Smart Microgrids for Rural Electrification

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***Abstract*— The energy poverty gap in South Africa affects approximately 1.63 million mainly rural households who do not have access to electricity. Energy poverty is particularly prevalent in deep rural areas that are far from the main grid and are too costly to electrify by MV grid extension. Microgrids are emerging as an effective off grid solution that can close the energy poverty gap and can supplement existing electrification programs. Further research and development is required to ensure that these systems can be effectively applied for rural electrification and can operate autonomously within specified limits whilst maintaining supply and demand. This paper outlines the fundamentals of an Eskom RT&D pilot site for the testing and development of 'smart' off grid solutions that can be used to support the current electrification program in South Africa and assist in reducing the energy poverty gap.**

I. Introduction

There are approximately 1.63 million South African households, 9.7% of the population, who do not have access to electricity [1]. (Stats SA, 2016). There are approximately 1.63 million South African households, 9.7% of the population, who do not have access to electricity. The 2008 White Paper on Energy Policy described the universal access to electricity for all South Africans as a cornerstone for development and social upliftment of all communities. The access to clean energy for all communities, albeit basic, remains a challenge for the majority of the developing world. The absence of energy services, which is the 'lifeblood of economic and social development', and the lack of basic services often leads to social unrest and despair [2]. In Sub-Saharan Africa, only 290 million of the 915 million inhabitants (31%) have access to electricity and the numbers without access are increasing rather than decreasing due to the fact that increasing population numbers outpace electrification programs [3]. The benefits of providing electricity to communities include poverty eradication, social upliftment, early childhood development, education and positively impacting the literacy levels of these societies.

In South Africa, there have been a significant number of households that have been electrified by the state owned utility company Eskom, as well as several municipalities, since 1994, which had culminated to the current electrification rate of close to 90% of the population [4]. There are, however, several challenges preventing the electrification of the remainder of mainly deep rural parts of the country. Amongst these challenges are the high cost of grid extension of the Medium Voltage (MV) network to remote areas, the low income levels of these communities, low density of rural populations and hard terrestrial conditions [5]. The current cost of grid extension exceeds an estimated $13000/km (approximately R200 000/km) and the breakeven point for grid extension compared to off grid systems is less than 35km [6]. The majority of deep rural communities, however, are located in excess of 35km from the main grid. This makes grid extension more uneconomical and slows down electrification to the remainder of the population.

The challenges regarding grid extension to deep rural areas imply that the energy needs of all poor households have still not been met in South Africa and the original target of universal access to energy for all its people is now expected to be achieved only in 2030 [7] In the absence of alternative means to close the nergy poverty gap to grid extension, some 1.63 million South African households will continue to be disadvantaged in terms of access to electricity. In Sub-Saharan Africa, the energy poverty issue affects a staggering 625 million households. The benefits that electricity brings to social upliftment and poverty eradication is far reaching and includes social upliftment, literacy, commercialization, sustainable farming and even gender equity.

In order to identify solutions to solve the energy poverty conundrum, various studies have found that alternative, off grid energy systems could be used to address the problem particularly for developing countries [8],[9].

Off grid energy systems, in the form of Microgrids (MG) can be firmly established as the preferred solution for deep rural electrification and to supplement or even replace traditional grid extension. These are electricity networks that are cited as the next evolution in power systems [10]. distribution networks containing distributed energy resources (distributed generators and energy storage devices) and controllable loads that can be operated in a controlled way either connected to the power network or in islanded mode” (Cigre C6.22).

As can be seen from Figure 1 below, the typical MG consists of 3 parts. Firstly, the power generation is derived from Distributed Generation (DG) sources such as Solar Photovoltaic (PV), wind or micro-hydro. In a hybrid MG configuration backup generation can also be from non-renewable sources such as diesel generators. The second part of the MG systems is the energy storage (ES) component, control systems, chargers and controllers. ES is typically from traditional storage technologies such as batteries but newer albeit more expensive technologies such as flywheels and super-capacitors are also emerging within the smart grid context. The third part of the MG system is the load network which is made up of the various consumer appliances. The power consumption is then provided for either directly by the DG sources or from the energy storage. The main advantage of a MG is that this self-contained power network can be built close to the load that it is intended to serve thereby overcoming the need to extend costly MV lines. This also reduces the line losses as the generation source is close to the load.

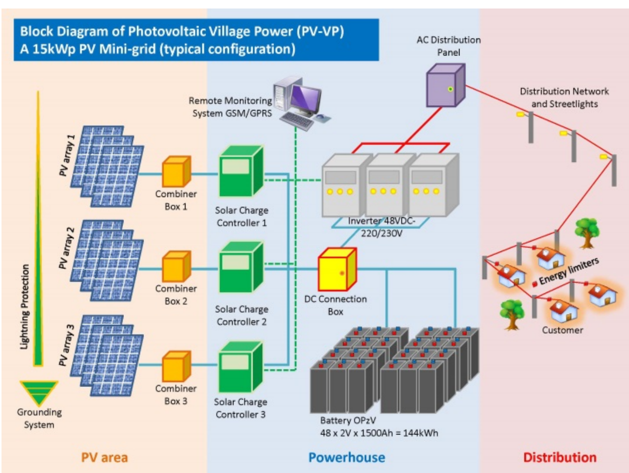

Figure 1 : Typical MG configuration (source: energypedia)

II. SMART MICROGRID PILOT

A Smart MG pilot project was designed and developed taking the fundamental components into account. In order to locate a suitable site to implement the pilot, specific selection criteria were used:

- A rural community with a suitable number of households
- A site that was reasonable distance from the RT&D office
- Community within Living Standard Measure (LSM) 1-3

Using these criteria, a rural farmworker community located in Ficksburg in the Free State was chosen for the pilot site. The community consisted of 14 households and fell within the LSM 1-3 group. The initial pre-concept phase involved discussions with the community to explain the nature of the pilot program, discuss the initial energy requirements and obtain permission to allow RT&D full access to the site over the duration of the pilot. Thereafter a weather station was installed in order to collect solar irradiation, wind speed and temperature data. The data was analysed to determine the most appropriate distributed energy resources to be used. In this case the average solar irradiance for the site was >500W/m^2, and the average wind speed was <2m/s. Since the average wind speed was below the general cut in wind speed for wind turbines and the solar irradiance was sufficiently high, solar PV was selected as the primary distributed energy resource.

A. Load requirements

The selected community had pre-existing low pressure solar geysers for supplying hot water. Cooking was also done using simple two plate gas cookers using LPG gas bottles. Hence the only load that needed to be served was refrigeration, lighting, cell phone charging and entertainment.

Table 1: Load requirements

Appliance	Load (kW) for 14 houses	Usage period (hours)	Energy (kWh/day)
Refrigerator	0.4	12	4.87
Led Lights	0.14	12	1.68
Street Lights	0.4	12	4.80
Entertainment	2.8	12	33.6
		Total kWh/day	40.08
		Total kW/day/per house	2.91

B. Solar Requirements

The PV plant has been specified according to the energy storage system.

Table 2: Solar and Energy Storage

Characteristic	Unit
Peak charging time (T)	6h
Storage Capacity ($S_{capacity}$)	90kWh

- Energy Storage Input Requirements:

$$Storage_{Input} = \frac{S_{Capacity}}{T} = \frac{90000}{6} = \underline{15kW}$$

- Inverter Output Requirements:

The Energy Storage (ES) system needs a minimum of 15kW input to charge the 90kWh in 6 hours. During the charging period the community also requires power at 1kWp per house for a total simultaneous maximum demand of total 14kW. One (1) kW is allocated for auxiliaries and losses. The total inverter output requirements are therefore estimated to be 30kW. The total inverters are depend on the size of the individual inverters available, therefore three 10kW inverters were chosen based on and configured in 3 bays.

$$\begin{aligned} Total_{Inveters} &= \frac{PV_{Capacity}}{Inverter_{Capacity}} \\ &= \frac{30}{10} \\ &= \underline{3} \end{aligned}$$

C. Energy Storage (ES)

The ES system is also configured in banks or bays. Each bank been made up of 10kWh capacity units capable of supplying 5kWp each.

The total ES capacity is therefore:

$$\begin{aligned} S_{ES} &= Banks \times Capacity\ per\ Bank \\ &= 3 \times 30\ kWh \\ &= \underline{90 kWh} \end{aligned}$$

50kWh per day will be allocated to the community and auxiliaries, 40kWh capacity will be reserved for autonomy. This enables the community to consume 2.85kWh per house per day which is sufficient for the running the appliances as listed in Table 2 above.

D. Backup Generation

A MG system operating as an off grid system is not able to provide unlimited power to serve the load it is connected to. In the case of a hybrid MG system consisting of DG resources such as solar PV or wind generation and ES, the power that can be generated is limited to the material/size of the PV panels or the wind turbine design. Moreover, the ES is limited by the size of the battery bank. A further complication is the intermittency of the DG sources. Useful 'sun-hours' is typically 5-6 hours for PV generation and wind speeds of > 6m/s may only be available for 50% of the day. On the other hand excessive wind speeds in some areas may have an adverse effect on power quality. This varies from location to location. In order to manage the intermittency of the DG sources and allow the MG to operate continuously, diesel generators are used to provide for backup power. However, a more feasible and cost effective approach is to manage the customer load rather than manage the supply. By reducing the customer load during low or intermittent DG output or low ES storage levels, the system is able to maintain the security of supply with minimal reliance on backup power sources such as diesel generators.

To ensure continuity of supply and further the research, diesel generation were include providing backup supply during high intermittency periods. This will however vary from location to location for future sites.

A diesel generator shall only operate under critical circumstances, charging the storage system and supplying the community under load limit conditions.

The minimum backup supply capacity:

$$\begin{aligned} Backup_{Capacity} &= \frac{Load_{Community} + S_{Capacity}}{T_{Charging}} \\ &= \frac{(3 \times 14) + 90}{6} \\ &= \underline{22kW} \end{aligned}$$

E. Load control

A load management strategy will be utilised for managing the supply-demand balance in a constrained MG system. This approach segments the customer load into essential and non-essential loads. This is physically hardwired at the customer's distribution board. Essential loads include lighting, refrigeration and entertainment (200W per house). This approach for load control in a rural community enables the load to be managed thereby lowering the capital and operational cost effective and can be an essential component of a smart MG. In order to implement load management, appliance control devices with intelligent control will be implemented. This will ensure that during times of intermittent DG output and low ES storage levels, the community load is managed to avoid system collapse.

F. Levelised cost of Energy (LCOE)

LCOE is an important benchmark for any power system and is used to compare the average production costs of various generation sources across the project lifecycle. LCOE is regarded as a valid comparison method by international agencies. LCOE takes into account factors such as capital costs, operating costs, financing costs as well as the duty cycle of the plant. These have a bearing on how a utility may perceive the sustainability of a MG and the investment in this new technology. The LCOE of a MG within the local environment is not fully understood nor has a benchmark figure been established. [10] ranks the LCOE of 13 generation technologies ranging from traditional generation such as nuclear and coal to renewable sources such as hydro and solar. The study shows that hydro and PV as having the highest financial sustainability. This may be due to the lower investment costs, low operating costs, high response time and other factors. The study, however, does not include the benchmark value of the LCOE of a typical MG system (determining the benchmark value for a typical rural MG system provides for a comparison to the LCOE of grid extension fed from traditional centralized generation sources for example). This may primarily due to the fact that the MG concept is a relatively new form of DG; therefore little or no historical data exists in the preliminary literature which indicates a need for further research in this area.

G. Optimisation

This project will seek to provide a feasible solution to Eskom for the mass roll out of large-scale MG electrification technologies. Furthermore, this approach will provide a view on the future impact that small scale renewable technologies may have on the future business model of Eskom including identifying the opportunities for the strategy in this regard.

The proposed pilot project will allow for a better understanding of the economic, technical and social aspects off-grid systems. This pilot project will also allow for the study relating to the optimisation of all the key objectives relating to Microgrid deployment. The single optimisation objectives are the cost optimisation (LCOE), high technical reliability (system availability) and social acceptance by the community (availability and quality of supply). However the optimisation may be a multi-objective where all the objectives need to be satisfied simultaneously.

Safety and operations are key issues that need to be researched thoroughly before Eskom embarks on mass roll out of MG technologies. In addition there is a need for the development of proper system and network infrastructure guidelines for MGs, including proper procedural, operations and maintenance plans. A MG or DG source may pose a high safety risk for the field services technical staff unless operating and maintenance procedures are adapted to provide for safe operations. Part of this research will be to assist in developing safe work and operating procedures for MG's.

III. METHODOLOGY

The MG pilot site will be utilized as a test-bed for extensive testing of the system in terms of technical functionality, system availability and the reliability of the various technologies and applications used. Smart control and load management as well as the customer interaction with the system will also be tested and monitored. This MG pilot system has several measurement and technical data collection points. These points will provide voltage, current, frequency, harmonics, power factor, and active and reactive energy profile data to be measured and analyzed over the duration of the pilot. Various load limits may be tested together with the ability to test various tariffs and pricing schemes. The system configuration can also be adjusted remotely by switching in PV, inverter and storage banks in order to determine the optimal configuration as conditions fluctuate. The modularity and flexibility of this pilot system will allow for this testing to be done.

Figure 2 provides a high level schematic of the MG and embedded measurements per device.

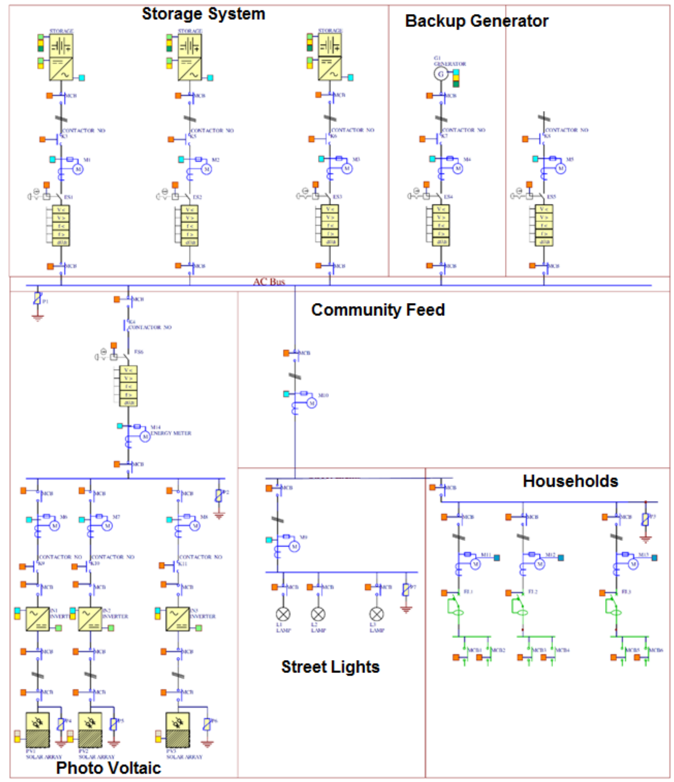

Figure 2 - Microgrid System

Figure 3 provides detail on the measurements taken by the smart controller as indicated by the color blocks in figure 2.

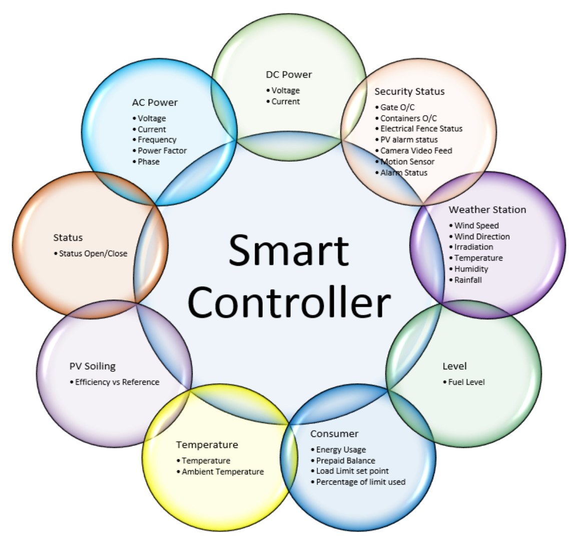

Figure 3 – Smart Controller Data Measurements

IV. CONCLUSION

The MG pilot developed under RT&D will allow for the further development of cost effective, technically reliable and socially acceptable off grid energy solutions. The pilot was initiated with due consideration of the community energy needs. This was done by extensive engagements and discussions. Thereafter the system was designed with the load requirements in mind as well as the need for further technical testing and development. So this pilot will provide answers to a number of concerns regarding the feasibility of MG's for off grid electrification. The study will only be completed fully once the system is operational for a suitable period of time. Factors such as seasonal variation (summer/winter), community load changes and growth in consumption will be the variables that need to be considered within the test cases.

REFERENCES

[1] Stats SA 2016. Statistics South Africa.

[2] Thompson, G. 2014. Democratization, Energy Poverty, and the Pursuit of Symmetry. Global Policy,. DOI: 10.1111/1758-5899.12103.

[3] EIA 2014. Annual Energy Outlook. Sourced online https://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf

[4] Bekker, B._, Eberhard, A., Gaunt, T. & Marquard, A. 2008. South Africa's rapid electrification programme: Policy, institutional, planning, financing and technical innovations. Energy Policy 36. Elsevier. doi:10.1016/j.enpol.2008.04.014.

[5] Department of Minerals and Energy (DME). 2008. Mini-grid hybrid viability and replication potential, The Hluleka and Lucingweni pilot projects, Final report, August 2008. Accessed 05 March 2014. Available at http://nano.co.za/MinigridReplicationViabilityFinalReportAug08.pdf.

[6] O. M. Longe, K. Ouahada, H. C. Ferreira & S. Chinnappen. 2014. Renewable Energy Sources Microgrid Design for Rural Area in South Africa. University of Johannesburg.

[7] Eskom Integrated Annual report 2016. Eskom Holdings (Pty) Ltd. Source www.eskom.co.za.

[8] Suberu, M.Y, Bashir, N, Adefemi O.M & Usman, U. 2013. Renewable energy distributed electricty generation and microgrid implementation in rural villages: a review. Arpn Journal of Engineering and Applied Sciences. VOL 6 (2).

[9] Azura, O. , Arranbide, I. & Zubia I. 2012. Rural Electrification based on renewable energies. A Review. International Conference on Renewable Energies and Power Quality.

[10] Maxim, A. 2014. Sustainability assessment of electricity generation technologies using weighted multi-criteria decision. *Energy Policy*