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Design and Analysis of Solar PV based Low-Power Low-Voltage DC Microgrid Architectures for Rural Electrification

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***Abstract*— Over 1.3 billion people worldwide primarily in Africa and South-East Asia have no access to electricity. Electrification of these remote rural regions through national power grids is largely unviable low due to i) a high infrastructure cost, and ii) limited power generation capacity in many countries. Therefore, low-power, low-voltage, solar photovoltaic (PV) based DC microgrids are becoming very popular in these regions. Many of these low voltage solar powered DC microgrids are based on central generation and central storage with efficiencies typically ranging from 60% to 75%. Therefore, it is important to design the architecture in an optimal manner to attain the highest possible efficiency. In this work, we analyze three possible distribution architectures and evaluate their operational efficiency with regards to typical spatial village orientations in developing countries. These include C-Architecture, O-Architecture and Cluster-Architectures with efficiencies of around 71%, 77.9% and 76.2%, respectively for a typical 40-house village at 24V DC distribution using 10 AWG conductor size. Based upon the comparative analysis in this work, an optimum distribution structure of a village can be proposed in accordance with its orientation (arrangement of houses) to achieve a higher operational efficiency and a reduced upfront cost. This work will typically be useful in design and implementation of new small microgrid systems as well as in up-gradation of existing microgrid systems to maximize their utility**

***Index Terms*—DC Microgrids, Power Distribution, Rural Electrification, Solar Photovoltaics**

I. INTRODUCTION

Access to electricity even at basic levels increases productivity and provides opportunities for economic development. Many households in developing regions still use fossil fuels (kerosene oil etc.) even for lighting purposes and the use of these fuels have many documented adverse effects. But unfortunately, most of these people do not have a choice in this regard. The usual source of electricity i-e the grid is unviable for many of these isolated villages and large upfront costs of electrifications are prohibitively high form many most of the developing countries [1, 2]. Therefore, a paradigm shift towards powering these villages through low cost and low power distributed renewable resources such as solar PV is seen in recent years [3-5] . Such microgrid systems are primarily based on DC distribution due to an inherent advantage in terms of an increased operational efficiency and economics for many remote locations where grid is unavailable or highly intermittent [6]. These integrated systems also have a better levelized cost of electricity compared to standalone systems as it takes advantage of usage diversity at a village scale. Therefore, trend has been shifted to off-grid electrification through solar energy and in the past several years South East Asia and Africa have seen significant growth in renewable energy generation [7].

Numerous Mini- or Micro- grids of varying capacities ranging from 1 kWp to 200 kWp have been installed in India. Prominent implementations include micro-solar PV plants (< 6 kW capacity) in Chhattisgarh and solar mini-grids in Sunderbans and Lakshadweep [8-11]. The most common commercial scale microgrids with central storage and central PV generation include Mera Gao Power (MGP) in Uttar Pardesh which provides 5W of DC electricity to each subscribing house in a village, with a limit of 0.2 amps enough to power two LED lights and a mobile-phone charging point. MGP has reportedly connected over 10,000 households spread across 400 villages. The specifics of electricity provision, like timing and duration of daily provision, are decided primarily by MGP on the basis of a fairly standardized model with limited involvement of villagers [8]. Similarly, small container based solar solutions on 12V and 24V are also being utilized in Africa [12-15].

Our work focuses on technical assessment of many of these distributed off-grid systems with low-power provisioning and evaluates their operational efficiency with regards to typical system orientations. While generic systems may be deployed for some village architectures, we suggest possible orientations for various typical villages to maximize the distribution efficiency and minimize the overall cost of these systems. This research and analysis will be helpful in design optimizations of future installation of solar powered microgrids in any rural area in terms of reduced cost and increased efficiency by keeping the topology of the village in perspective before actually installing the system itself. In addition, a detailed analysis of many existing systems is possible through this work with possibilities of efficiency improvement in retrofitting various distribution architectures. To the best of our knowledge, mapping electrical distribution architectures with spatial arrangement of rural village houses is being explored for the first time in this work. This will have many tangible benefits in terms of enhancing system efficiencies in these low-cost low-power systems.

II. COMMON VILLAGE ARCHITECTURES

In order to design an efficient power distribution architecture that ensures the optimal power flow from source end to load end, it is important to analyze the spatial distribution of houses in various villages across developing countries. Typically, two main arrangements of houses are found: a) Linear arrangement in which houses are generally strung along length-wise on the two sides of a road b) clustered arrangement in which houses are situated in independent fields or in clusters of multiple huts, all belonging to a single close kinship group [16]. Some other similar orientations also occur such as Zulu's in Southern Africa where people built houses shaped like beehives. They built their houses in a circular fenced compound forming a cluster [17]. In order to electrify these villages, generally standard radial systems are installed irrespective of the structure of village and orientation of houses. However, the distribution efficiency of these systems can be significantly enhanced by taking the structure of village into account and fitting the right microgrid distribution architectures on it.

III. PROPOSED POWER DISTRIBUTION ARCHITECTURE

Based upon the structure of village and spatial distribution of houses, we propose two broad power distribution architectures. The proposed architectures cover almost all types of village configuration discussed in section II. These include linear architecture and cluster architecture for a microgrid built around a village having 'N' houses with up to two generation and storage hubs.

A. Linear Power Distribution Architectures

Linear architecture is best suit for those villages where linear spatial distribution of houses is found. In linear configuration houses are typically situated along the length of the road. Depending upon the availability of generation and storage hubs, linear architecture may further be categorized in to 1) 'C' configuration and 2) 'O Configuration'.

1) Linearly Distributed 'C' Architecture

For a village having 'N' houses, the visual representation for linearly distributed 'C' architecture is shown in Fig. 1. It shows spatial arrangement of houses, power distribution architecture along with the placement of generation and storage units. Distribution conductors are laid in a linear manner while generation and power processing and storage units (PPSU) are placed at one end of a street, thus formulate a 'C-like' structure and is termed as linearly distributed C-architecture DC microgrid. This village architecture is a simplistic model of some linear villages found in India such as Konkan and Puri district villages [8].

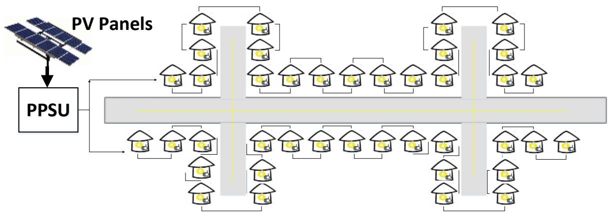

Fig. 2. Topological Diagram of Lnearly Distributed 'C' Architecture with solar PV generation and power processing and storage units (PPSU)

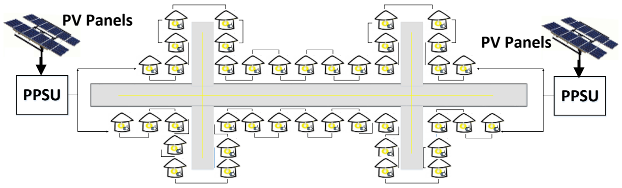

Fig. 1. Topological Diagram of Lnearly Distributed 'O' Architecture

2) Linearly Distributed 'O' Architecture

Based upon the availability of the land for generation and storage hubs, PV generation unit and PPSU may be located at both ends of the street.

Thus, such a structure in which conductors are laid in a linear manner, interconnecting generation and storage at both ends of the house load formulates a linearly distributed 'O' architecture DC microgrid as shown in fig. 2. The introduction of this architecture is to analyze the effect of having two generation and storage units on system efficiency and distribution losses.

B. Non – linear Clustered Architecture

Cluster architecture suits best to those villages in which either there is a clustered arrangement of houses or if there is houses are distributed in a random manner. Length of each cluster and number of houses in each cluster may vary depending upon the structure of village. In addition, the distance among various houses along with the distance of each house from the central generation and storage hub may vary. This cluster architecture is therefore further classified as 1) uniformly distributed cluster architecture 2) randomly distributed cluster architecture.

1) Uniformly Distributed Cluster-Architecture

A uniformly distributed clustered architecture of DC microgrid interconnecting 'n' clusters having 'N/n' houses per cluster with the centrally placed generation and storage hub is shown in fig. 3. Such types of villages are common in sub-Saharan Africa which are located in remote areas, with small independent communities of around 50-100 houses in reasonably close proximity.

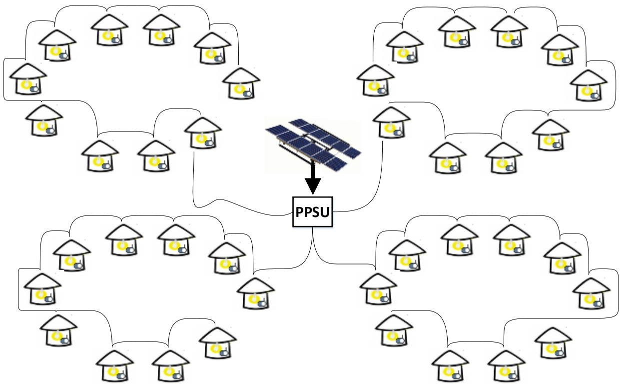

Fig. 3. Topological Diagram of Non- Linear Clustered Architecture

The distribution efficiency in these cluster arrangements are a function of the arrangement of houses in each cluster. Fig. 3 shows a uniformly distributed cluster arrangement where each cluster has similar number of houses. Since the number of houses and their arrangement in such a clustered architecture are largely uniform, therefore, worst voltage dips (on the microgrid) generally occur across the last household of each cluster.

For constant loading of these architectures, ring scheme of interconnection (connecting last house of each cluster with first house) does not add much in terms of enhanced efficiency and reduced voltage dips at the rare ends.

2) *Randomly Distributed Cluster-Architecture*

In many practical scenarios, large variation in the overall number of village houses per cluster is likely to be observed. Therefore, detailed power flow analysis techniques must be used to find the optimum distribution architecture including number of houses in each cluster to achieve the highest possible distribution efficiency and minimum possible voltage dips far away from the generation hub. In such architectures, it is possible to further enhance the distribution efficiency and minimize the voltage drops at the rear ends at the cost of an extra conductor using ring scheme of interconnection to connect the last house to the starting house of each cluster.

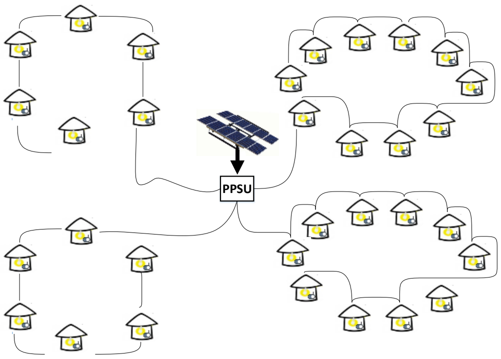

Fig. 4. Topological Diagram of Non- Linear Randomly Distributed Clustered Architecture

IV. ENERGY BALANCE MODEL FOR MICROGRID

In order to design optimal system capacity with lowest possible cost, it is important to analyze the system in terms of load requirements, converter requirements, supply availability, storage size estimation and loss analysis. In this section we evaluate overall distribution losses in the system through Newton-Raphson Method modified for DC power flow analysis [18] and workout an energy balance model to accurately estimate the system sizing requirement. In addition, worst voltage dips in any distribution architecture are likely to add constraints on DC-DC converter requirements, so the presented analysis will also be much useful for analyzing converter requirements. In order to assess this, we consider a uniform loading on each house and therefore worst voltage dips will be observed at the rear end of the village. This parameter is also calculated (equation 7) and shown in results and discussion section.

For this analysis, we consider a typical village consisting of 'N' houses electrified via solar PV panels having maximum power generation capacity 'S_{max}' and a battery storage system having capacity "C" with allowable maximum and minimum State of charge 'SOC_{max}' and 'SOC_{min}', respectively. Solar PV generation 'S(t)' will vary with the time depending upon the input irradiance and ambient temperature, therefore, battery state of charge 'SOC(t)' will also vary with time depending upon 'S(t)' and load requirements. Load demand of each house 'i' at any time is given by '$P_i(t)$' and it may vary from 'P_{max}' to 'P_{min}'. Therefore for any time interval 'Δt' balance of energy at microgrid is given by (1)

$$S(t)\,\Delta t = V_B(t)\,\Delta SOC(t) + \sum_{i=1}^{N} P_i(t)\,\Delta t + P_{loss}(t)\,\Delta \mathrm{t} \qquad (1)$$

Where, '$V_B(t)$' is the terminal voltage of the battery, 'P_{loss}' is the total distribution loss in transferring of power from battery to households subject to the constraints given by (2).

$$\begin{array}{l} S(t) \le \mathrm{S}_{\max}\ ,\ \mathrm{SOC}_{\min} \le SOC(t) \le SOC_{\max} \quad ;\forall i,t \\ \mathrm{P}_{\min} \le P_i(t) \le P_{\max} \qquad ;\forall i,t \end{array} \qquad (2)$$

Since battery is a storage device with efficiency 'η_B', it may take energy from PV panels or may supply power to the load so depending upon the net energy flux in the battery, 'ΔSOC(t)' can be positive or negative. Therefore, 'ΔSOC(t)' will be negative in durations of no solar power generation and the stored energy in the battery will be used to meet the load demand. A DC-DC converter having efficiency 'η_G' is employed at the generation end to synchronize the varying output of PV with the grid voltage 'V_G' therefore, (1) may be written in terms of grid voltage 'V_G', converter efficiency 'η_G', battery efficiency 'η_B', output current of PV panel '$I_o(t)$', battery current '$I_B(t)$', load current '$I_i(t)$' and load voltage '$V_i(t)$' subject to the constraints given by (2).

$$\eta_G V_G(t) I_o(t)\Delta t = \eta_B V_G(t) \mathrm{I_B}(t)\Delta t \;+ \\ \sum_{i=1}^{N} V_i(t) I_i(t)\Delta t + P_{loss}(t)\Delta \mathrm{t} \qquad (3)$$

Since distribution loss '$P_{loss}(t)$' is a function of configuration of village, grid voltage 'V_G' and permitted load levels to each household, therefore, in order to estimate the energy balance, '$P_{loss}(t)$' must be evaluated. In order to evaluate distribution losses, 'N' house village may be modeled as a combination of interconnection resistance of the laid conductor. For each configuration of the village, a unique conductance matrix 'G' can be formulated depending upon the spatial distribution between houses and length of conductor laid.

For each house there will be two interconnecting nodes, one node at the interconnection with neighboring house and the other node at the interconnection of microgrid and load in each house. Therefore, in total, there will be 2N*2N nodes conductance matrix 'G' may be written in the form of individual conductance 'g_{xy}' between any arbitrary node 'x' and 'y'. Where, each individual item 'G_{xy}' of conductance matrix 'G' is given by (5)

$$G = \begin{bmatrix} G_{11} & G_{12} \cdots\cdots & G_{1,2n} \\ G_{21} & G_{22} \cdots\cdots & G_{2,2n} \\ \vdots & \vdots \;\ddots & \vdots \\ G_{2n,1} & G_{2n,2} \cdots\cdots & G_{2n,2n} \end{bmatrix} \quad ; G \in R^{2n\times 2n} \qquad (4)$$

$$G_{xy} = \begin{cases} \sum_{y=1}^{2n} g_{xy} & ; \forall \mathrm{x} = y \\ -g_{xy} & ; \forall \mathrm{x} \neq \mathrm{y} \end{cases} \qquad (5)$$

This 'G' matrix can be used to calculate the total distribution losses as discussed in our earlier work based upon the Newton Raphson method modified for DC power flow analysis [18], where, 'V_x' and 'V_y' are the voltages at arbitrary nodes 'x' and 'y' after convergence of algorithm. Once the voltages after convergence are known, these values are used to calculated the overall line losses and worst voltage dip using (6) and (7)

$$P_{loss} = \frac{1}{2}\sum_{i=1}^{2N}\sum_{j=1}^{2N} G_{xy}\left[V_x\left(V_x - V_y\right) + V_y\left(V_y - V_x\right)\right] \qquad (6)$$

$$VD_g = V_x^{\max} - V_x^{\min} \qquad (7)$$

Where, 'V_x^{max}' and 'V_x^{min}' are the maximum and minimum values of voltage at any bus after kth iteration. Therefore, using (8), complete energy balance at microgrid is governed by (8)

$$\eta_G V_G(t) I_o(t)\Delta t = \eta_B V_G(t) \mathrm{I_B}(t)\Delta t + \sum_{i=1}^{N} V_i(t) I_i(t)\Delta t \\ + \frac{1}{2}\sum_{i=1}^{2N}\sum_{j=1}^{2N} G_{xy}\left[V_x\left(V_x - V_y\right) + V_y\left(V_y - V_x\right)\right]\Delta t \qquad (8)$$

Equation (8) is the energy balance model that governs the operation of microgrid and can be used to control the flow of the requisite amount power from solar PV panel to battery and load requirements to individual household. This will not only allow us to optimally size the system with various loads but would allow us to incorporate possibility of elastic loads when the total load demand and losses are lower than the solar PV generation. However, this aspect is not covered within in the scope of current work.

V. RESULTS AND DISCUSSIONS

A typical village having 40 houses is considered for all three types of spatial distribution of houses in the village. The load on each household is considered 5W, while the distance between each two consecutive houses is taken 10m. In order to analyze the effect of distribution voltage levels on operational efficiency of the proposed microgrids, two possible voltages of LVDC i.e. 24V and 48V are considered. Similarly, to analyze the effect of conductor size, standard conductor sizes varying from AWG-10 to AWG-14 are considered. Based upon the analysis presented in section IV and our earlier work [18], distribution losses , efficiency and worst voltage dip of the distribution system are calculated for each of the proposed configuration.

The number of houses in cluster arrangement is considered randomly distributed with total four clusters out of which two clusters contain 15 houses each, while the rest of two contain 5 houses each. Results for the efficiency of 'C' architecture at two voltage levels, i.e. 24V and 48V with varying conductor size (AWG 10 to AWG 14) are shown in Fig. 5. This shows that for lower distribution voltage level i.e. at 24V, the difference in efficiency at various conductor sizes is apparent, while at relatively higher voltage level i.e. 48V this difference in efficiency for different conductor is lower. Thicker conductor increases the capital cost of the system while lower voltage levels are safer distribution options and therefore a trade-off between cost of conductor and protection equipment to ensure safety, voltage level and conductor sizes may be selected for a given configuration of the village. 48V DC may generally be considered safe but extra precautions in terms of minimum currents on the grid may be taken in case of broken wires due to high winds etc.

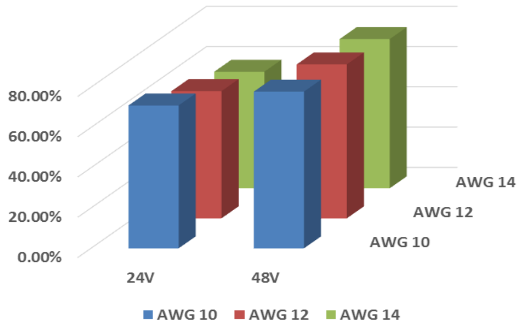

Fig. 5. Results for Distribution Efficiency of 'C' Architecture for Various Conductor Sizes and Voltage Levels

Table 1: Comparative Results of Efficiency and Worst Voltage Dip between ‘C’ ‘O’ and Cluster Architecture

System Architecture	Conductor Size (AWG)	Distribution Voltage Level 24V		Distribution Voltage Level 48V	
		η (%)	VD (%)	η (%)	VD (%)
Linear ‘C’	10	70.96	16.33	77.82	3.98
	12	63.15	29.94	76.44	6.47
	14	57.90	33.5	74.10	10.68
Linear ‘O’	10	77.87	3.80	79.43	1.01
	12	76.53	6.14	79.09	1.60
	14	74.18	10.29	78.55	2.60
Cluster	10	76.20	8.69	79.03	2.24
	12	73.52	14.56	78.43	3.62
	14	67.93	26.51	77.45	5.84

A detailed comparison calculated results between ‘C’, ‘O’ and randomly distributed Cluster-architectures is tabulated in Table.1. This shows the distribution efficiency (η) and worst voltage dips (VD) of these schemes for various voltage levels and various conductor sizes. From the detailed comparison table it can be seen that distribution of generation and storage units at the two ends of the system in ‘O’ architecture results in better system performance in terms of higher efficiency and lower voltage dips at the rare ends as compared to ‘C’ architecture and ‘Cluster-architecture’.

Further it can be seen from the table that various distribution architectures have different losses and therefore requirements on the panel sizing will vary. A detailed analysis such based upon the energy balance model provided in this paper will be very useful in estimating accurate ROIs for such systems along with cost minimizing through proper selection of distribution architectures in line with spatial distribution of subscribing houses in a village.

VI. Conclusion

A methodology for selecting efficient distribution architecture of PV based DC microgrids with respect to village configuration has been presented in this work. The detailed loss analysis and energy balance model shows that in linearly distributed villages ‘O’ architecture is the most optimal architecture for rural electrification, while clustered architecture is recommended for non-linear spatial distribution of houses in a village. For a typical village, microgrid built around ‘O’ architecture has higher efficiency in comparison to ‘C’ architecture. For non- linear villages, optimal cluster architecture can be formulated based upon the presented analysis. The proposed energy balance methodology allows efficient system planning (sizing, storage requirements and conductor selection) in accordance with village configurations. This work can therefore be used in planning for new optimal low-voltage systems along with enhancing efficiencies by retrofitting distribution architectures in existing systems.

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