 compares the primary energy usage with the Human Development Index (HDI), with marker sizes representing the CO2 emissions for various developing and developed countries. The energy usage and emissions statistics used here are the most recently available as given by the World Bank's database. HDI is used by the United Nations Development Programme (UNDP) as a measure of the standard of living in a specific country/region. This index is a summary statistic composed of three basic dimensions of human development - i.e. a long and healthy life, access to knowledge and a decent standard of living [6]. It is also a relative statistic that is available for most countries. In Fig. 4, the targeted area is common to all countries - i.e. high sustainability and high standard of living, but the challenges facing each country in achieving this target differ significantly. For developed countries, the aforementioned pre-existing infrastructure must be replaced with sustainable alternatives without compromising living standards or HDI. The challenge for developing countries is to ensure that new infrastructure for improving the standard of living is sustainable.

DRESs offer developing countries of Sub-Saharan Africa the potential opportunity to follow a vertical trajectory (with respect to Fig. 4) without having to introduce large-scale fossil-fuel based infrastructure – i.e. a potential ‘fast-track route’ to the target. The presented Picogrid concept was developed considering these aforementioned challenges and the need for a decentralised solution which best exploits the renewable energy potential of Sub-Saharan Africa.

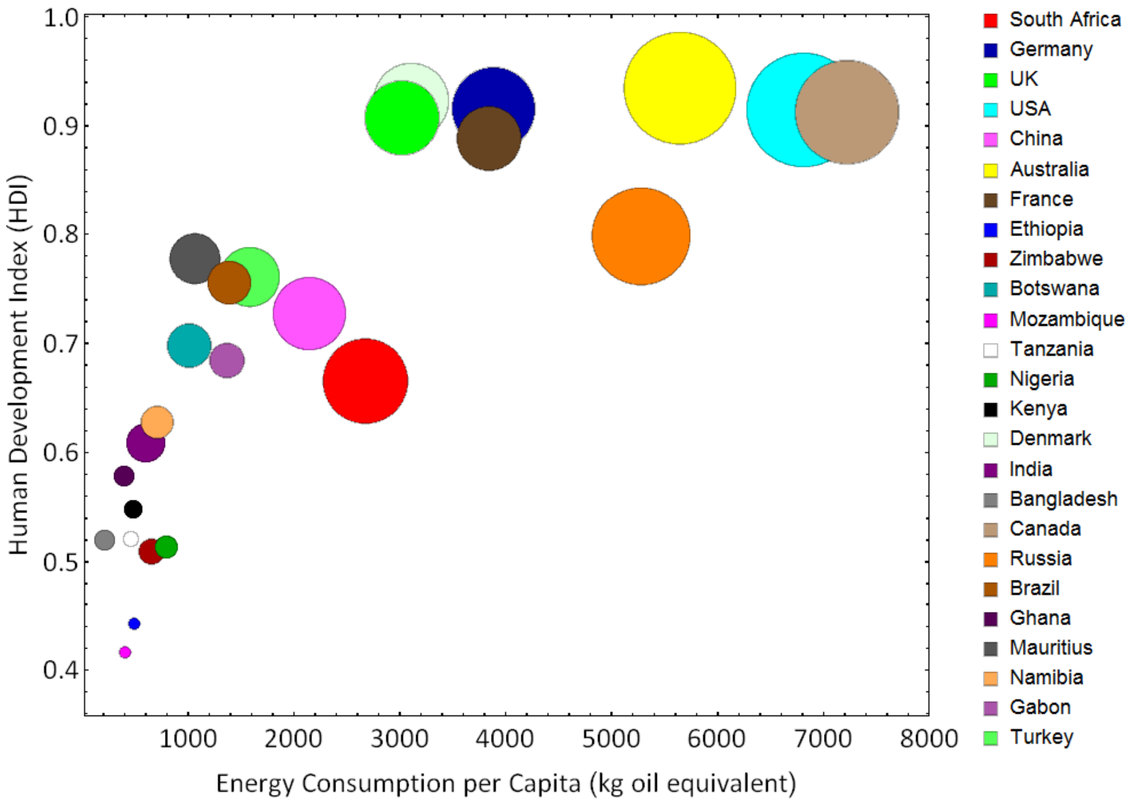

Fig. 4. Human Development Index, energy use per capita and CO2 emissions of selected developed and developing countries.

3. Picogrid

Plug-and-play, low-cost and flexible are features that have been long since desired for solar power systems [7]. Advancements in power converter technologies [8, 9], DC bus signalling and flexible storage strategies [10, 11] are paving the way for realising these features and accelerated uptake of DRESs. The Picogrid is an endeavor to build on these concepts and capitalise on the latest technological advances power electronics and renewable energy technologies like PV in order to provide flexible rural electrification systems.

3.1. Architecture

The proposed picogrid allows for the flexible arrangement of appliances as load nodes. This eliminates the constraints imposed on the end-user by typical solar home systems available today. This flexibility also allows for the evolution of operational solutions on-site and the freedom to address the voltage-drop problem that exists in any purely radial electricity distribution system. The freedom to deploy additional sources at different points on the Picogrid can also mitigate voltage-drop problems. The cornerstone for the flexible topology is the availability of three grid-connection ports on each node module of the Picogrid. Figure 5 illustrates this concept, where one line represents both the positive and negative conductor (DC system) required for making the connection. This approach allows for more intricate topologies of almost any configuration to be constructed when a large number of nodes - each with three ports - are connected together. The flexible architecture of the Picogrid is also attributed to its scalability and plug-and-play features. Figure 6 shows a solar source or PV node interface to the Picogrid. The addition of new nodes to grow and extend the system should be a straightforward procedure for the end-user. Ideally, there should be no upper limit on the growth or extension of the grid. Overloading should be dealt with transparently to assist the user in arriving at a workable system, even if by trial and error. Basic errors like short-circuits and overloading can be dealt with in an elegant and transparent fashion. This is important as the end-user is not intended to have formal training. A light form of user interaction can be expected based on error indications. Safety of people, animals and equipment are a priority and therefore any operational mistake or error should at most lead to a safe shutdown of the system. For example, an over-current fault should not lead to a fire hazard but rather a blown fuse or preferably a safe and elegant shutdown of the system. A low DC voltage (eg. 12V) can work well in this regard.

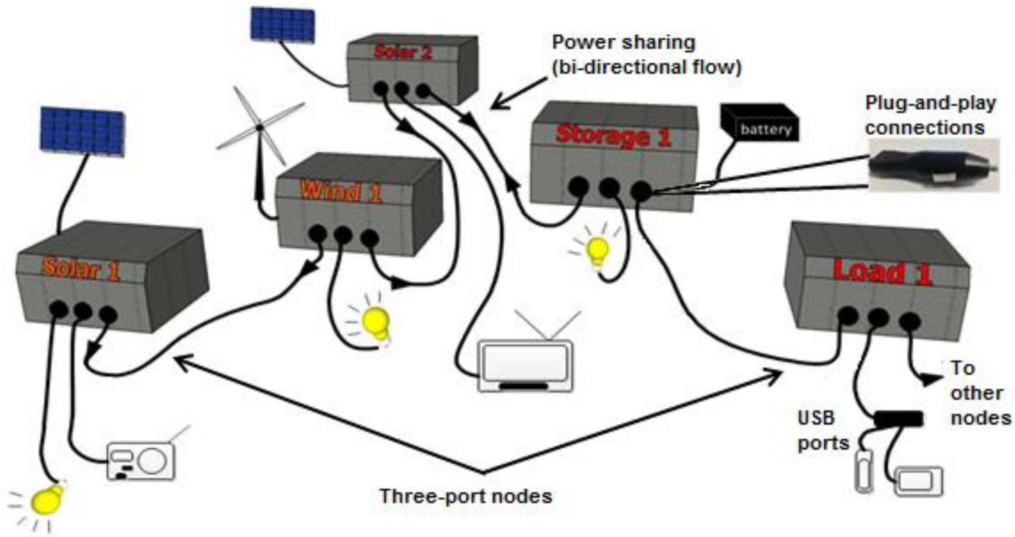

Fig. 5. Picogrid with three-port node connections for flexible configuration

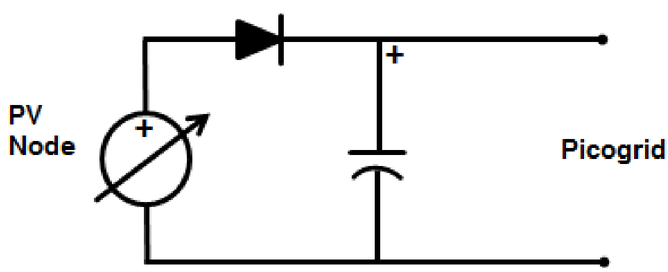

Fig. 6. Picogrid interface for solar source node

Besides having inherent compliance with modern electronic loads, renewable energy sources and storage devices, the DC system is attractive because it avoids the complexities of AC systems such as synchronisation and reactive power flow. The envisaged rural application is without ongoing high-level technical support and the Picogrid therefore exhibits high resilience. The abilities to self-configure and to self-heal when certain errors/faults are present will be extremely valuable in successful deployment. For example, faulty nodes will be automatically disconnected and the health of the system (and node) will be automatically checked after a severe fault in order to restore normal operation. Once the basic elements - i.e. a single a source, load and store - have been plugged in the system should commission and operate by itself. Thereafter, extending the system with additional loads, sources or storage is completely transparent to the user.

3.2. Intelligent Nodes

Biomimetics deals with the study and imitation of nature's designs, methods and processes, and is becoming increasingly involved with emerging subjects of science and engineering [12]. An example is the use of social systems in nature for the development of distributed artificial intelligence. Social insect colonies - although comprising very simple individual organisms with limited capabilities - can perform highly complex tasks with a high degree of flexibility and robustness in a dynamic environment.

The intelligent nodes on the autonomous Picogrid takes inspiration from a class of self-organising behaviour in social insects called stigmergy [13]. Each node performs its assigned task in collaboration with other nodes to fulfil the overall goals of the picogrid. In this way, collective activity is coordinated by each node's response to and modification of its local environment as opposed to instructions from a central controller.

This stigmergic agent-based approach offers the following benefits:

- More simple agents are used instead of a single complex agent which decreases the overall complexity of the Picogrid system.
- The reliance on a single controlling entity is eliminated thereby decreasing the likelihood of catastrophic failure.
- The internal state of each agent does not need to be directly known by another agent, or by a single controlling agent, thus eliminating the need for related infrastructure.
- System-level outcomes may be achieved through sub-system tasks which improves modularity, flexibility and robustness.

- The use of bounded agents (intelligent nodes) in a potentially unbounded environment (Picogrid) supports scalability.

The Picogrid concept is therefore based on intelligent energy processing nodes and passive or intelligent load nodes interconnected to form an electrical energy distribution grid. The Picogrid requires at least one node (either a source or a storage node) in order to kick-start the grid. The nodes can be connected in any configuration and are able to indirectly coordinate with one another based on the voltage level of the Picogrid. A user simply has to plug the different nodes together and add loads. Any node added to the grid will self-initialise in a stigmergic manner by first checking the grid voltage and then suitably responding with respect to existing nodes on the grid.

3.3. Protocol

The core of the Picogrid operation is the behavioural protocol obeyed by all the nodes on the grid. The protocol is simple and the goal is to ensure that the grid reaches and maintains stability. This will ensure the maximum level of supply integrity. Some level of fluctuation on the system is permitted, DC-bus voltage variation in this case, to allow for the various nodes to monitor events on the Picogrid [14]. Essentially, all intelligent nodes operating on the Picogrid will endeavour to stabilise the voltage. Hence, source nodes will adjust their supply current into the grid to ensure voltage stability and storage nodes will also do the same by charging and discharging. Intelligent load nodes will add and shed loads according to prescribed priority levels to stabilise the grid. This mirrors the operation of any large utility grid. The goal here is to implement this as a form of cooperative control through distributed decision making rather than relying on a centralised controller.

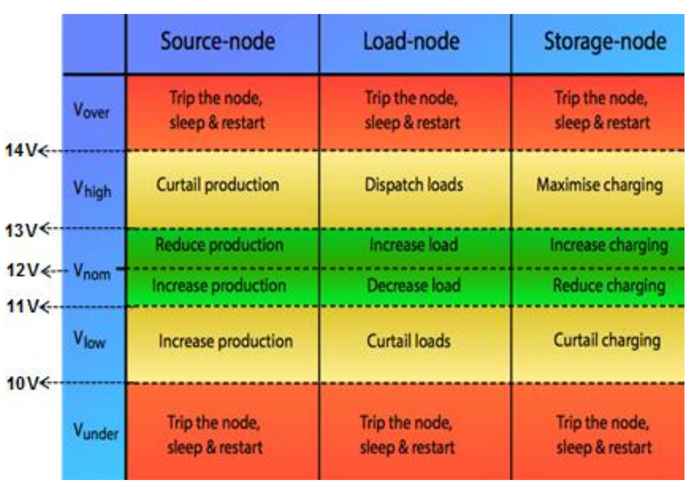

Fig. 7. Picogrid protocol showing different actions taken by the nodes according to grid conditions

Figure 7 shows the different actions taken by each node that connects to the Picogrid. There are five different states based on the voltage level of the Picogrid; V_{over}, V_{high}, V_{nom}, V_{low}, V_{under}. The Picogrid operation revolves around the green zone shown in figure 7. This is the stable region with a nominal voltage of 12V. Each node's action is thus aimed at keeping the Picogrid in the green zone. The first step for every node that connects to the grid is to check the current state of the Picogrid and then take the necessary action. Changes in climatic conditions will affect the state of the grid due the use of renewable sources. For instance, a very sunny or windy day (if micro wind turbine utilised) will increase the power generated by a solar or wind node respectively. This will tend to push the state of the grid towards the V_{high} or V_{over} regions shown in figure 7.

The embedded intelligence of a source node enables it to respond accordingly - i.e. either increase or decrease its power generation - depending on the state of the Picogrid. A storage node will charge the battery when the Picogrid is in V_{high} or V_{over} states. The node will then sleep (or trip if necessary) and restart only if the battery is full and the Picogrid is still in the V_{over} state. A load node will initiate load shedding when there is not enough power on the Picogrid such that it falls in the V_{low} and V_{under} states. The reverse of this process occurs when there is excess power on the Picogrid.

4. Future Work

The proposed Picogrid concept has been validated on an experimental 12V DC system at Wits University over the past two years (2014 - 2015). Ongoing research and development can bring exactly the same benefits to 48V systems, which can provide higher power, and eventually extend this concept to even higher voltage and power in both DC and AC forms.

5. Conclusion

The Picogrid concept presented in this paper allows for low power, modular, extensible electricity supply, based on renewable energy sources. Its open architecture allows for multiple manufacturers or vendors to supply a variety of different equipment that will safely interact to form a larger electricity distribution system, provided the equipment conforms to the Picogrid standard as discussed here.

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