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# A Novel Energy Management Technique for Shared Solar and Storage Resources in Remote Communities

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***Abstract*— World over, the cost of PV equipment continues to decrease. Coupled with their quick time to install and the advancement of renewables in the face of climate change; they are fast becoming an appealing solution for remote communities that still have no access to national grids. In this paper, we study management of the state of charge (SOC) of batteries in an off-grid situation where multiple prosumer installations in different areas are interconnected to a shared distribution line. Each distinct installation consists of Photovoltaic power generation (PV), Storage batteries (BT), converters, their connection line DC power bus, and AC loads connected via an inverter, all modeled MATLAB / Simulink Simscape Power Systems. We develop a tool for improving BT utilization, monitoring, and managing energy consumption while maintaining the voltage at acceptable levels. Considering Uganda as an example, our research suggests a solution for electrifying remote communities by installing shared solar and storage units.**

***Index Terms*-- Battery Management Systems, Energy Management, Microgrids, Photovoltaic Power Systems, Remote communities, Storage Battery.**

## I. INTRODUCTION

Africa is turning to solar photovoltaics (PV) to enhance energy security because they offer a rapid cost-effective way to connect the approximately 600 million Africans who lack electricity access. Mini-grids operating solar PV and off-grid solar home systems also provide higher quality energy services at the same or lower costs than the alternatives.[1]

Adadevoh and Anderson et al in [2], [3] make a case for the viability of shared solar as a solution for energy supply in remote communities by exploring various installed shared solar examples in different locations around the world. However, they do also conclude that there are gaps in legislation that are major challenges to the shared solar solution.

In Uganda, to increase electricity access for the rural population from 7% in 2013 to 51% in 2030, the government launched a Rural Electrification Strategy and Plan (RESP) with support from the private sector and international partners like the World Bank. In this plan, they sanctioned off-grid electrification services comprising energy service technologies not dependent on the national grid. Private sector inclusion was in attendance to the financial risk associated with the cost of extending the infrastructure to areas where people are poor and industrial development hasn't taken place.[4] Fig. 1 shows the electricity operational distribution lines in Uganda showing largely uncovered remote areas of the country.[5]

The sun is an abundantly available resource in most parts of Africa, given its geographical location. This indicates a very big solar power generation potential. Also, through selling shares to the local community and partnership with the private sector, Kilembe Investments Limited, a RESP project in Uganda displays the potential of internal funding as provided for in RESP to build private distribution and transmission networks.[6]

Raja et al and Najafi et al in [7], [8] discuss the need for a standard distribution system model that can provide a unified framework to investigate power and load sharing among microgrids. They proceed to propose models not specific to the management of battery SOC but rather multiple variant generations and consider only the minimum and maximum BT SOCs like most of the reviewed research publications. In[9], [10], the authors propose and analyze various microgrid models in view of optimum interconnection modes.

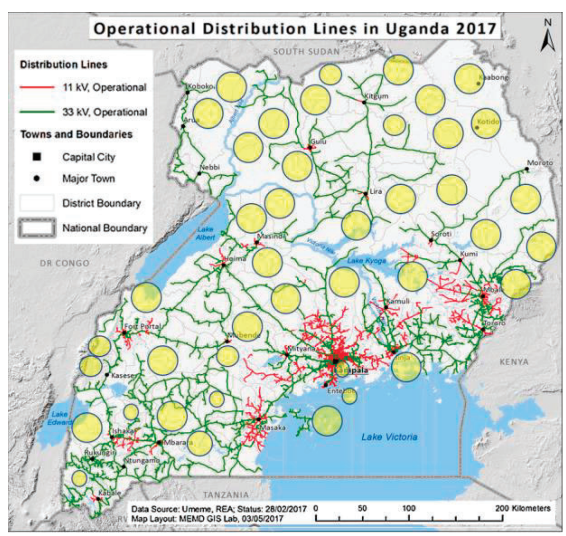


Fig 1. Operational Distribution Lines in Uganda. *(Areas marked in circles have no grid access)*

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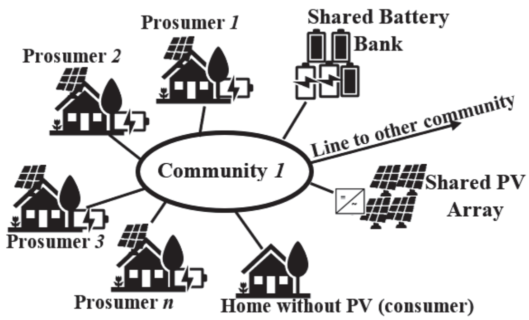


Fig 2. Proposed Community Mini-grid Layout

Lead-acid batteries used in the experiment are convenient because of low cost and are versatile but could decline in performance without proper management. Most notable among other issues is the depth of discharge damage that could result if batteries discharge or charge to extremes. [11]

In this paper, we propose and simulate shared solar and storage systems between communities as a viable solution to extending electricity in remote communities. We also develop a tool that uses a distributed control method, monitors and control power interchange, voltages, current, and battery SOC, maintaining uptime of all customers in the system without the need for a grid connection.

## II. Proposed Solution Layout

Fig. 2 shows our proposed solution for the remote areas in Uganda. We propose a mini-grid where various prosumers (microgrids) are interconnected per community. Prosumers (with PVs and BTs) are connected to a shared line within the mini-grid with two-way energy flow. Consumers (without PV generation) can also connect to the shared line as paying clients.

Community battery banks (serving as power sinks in cases of excessive generation and as communal energy storage) and PV Generation array installations that will support energy generation in the community microgrid can be connected. Each Community mini-grid is proposed to be capable of interconnection with other communities' Mini-grids within an acceptable transmission distance range considering line losses.

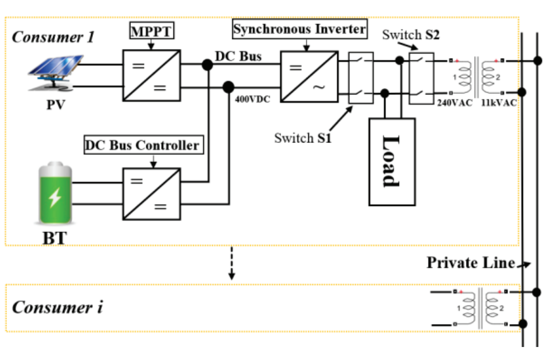


Fig 3. Individual Prosumer Installation Layout

This interconnection results in a cluster of interconnected Minigrids where areas that receive more sun in a day and achieve higher generation capacity or those with low energy consumption can support those with insufficient generations. Hence prosumers can benefit from shared resources and potentially earn from power interchange. The distributed method of control is currently proposed for microgrid voltage and BT SOC management.

However, distributed control can pose monitoring and control challenges for instance when there are failures on the network. Centralized systems too come with challenges such as a single point of failure, inflexibility, and high cost of communication as described in [12], [13]. Therefore, in the future, we plan to build a hybrid control system tool that will exploit the advantages of both control methods. It will include distributed control for community microgrids and central control per cluster. The tool will also serve as an energy management monitoring tool to support the operation of the clustered interconnected microgrids in maintenance, tariff management, and accounting for interchanged power for the business end.

In this paper, we focus on distributed control by developing a tool that monitors interchange power, performs voltage, and current control while managing the battery SOC within each distinct prosumer installation.

## III. System Operation Strategy for the Microgrid

### A. *Voltage Control in Prosumer Installation Design*

Individual prosumer installation design is as shown in Fig. 3. Each installation contains various components described that participate in the stability of the system through voltage and frequency control as well as management of the BT's SOC.

#### 1) *PV system*

It comprises PV, unidirectional DC/DC converter, and MPPT Controller. With solar radiation and air temperature as inputs, the PV panel obtains a current-voltage (I-V) characteristic curve. Based on this curve, maximum power point tracking (MPPT) control by the incremental conductance method is implemented within the unidirectional DC / DC converter, delivering a DC voltage to the DC bus.

#### 2) *Battery system*

The BT system consists of BT and a bidirectional DC/DC converter. BT adopts a simple model comprising a voltage source and internal impedance. The DC bus voltage stabilization control block shown in Fig. 4. is implemented by a bidirectional DC/DC converter. The DC bus voltage is maintained at the reference value $V_{ref}$ 400[VDC].

Proportional Integrator (PI) control is implemented on the difference between $V_{ref}$ and the measured value $V_{bus}$; and the output is set as the BT current reference value $I_{ref}$. Thereafter, PI control is also performed on the difference between $I_{ref}$ and measured value $I_{BT}$. Finally, the duty ratio $d$ is calculated that is used to control converter switching.

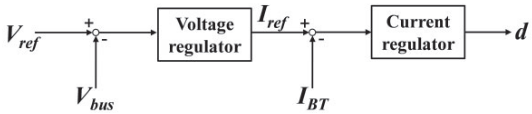


Fig 4. DC Voltage and Current PI Controller

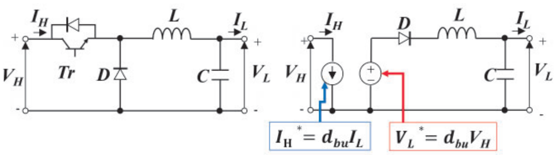


Fig 5. DC/DC Buck Converter Circuit model

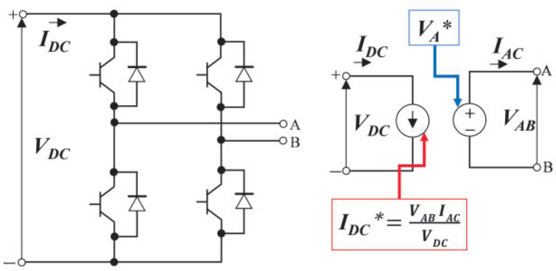


Fig 6. DC/AC Inverter Circuit Model

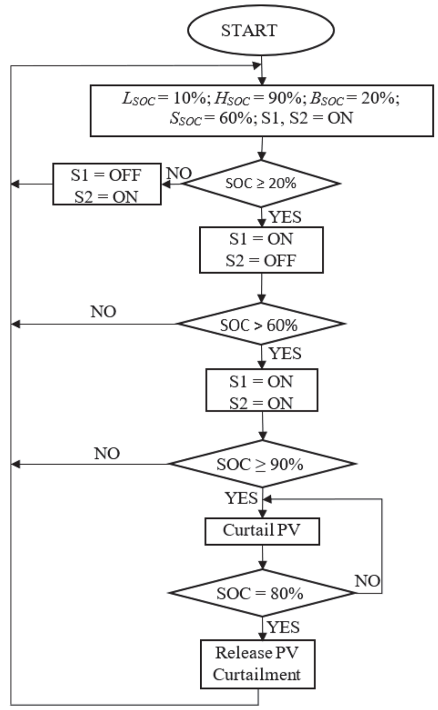


Fig 7. SOC Mangement Flow Chart

*3) Multifunctional Power conditioner (PCS)*

It includes DC/DC Buck converter connected from the DC bus, DC/AC inverter, Synchronous controller, and a single-phase load.

We adopt the inverter discussed in [14] capable autonomous control for advanced inverters that cooperate with EMS and provide synchronization power using PV prediction. As in the step-down DC/DC converter shown in Fig. 5, the input was represented as a current source and the output is represented as a voltage source. The duty ratio $d_{bu}$ shown in Fig. 5 was used. The reference value $V_{Lref}$ of the low-voltage side is PI controlled with respect to its difference with the measured value $V_L$, and the output is set as the low-voltage side current reference value $I_{Lref}$. Thereafter, PI control is performed on the difference between $I_{Lref}$ and the measured value $I_L$. Finally, the duty ratio $d_{bu}$ is calculated.

In the single-phase inverter model (Fig. 6), $V_{DC}$ and $I_{DC}$ are voltage and current on the DC side, and $V_{AB}$ (240VAC in our example) is a single-phase line voltage. $V_A$ gives the assumed single-phase AC voltage, phase, and frequency. $I_{AC}$ is the current flowing through each phase. Current $I_{DC}$* which is the equivalent of the input current is obtained from the quotient of the output power of the single-phase inverter and the DC voltage $V_{DC}$ of the input side. Input voltage $V_A$* input generates the AC waveform.

## *B. SOC Monitoring and Control strategy*

Switches S1 and S2 toggle ON (1) and OFF (0) depending on the preset SOC limit values and measured battery SOC according to the algorithm in the flow chart in Fig. 7. By introducing S2, we can control power interchange for each distinct prosumer.

Foremost, the SOC lower ($L_{SOC}$) and upper limits ($H_{SOC}$) of 10% and 90% are assumed but in practice, it is recommended to compare with battery manufacturer specifications. This protects from complete battery discharge or overcharging that has a negative effect on battery life.

Next, the $B_{SOC}$ value (e.g. 20%) and $S_{SOC}$ (e.g. 60%) value are defined based on a prosumer's energy need. It should be noted that some prosumers like hospitals would require higher $S_{SOC}$ defined as compared to recreational installations.

$$B_{soc} = \text{BT SOC at which prosumer purchases Power}$$

$$S_{soc} = \text{BT SOC at which prosumer sells Power}$$

Above the upper SOC limit, the PV curtailment takes effect to avoid battery overcharging. Once the SOC falls to 80%, the PV curtailment is released. Table I indicates the status of the switches and defined operating modes for the BT. The critical (RED) mode happens when there is a failure to connect to the private line. This is not demonstrated in this paper. Also, the initial SOC of batteries is determined arbitrarily.

TABLE I. BT SOC OPERATION MODES

| Mode of Operation | Status of Switches | PV power flow |
|---|---|---|
| Desired (GREEN) | S1, S2=**on** | To battery, Load, and Private line |
| Normal (BLUE) | *S1*=**on**, *S2*=**off** | To battery, Load |
| Emergency (ORANGE) | *S1*=**off**, *S2*=**on** | To battery |
| Critical (RED) | *S1*=**on**, *S2*=**off** | To battery, load |

### C. Efficient Power Transmission

An ideal linear transformer is preferred to step up the voltage from 240VAC to 11kVAC for transmission to other prosumers within the same community. Between community mini-grids, another transformer steps up the voltage from 11kVAC to 33kVAC. High voltage transmission results on lower $I^2R$ losses on the transmission line since the transmission current is reduced according to Ohm's law.

## IV. SIMULATION AND RESULTS

### A. Simulation Conditions

A one-day simulation was carried out using real weather data for sunny and cloudy cases considering the interconnection of two communities under different weather conditions as shown in Fig. 8. Area 1 is under normal summer sunny-day weather conditions while Area 2 is under summer rainy-day weather conditions. The data was collected from our laboratory rooftop at Hiroshima University.

The specifications of each prosumer's PV, BT systems are all the same and set as follows; PV system: Open voltage: 29.7 [V/piece], number of series:1 3 [pieces], Short-circuit current: 8.6 [A/piece], parallel number: 2 [pieces], PV output: 5 [kW], BT system: Rated capacity: 40 [Ah], Nominal voltage: 48 [V], rated output: 2 [kWh], parallel number: 8 [pieces], Rated discharge current: 69.4 [A] We assume unity power factor in this simulation.

Dedicated Switches S1 and S2 were installed for all prosumers except prosumer A2 and prosumer B1. Table II shows the SOC initial value ($I_{SOC}$), $B_{SOC}$, and $S_{SOC}$ values set for each prosumer's BT. Switch S2 has an early turn ON function to anticipate Switch S1 turn OFF. Prosumers that require a higher degree of emergency backup supply such as a hospital would require higher $B_{SOC}$ and $S_{SOC}$ set values (A3, B1), whereas prosumers who do not require emergency backup supply such as a department store (A1, A3, B3, B4) would set lower SOC limit values.

TABLE II. BT SOC SET VALUES

| Prosumer | $I_{SOC}$ (%) | $B_{SOC}$ (%) | $S_{SOC}$ (%) |
|---|---|---|---|
| A4, B2 | 60 | 45 | 60 |
| A3, B4 | 20 | 10 | 15 |
| A1, B3 | 80 | 10 | 15 |

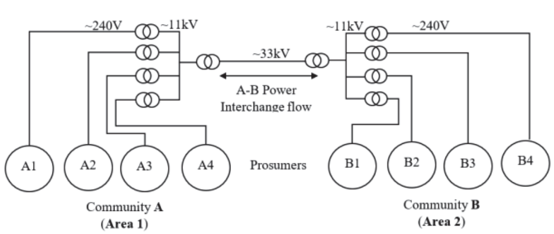


Fig 8. Simulation Configuration Layout

### B. Simulation Results

All 8 prosumers in the two areas were able to maintain supply throughout the day. Below, we analyze the behavior of the system when subjected to implemented voltage and SOC management controls for selective cases.

According to Fig. 9, Prosumer A3 maintained supply, with support from the battery storage, for most of the day until about 19:00hrs when PV generation reduced to 0kW. However, since the battery SOC dropped below 15%, switch S2 turned on early between 16:00hrs and 18:00hrs. This was in anticipation of switch S1 turn off that took place after 22:00hrs when the BT SOC reached the lower limit. At this point, power interchange kicked in. Through this process, Prosumer A3 maintained supply with support from the shared line.

A similar case takes place for prosumer B4. (Fig. 10) Supply from private line kicks in at about 20:00hrs after switch S1 turns off. Switch S2 had turned on at about 19:00hrs in when the BT SOC declined below 15%. At this point, the prosumer is anticipating switch S1 turnoff which takes place shortly after.

The graph in Fig. 11 shows a typically stable DC Bus voltage owing to the PI control system employed in the design. It mainly ranges within ±5VDC range, apart from cases like that of prosumer A3 and B4 which happened when switch S1 turned off to effect power interchange. However, soon the spike stabilized, owing to the PI control system. The DC bus voltage was maintained even when it faced intermittent PV energy generation as observed between 10:00hrs and 12:00hrs as observed in Fig. 9 for prosumer A3.

Power interchange took place between the two communities, majorly from community A under sunny weather conditions as shown in Fig. 12. The interchange curve for prosumer B4 in community B indicates that interchange took place from community A to B. This is observed from A-B Power rise towards 22:00 that corresponds to the rise in interchange power curve of prosumer B4 in Fig.10.

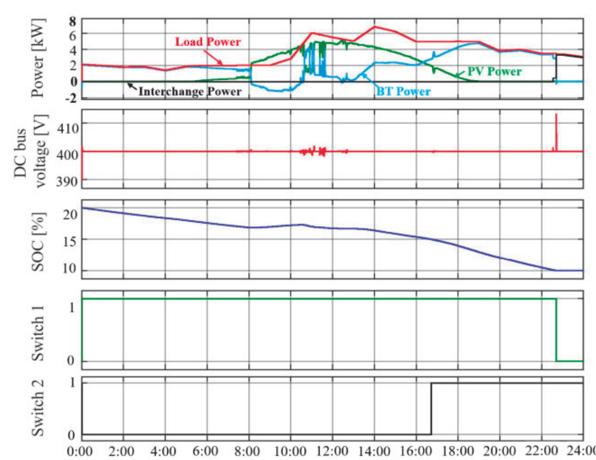


Fig 9. Performance Wave Characteristic for Prosumer A3

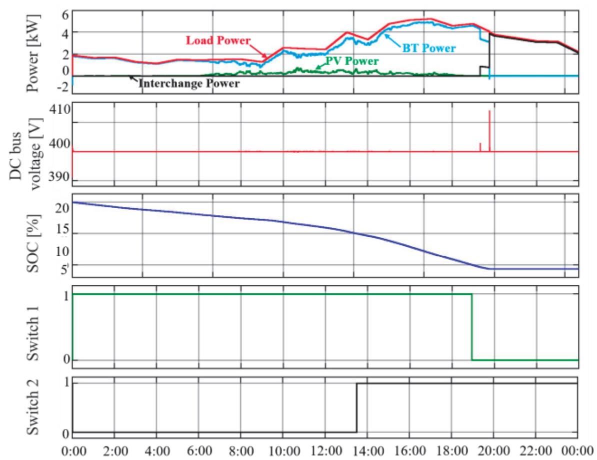


Fig 10. Performance Wave Characteristic for Prosumer B4

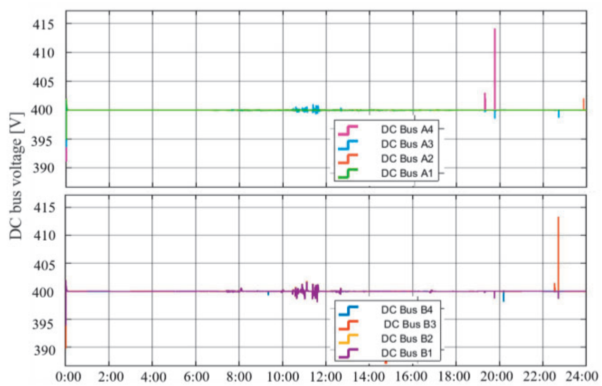


Fig 11. DC Bus Voltage Control Waveforms

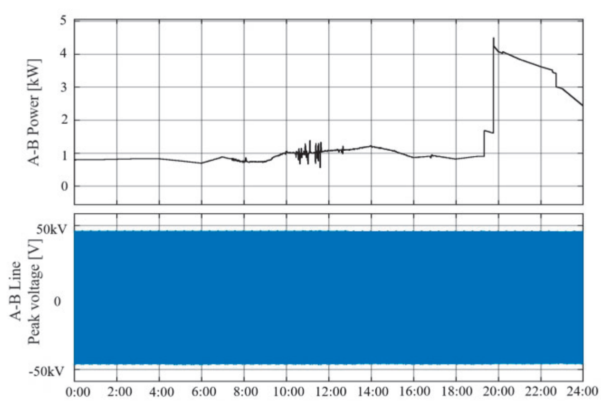


Fig 12. Inter-community Power Flow Characteristic

## CONCLUSION

The result of this research is a tool that monitors, manages, and controls BT SOC; for prosumer uptime and battery health protection, voltage through the MPPT, and PI controller method. We achieved autonomous distributed control in connecting two mini-grids simulated under different weather conditions and succeeded in maintaining uptime over a 24 hour period. We propose this solution for the electrification of remote communities as described in Uganda.

Next, we hope to realize frequency, active and reactive power control with real-time and day-ahead forecasting for both loads and PV output with a hybrid control scheme taking advantage of the good qualities of both distributed and central control systems.

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