Optimal Planning and Design of Low-Voltage Low-Power Solar DC Microgrids

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Abstract — Low-voltage, low-power solar photovoltaic (PV) based DC microgrids are becoming very popular in non-electrified regions of developing countries due to a) lower upfront costs compared to utility grid alternatives and b) limited power needs of rural occupants. The optimal planning of distribution architecture along with sizing of various system components such as solar panels, batteries and distribution conductors is essential for minimizing the system cost and enhance its utilization. In this work, we develop a framework for optimal planning and design of low-power low-voltage DC microgrids for minimum upfront cost. The analysis is based on a) region-specific irradiance and temperature profiles, b) constraints in storage and distributions, c) distribution loss analysis and d) optimum component sizing (storage, conductor and PV panel) requirements based upon an energy balance model for a 24-hr operation. We further analyze the merits of tailoring distribution architecture for maximizing the system utility in the planning of future microgrid deployments.

Index Terms— Distributed Generation, Newton-Raphson Method, Rural-Electrification, Microgrid

NOMENCLATURE

The notation used throughout the paper is stated below for quick reference. Other symbols are defined as required.

A. Indexes

\( t \) Instant of time ranging from 1 to \( T \).
\( i \) House number ranging from 1 to \( N \).
\( x \) Conductor bus number ranging from 1 to \( N \).
\( y \) Conductor bus number ranging from 1 to \( N \).
\( j \) Irradiance recording ranging from 1 to \( N_D \).

B. Parameters

\( N \) Number of houses in the village.
\( A \) Area of installed PV panels (\( m^2 \)).
\( \eta_m \) Name plate efficiency of PV panel/module.
\( \eta_{PL} \) Efficiency reduction factor due to panel losses.
\( I(t) \) Incident irradiance at time \( t \) (\( W/m^2 \)).
\( I_{tc} \) Temperature compensated irradiance at time \( t \) (\( W/m^2 \)).
\( I_{m} \) Mean temperature compensated irradiance (\( W/m^2 \)).

\( I_{tc}^{i} \) temperature compensated irradiance at \( i \)th dip (\( W/m^2 \)).
\( N_D \) Total number of irradiance recordings below \( I_{tc}^{m} \).
\( T_{cell}(t) \) Temperature of cell at time \( t \) (\( ^\circ C \)).
\( T_{amb}(t) \) Ambient Temperature at time \( t \) (\( ^\circ C \)).
\( G \) Conductance matrix of village distribution.
\( g_{xy} \) Individual Elements of conductance matrix.
\( V_x \) Voltage at node \( x \) (V).
\( V_y \) Voltage at node \( y \) (V).
\( V_{max} \) Maximum voltage after convergence (V).
\( V_{min} \) Minimum voltage after convergence (V).
\( SOC_{max} \) Maximum value of battery state of charge (\%).
\( SOC_{min} \) Minimum allowable battery state of charge (\%).
\( P_t \) Power demand of the house at time \( t \) (W).
\( P_{max} \) Maximum power demand of the house (W).
\( P_{min} \) Minimum Power demand of the house (W).
\( P_{loss} \) Distribution losses (W).
\( \eta_D \) Distribution efficiency.
\( \eta_{PL} \) Efficiency degradation due to PV panel losses.
\( \eta_{m} \) PV module efficiency.
\( \eta_{MP} \) Efficiency of DC-DC converter in CPPU.
\( \eta \) Efficiency of DC-DC converter at each house.
\( \eta_B \) Charging/discharging cycle efficiency of battery.
\( VD \) Worst voltage dips for power distribution (W).
\( w_1 \) Per kWh cost of battery ($).
\( w_2 \) Per kW cost of PV panel ($).
\( w_3 \) Per meter cost of distribution conductor ($).

C. Acronyms

MPPT Maximum Power Point Tacking
CPPU Central Power Processing Unit
AWG American Wire Gauge
LV Low-voltage
LP Low-power
kWp Kilo Watt Peak
PSH Peak Sunlight hours
IVF Irradiance Volatility Factor

D. Decision Variables

\( C_B \) Battery energy capacity (Whr).
\( S_{max} \) Nameplate power capacity of PV panels (Wp).
\( X \) Size of the distribution conductor (AWG).
\( E_d(t) \) Time varying energy state of the battery (Whr).
\( E_{SB}(t) \) Energy flow from solar to battery at time \( t \) (Whr).
\( E_{SL}(t) \) Energy flow from solar PV to load at time \( t \) (Whr).
\( E_{RL}(t) \) Energy flow from battery to load at time \( t \) (Whr).

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I. INTRODUCTION

Access to electricity even at basic levels increases productivity and provides opportunities for economic development. According to the International Energy Agency (IEA), more than 500 million occupants in South Asia (India, Pakistan and Bangladesh) and further 500 million in Africa have no access to any form of electricity [1]. These occupants have to rely on unhealthy resources, like kerosene oil, even for lighting purposes and the use of these fuels have many documented adverse effects [2]. Unfortunately, most of these people do not have a choice in this regard. The major source of electricity i.e. the grid is unviable for many of these isolated villages and large upfront costs of electrification through national grids are prohibitively high for most of these developing countries [3, 4]. Therefore, a paradigm shift towards powering these villages through low cost (and consequently low-power) distributed renewable resources such as solar PV is seen in recent years [4-7]. Such microgrid systems are primarily based on DC distribution due to an inherent advantage in terms of an increased operational efficiency and economic viability for many remote locations where the grid is unavailable or highly intermittent [8-10]. 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 [5]. Therefore, the focus for rural electrification has been shifted to off-grid electrification through low-cost solar DC microgrids [5, 6, 11].

Numerous Mini- or Micro- grids of capacities ranging from 1 kWp to 200 kWp have been proposed in the literature [12-17]. Low power microgrids generally provide low power provision of a few watts to a few tens of watts per home as compared to high power microgrids which allow provisions of several hundred watts or higher. Prominent practical implementations for low-cost rural electrification include micro solar PV plants (referred as microgrids) in India including Chhattisgarh, Sunderbans and Lakshadweep [16, 18]. However, the most common commercial scale microgrid is the Mera Gao Power (MGP) in India which provides 5W of DC electricity to each subscribing house in a village, for only 8-hrs per day, enough to power an LED light and a mobile-phone charging point. MGP has reportedly connected over 10,000 households spread across 400 villages [17, 19]. In 2012, Uttar Pradesh and Renewable Energy Development Agency (UPNEDA), installed 1 kW DC microgrids in 11 districts covering around 4,000 houses [20]. Another, recent successfully deployment in Africa includes up to 600W microgrids providing lighting and mobile phone charging typically up to 10W for 8-hr daily operation [21]. Other small container based solar solutions on 12V and 24V are also being readily utilized in Africa [12, 14, 22].

While these (and other similar low voltage low power) systems are becoming popular for off-grid rural electrification, formal analysis on optimal component sizing and loss evaluation is not addressed in the literature. Generic microgrid systems planned without taking the regional characteristics in to consideration are significantly oversized and are not a good fit for all environments and regions. Thus, for DC microgrids, there is a need to plan efficient distribution schemes based upon the detailed loss analysis along with quantification of optimal system sizing incorporating local conditions for overall cost minimization and enhanced system utilization.

This paper therefore focuses on optimal planning and design of low-voltage off-grid DC microgrids with local PV generation and storage for low-power provisioning. Various critical parameters that affect the optimal sizing of system components are identified and analyzed for optimal system assessment. In order to analyze the impact of distribution architecture on optimal component sizing, we related distribution losses to actual structure of the village and spatial distribution of houses in it. Two possible architectures of DC distribution (D-architecture and C-architecture) have been analyzed for power flow and associated distribution losses. So, our first contribution lies in quantification of distribution losses with respect to distribution architectures in line with common settlements in South Asia.

Our second contribution lies in the detailed analysis (and assessment) of various locations in India, (given in table I) from optimal cost, component sizing and distribution architecture planning perspective. It has been identified that optimal sizing of the system components is highly dependent upon region-specific time varying profile of irradiance and temperature throughout the year. Unfortunately, it is a common practice to use mean values of regional irradiance and temperature for system sizing which may lead to in accurate system sizing [23, 24].

Our third and major contribution is the formulation of the optimization framework for the selection of microgrid components, including PV generation capacity (kWp), battery storage capacity (kWh) and distribution conductor sizing (AWG) for minimum cost solution. To the best of our knowledge, optimal planning of system components for DC Microgrids considering the impact of distribution architecture has not been presented in literature and we believe that it will be highly beneficial for future DC microgrid deployments. Further, quantification of losses for distribution architectures with spatial arrangement will be critical in retrofitting current systems to enhance the overall capacity and system efficiency.

Kindly note that the focus in this work is on lowest cost topologies for basic rural electrification. High power microgrids (with household provisions for several hundred watts) are generally unviable (due to high up front cost and lack of micro-financing options) and not commonly implemented for self-sustained rural electrification. Therefore, we restrict our analysis to low-power and low voltage DC microgrids which are considered safe for direct touch and potentially do not create any electric shock or fire hazards when implemented at lower voltage levels (24V and 48V) with 100VA name plate capacity [23-25]. Importantly, the methodology presented in this work, for the optimal component sizing and optimal distribution architecture planning, is generic and equally applicable for higher power DC microgrids. However, lower voltages (24V and 48V) are not suitable for very high power system, as distribution losses would be very high for low distribution voltages.
Attempts to maximize efficiency, but they require sophisticated protection mechanisms for their safe operation [24].

The organization of the rest of the paper is as follows. Section II presents an overview of existing structures of villages and associated arrangement of houses in developing regions. In Section III an energy balance model incorporating various system losses for microgrid operation is presented. System model along with objective function formulation and constraints identification for optimal sizing of microgrid components is presented in section IV. In section VI, we present and discuss the optimal component sizing for various locations in India based on the formulated framework.

II. COMMON VILLAGE ORIENTATIONS

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 (orientation) of houses commonly found in villages across the developing countries. Typically, two main arrangements of houses are found:

a) Linear arrangement in which houses are generally situated alongside a central street/road.

b) Clustered arrangement in which houses are situated in independent fields or in clusters of multiple huts/homes [26].

Northern Africa and Namibia show highly clustered settlement and population distribution patterns [27]. However, in Asia, primarily in South East Asian countries such as India, Pakistan and Bangladesh, the most common forms of rural settlements is linear arrangement of houses which are situated across roads in order to facilitate access to infrastructure facilities, markets and resources [28, 29]. In this work, we develop a system model for these linear architectures and formulate optimization framework for planning and design of low-power and low-voltage DC microgrids situated in these linear settlements. In a linear village structure, houses are generally uniformly spaced; therefore, can be connected to PV generation and storage point via a linearly spaced radial architecture for the distribution of power. The placement of PV generation and storage unit is not an additional concern due to uniformity of the distribution architecture. However, in a clustered non-linear architecture, houses may not be uniformly spaced; therefore an additional concern of PV generation and storage unit placement arises because it directly affects the distribution losses and associated optimal sizing calculations. Due to inclusion of an additional objective i.e. optimal placement of PV generation and storage unit, the overall objective function no longer remains linear, rather it becomes a combinatorial optimization problem. The design of clustered architectures, suitable for African countries and framework for their optimal sizing require sophisticated optimization techniques due to their non-linear nature and are not detailed in the current scope of work.

Typically, in order to electrify these villages, standard radial systems with single generation and storage hub is installed [16, 17, 30, 31]. However, the distribution efficiency of these systems can be significantly enhanced by considering a second generation hub if the provision is available. Therefore, we consider linear distribution microgrid architecture with up to two generation and storage hubs. These proposed structures can then be classified into C- distribution architecture and O- distribution architecture depending upon the number of generation and storage hubs.

A. Linearly Distributed C-Architecture

The visual representation for linearly distributed C-architecture is shown in Fig. 1. Distribution conductors are laid in a linear manner while generation and power processing and storage units (PPSU) are placed at the start of a village, thus formulate a C-like structure and is termed as linearly distributed C-architecture. This village architecture is a simplistic model of villages found commonly in India [17].

B. Linearly Distributed O-Architecture

Based upon the availability of the land, PV generation unit and PPSU may be located at both ends of the central 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 (Fig. 2). While keeping the overall generation and storage capacity the same, the introduction of this architecture having two similar generation and similar storage units on system enhances its overall efficiency as discussed in section VI.

| TABLE I SPECIFIC REGIONS FOR ANALYSIS WITH IRRADIANCE PROFILES |
|---|---|---|---|---|---|
| Regions | Annually Averaged PSH | Regions | Annually Averaged PSH |
|---|---|---|---|---|---|
| 2. Delhi | 5.035 | 8. Indore | 5.457 |
| 4. Raipur | 5.280 | 10. Aurangabad | 5.604 |
| 5. Ranchi | 5.328 | 11. Jhodapur | 5.664 |
| 6. Bangalore | 5.808 | | |

Fig. 1. Topological Diagram of Linearly Distributed C-architecture with Solar PV Generation and Power Processing and Storage Units (PPSU)

Fig. 2. Topological Diagram of Linearly Distributed O-architecture with Solar PV Generation and Power Processing and Storage Units (PPSU)
III. ENERGY BALANCE MODEL FOR A DC MICROGRID

In order to design an optimal system, it is important to analyze the system in terms of load requirements, converter requirements, supply availability, storage size and loss analysis. In this section we evaluate various loss elements in the operation of microgrid. These losses mainly include i) panel losses in the PV output due to low irradiance, soiling and mismatch, ii) Degradation in PV output due to temperature, iii) DC/DC converter losses, iv) battery charger/discharge cycle losses and v) distribution losses.

The output produced by PV panels is a function of incident irradiance and temperature. However, due to panel losses and temperature degradations, output of PV panel is generally lower than its name plate capacity. Low irradiance losses generally vary linearly with the peak sun hours (PSH) of the incident irradiance. A mathematical model to quantify low irradiance loss has been presented in our earlier work [32]. The degradation in output characteristics of PV Panels due to soiling and mismatch of cells and temperature, discussed in [33, 34], are also incorporated. Therefore, considering panel losses and the temperature degradation effect, \( S(t) \) is given by (1)

\[
S(t) = A \cdot \eta_{PL} \cdot \eta_{m} \cdot I_e(t)
\]

Where, \( I_e \) is the temperature compensated irradiance and depend upon \( I(t) \), and \( T_{cell} \) and is given by (3) [35].

\[
T_{cell}(t) = T_{amb}(t) + (0.01875 \ast I(t))
\]

\[
I_e(t) = (1 - (T_{cell} - 25) \ast 0.0045)I(t)
\]

The output from PV panels is processed through MPPT DC/DC converter which incurs losses in PPSU along with further DC/DC losses at the distribution panel of each house (see Fig. 3). The efficiency of a typical DC-DC converter is a quadratic function of its output power (percentage loading), remains constant at constant output loading and varies significantly at low loading levels. However, the converter losses can be linearized and its efficiency can be considered as a constant for majority of its operational range [36]. For instance in [36], it has been shown (figure 4) that for a typical DC-DC converter, its efficiency exhibits very slight variations (±2%), during its operation between 25 to 95 percent of its rated output power loading. Therefore, the rating of CPPU converter is approximated such that at other than very low input irradiance values (at which there is no significant output power contribution from the module), the converter can operate in constant efficiency range. Similarly, for household converters, only constant output loading of each household is considered, therefore, converter efficiency is taken as constant. For variable loading scenarios, detailed analysis on converter losses may be included using (8) and (14) for accurate sizing estimations [36]. Battery charging/discharging cycle efficiency (\( \eta_{b} \)) depends upon the battery technology and manufacturer specifications. For the system evaluation, lead acid battery is considered, while its charging/discharging efficiency is considered constant for the simplicity of analysis.

Distribution efficiency is assessed by calculating distribution losses in the system through Newton-Raphson Method modified for DC power flow analysis [37]. \( P_{loss}(t) \) accounts for distribution losses and is a function of a) distribution configuration in a village, b) distribution voltage level and c) permitted load levels to each household and must be critically analyze. In order to quantify distribution losses, an \( N \)-house village is modeled as a combination of interconnection resistance of the laid conductors as shown in Fig. 3 and Fig. 4. For each configuration (\( C \) or \( O \)) of the village, a unique conductance matrix \( G \) can be formulated depending upon the spatial distribution between house and length of conductor laid and is given by (4) and (5).

\[
G = \begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1N} \\
G_{21} & G_{22} & \cdots & G_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
G_{N1} & G_{N2} & \cdots & G_{NN}
\end{bmatrix} \in \mathbb{R}^{N \times N}
\]

(4)

\[
G_{xy} = \begin{cases}
\sum_{y=1}^{N} g_{xy} & ; \forall x = y \\
- g_{xy} & ; \forall x \neq y
\end{cases}
\]

(5)

This \( G \)-matrix can be used to calculate \( P_{loss} \) and worst voltage dip (VD) as discussed in our earlier work [37, 38] and are given by (6) and (7).

\[
P_{loss} = \frac{1}{2} \sum_{x=1}^{N} \sum_{y=1}^{N} G_{xy} \left[ V_x (V_x - V_y) + V_y (V_y - V_x) \right]
\]

(6)

\[
VD = V_{max} - V_{min}
\]

(7)

For energy balance model, we consider a typical village microgrid orientation consisting of \( N \) houses electrified via solar PV panels having maximum power generation capacity \( S_{max} \) (kWp) and a battery storage system having energy capacity \( C_b \) (kWh). Solar PV generation \( S(t) \) will vary with time depending upon the input irradiance and ambient temperature, therefore, battery state of charge and associated state of energy \( E_{B}(t) \) will also vary with time depending upon \( S(t) \) and load requirements. Load demand of each house \( i \) at any time is given by \( P_i(t) \). Therefore, for any time interval \( \Delta t \), the balance of energy at microgrid is given by (8)

\[
\eta_{MP} S(t) \Delta t = \eta_{b} \Delta E_{B}(t) + \sum_{i=1}^{N} \eta_{b} P_i(t) \Delta t + P_{loss}(t) \Delta t
\]

(8)

Where, \( \eta_{MP} \) is the efficiency of DC/DC converter employed at PPSU responsible for maximum power point tracking, battery charging and maintenance of distribution voltage and \( \eta_{b} \) is the efficiency of DC/DC converter employed at the distribution panel of each house. Since battery may take energy from PV panels or may supply power to the load at any time \( t \) depending upon the net energy flux in the battery, \( \Delta E_{B}(t) \) can be positive or negative. \( \Delta E_{B}(t) \) 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.
IV. SYSTEM MODEL FORMULATION FOR OPTIMAL COMPONENT SIZING

In order to optimally size various system components including PV generation capacity \( S_{\text{max}} \), battery storage capacity \( C_B \) and conductor size \( X \) (AWG) for minimum cost of installation, we consider the energy flow diagrams for C- and O- distribution architectures (as dictated by (8)) as shown in Fig. 3 and Fig. 4, respectively.

A. Objective function

The overall optimization problem is therefore, the minimization of objective function (9), subjected to the constraints defined by (10) - (17).

\[
\min \left( E_{\text{SL}}, E_{\text{BL}}, S_{\text{max}}, C_B, X \right) \sum_{t=1}^{T} \left[ \omega_1 C_B + \omega_2 S_{\text{max}} + \omega_3 X \right] \\
\text{s.t.} \quad E_{\text{SL}} \geq 0, E_{\text{BL}} \geq 0, S_{\text{max}} \geq 0, C_B \geq 0 ; \forall T
\]

B. Inequality Constraints:

Non-negativity constraints on decision variables

\[
E_{\text{SL}} \geq 0, E_{\text{BL}} \geq 0, S_{\text{max}} \geq 0, C_B \geq 0 ; \forall T
\]

Since the battery lifetime is dependent upon its depth of discharge (DOD), therefore, energy level of the battery \( E_B(t) \) at any time \( t \) is not allowed to go below its minimum energy level dictated by allowable minimum state of charge \( S_{\text{SOC}} \).

\[
E_B \geq S_{\text{SOC}} - C_B ; \forall T
\]

C. Equality Constraints

The constraints on solar energy dictated by (12) as the generated energy can either be used to supply load or to charge the battery including the losses encountered in the path of power flow.

\[
\eta_{\text{MP}} S(t) = E_{\text{SL}}(t) + E_{\text{BL}}(t) ; \forall T
\]

Constraints on battery energy are given by the net balance of influx and out-flux of energy and are given by (16)

\[
\Delta E_B = E_B(t) - E_B(t-1) = \eta_B E_{\text{SL}}(t) - E_{\text{BL}}(t) ; \forall T
\]

The constraints on load are defined by (14) such that load demand must always be fulfilled either through battery or solar PV output. For constant household power loading scenario as discussed in the current scope of the work, converter efficiency \( \eta_B \) is considered constant. Therefore, linearization of load constraints does not result in any significant loss of accuracy. However, in case of variable household loading, non-linear accurate models for converter efficiency need to be included for accurate estimations [36].

\[
\frac{1}{\eta_i} \sum_{i=1}^{N} P_i(t) \Delta t + \sum_{i=1}^{N} P_{\text{loss}} \Delta t = E_{\text{SL}}(t) + E_{\text{BL}}(t) ; \forall T
\]

The optimal PV size \( S_{\text{max}} \) is determined by the maximum output power produced by PV array. Similarly, optimal battery size \( C_B \) is determined by the maximum energy state attained by the battery, therefore (15) and (16) dictate the equality constraints associated with the objective function for the optimal sizing of PV and battery respectively.

\[
S_{\text{max}} = \max(S) ; \forall T
\]

\[
C_B = \max(E_B) ; \forall T
\]

A range of possible conductor sizes for DC distribution are considered from American wire gauge (AWG) table [39]. Therefore, constraints on conductor size are given by (17).

\[
X \in \{4 \text{AWG}, 6 \text{AWG}, 8 \text{AWG}, 10 \text{AWG}, 12 \text{AWG}, 14 \text{AWG}, 16 \text{AWG}\}
\]

For considered range of operation, the stated objective function along with equality and inequality constraints exhibit linearity as shown by (9)-(17). Therefore, optimization problem is written in standard linear form and is solved through linprog function in MATLAB.

V. RESULTS AND DISCUSSIONS

For the current scope of work, we consider a typical linear village structure in South East Asia having (typically) 40 houses and distance between two consecutive houses is (typically) 10m. We consider both C- and O- architectures along with two distribution voltages of 24V and 48V. Optimal selection of PV panel size, battery storage capacity and conductor size is performed for 5W (case 1) and 10W (case 2) provision and is based upon problem formulated in section V.

The idea is to account for the impact of instantaneous fluctuations in PV generation (based upon timed fluctuations in instant irradiance and temperature) and losses on system sizing, therefore, selection of time base is critical. Selection of smaller time base results in better resolution to account for instantaneous changes, however, requires more computational resources for data processing. The proposed methodology is generic and can be applied for any time base, based upon the availability of solar irradiance data, load profile and computational resources for optimization problem solving. For current optimization problem, discrete time interval of 1 hour with constant load demand for each house is used as time base for all the calculations. Hourly variations in the irradiance and temperature data are taken from NREL [40]. According to the presented optimization problem optimal PV, battery and conductor sizing is determined.

![Fig. 3. System Diagram for Energy Flow in C-architecture with N Houses.](image-url)
PV panel losses are considered 8% for both cases. Although the converter losses are quadratic in nature but due to fix load assumption and for simplicity in optimization problem formulation, DC-DC converter losses for CPPU as well as individual household distribution panel converter are considered 10% for both cases. Battery cycle efficiency $\eta_b$ is considered 95%, and is assumed constant for simplicity of analysis. The cost of panels per watt-peak ‘$w_1$’ is taken as 600$/kWp$ (including the cost of mounting frame) and lead-acid battery cost per kWh ‘$w_2$’ is taken as 120$/kWh$ and gauge sizes cost is taken at 1671, 1305, 947, 588, 358, 250 and 204 $ for 4, 6, 8, 10, 12, 14 and 16 AWG, respectively [41-43]. While there are variations in these costs but we took most commonly found prices at which sourcing is readily available. For overall system cost calculation, fixed cost of 300$ has been included which accounts for CPPU and converter cost.

A. Case 1: 24-7 5W Supply to 40 Houses for a 365-day Operation

Based upon the analysis presented in section IV, the distribution efficiency, $\eta_d$ and worst voltage dips, $VD$ calculated for following cases are plotted in Fig. 5.

i. C-24V (C-architecture with 24V distribution)
ii. O-24V (O-architecture with 48V distribution)
iii. C-48V (C-architecture with 48V distribution)
iv. O-48V (C-architecture with 48V distribution)

VD is critical in terms of power electronic converter requirement at each subscribing household. While, generally, a 20% input voltage variation capability is allowed in most power electronic converters, the performance is optimal close to the rated input voltages. For this particular analysis, we limit the optimum component selection at 20% variations in the grid voltages. It is also interesting to note that O-24V and C-48V have similar voltage dips and efficiencies for all wire sizes. This is because of the uniform loading and equal generation at both ends of the O-architecture. In case of non-uniform loading and unequal generation, the characteristics of C-24V and O-48V will not necessarily resemble, therefore, detailed distribution loss analysis has to be performed as discussed in [37]. Along with the selection of PV panel and battery size, one important parameter is the optimization of the conductor size. The cost of conductor increases with its decreasing gauge thickness and vice versa while an opposite trend for system distribution efficiency is observed. Therefore, in order to analyze this effect in terms of cost, Fig. 6 (based on 365-day study on the solar irradiance data of Bihar, India) is plotted. The cost of distribution losses is calculated by taking the difference between overall system cost with distribution losses at a particular AWG and the overall system cost with ideal conductor having zero distribution losses.

From Fig.6 it can be seen that conductor cost decreases with the increase in gauge size while the cost associated with the distribution losses increases at higher gauge values. Thereby, our optimization problem calculates the optimal point such that overall cost of the distribution losses and upfront cost of conductor is minimal. For instance, for C-24V distribution architecture, 10AWG is optimum compared to its operation at 12AWG where its operation would be less efficient and sub-optimal from cost perspective. Alternatively, at 8AWG the system will be more efficient but at the resulting cost would be higher compared to the optimal value at 10AWG. In the current case study, the two cost functions i.e. cost of distribution losses and cost of conductor intersect due to similar scale. However, in general (for all cases), it may not be the case. We are interested in finding the minima rather than the intersection for calculating the optimal conductor size and there may not be an intersection point for certain cases where cost of conductor is considerably higher than cost of distribution losses and vice versa.
For further analysis of the impact of region-specific data i.e. time varying incident irradiance and temperature profiles on the cost and sizing of the system, results of a 365-day study for multiple locations in India (Table 1), depicting optimal panel sizing, optimal battery capacity and overall optimal installation cost are shown in Figures 7, 8 and 9 respectively. These areas are selected based upon their spatial distribution on the map and variation in annually averaged, daily PSH.

From Fig. 7-9, a few important observations can be made.

1) Optimal PV sizing varies approximately linearly with the average daily PSH (fig. 7).

2) Average daily PSH are not a direct measure for optimal battery sizing (fig. 8).

3) As the battery cost constitutes a predominant portion of the overall cost of the system, the overall cost of the system also does not vary linearly with the daily PSH (fig. 9).

Fig. 7 and table I verify that “optimal battery sizing is not directly related with the average PSH and the information of average PSH only is not sufficient for optimal sizing of battery storage requirements.” Rather, a detailed analysis on the variations pattern of PSH is needed to calculate the optimal battery storage requirements. For instance, in fig. 8, for all four cases, the battery requirements are lower for PSH=5.3 in comparison to PSH=5.4 and PSH=5.5. Thus, if a proper investigation is not made for daily variations in PSH, it may lead to incorrect sizing estimations. Therefore, a detailed analysis has been conducted to find the relationship between volatility of irradiance and battery sizing. In order to analyze the variations in incident irradiance, an irradiance volatility factor (IVF) has been defined, which accounts for the number of dips from the mean temperature compensated irradiance and their corresponding extent of deviation normalised over mean irradiance.

\[
IVF = \frac{1}{N \Delta I_{\text{tc}}} \sum_{i=1}^{N \Delta I_{\text{tc}}} (I_{\text{tc}}^{m} - I_{\text{tc}}^{d})
\]

Where, \( N \) is the total number of temperature compensated irradiance recordings out of which \( N \) numbers of recordings are below mean temperature compensated irradiance \( I_{\text{tc}}^{m} \) and \( I_{\text{tc}}^{d} \) is the temperature compensated irradiance of \( i^{th} \) dip. Using (18), IVF has been calculated for various regions under observation and it is found that battery sizing varies in direct proportion with IVF as shown in fig. 8. It is evident from fig. 8 that the irradiance patterns having minimum number of dips and less deviations from the mean intensity, consequently having lower IVF, will reduce the battery size. Regions with higher IVF, will require higher battery sizing despite of possibility of having high mean irradiance (point corresponding to PSH=5.4). Therefore, IVF can be considered as a true indicator for battery sizing rather than mean irradiance for optimal sizing estimation.

B. Case 2: 24-7 10W Supply to 40 Houses for 365-days Operation

The most critical aspect is the calculation of optimal sizing for higher power (10W) is the worst voltage dip along with distribution efficiency of each distribution topology (see Fig. 10). With the increase in power provisioning, the distribution losses (FR) increase significantly compared to case 1 (5W household load). However, like case 1, C-48V and O-24V have very similar voltage dips and overall distribution efficiencies. Moreover, distribution at lower voltage level i.e. 24V with C-distribution architecture becomes practically infeasible due to higher losses and higher voltage dips.
The increased distribution losses can be compensated by selecting a thicker conductor which will increase the cost of the system. Therefore, it becomes even more critical to optimally size the conductor by taking the capital and relative cost of distribution into account. The proposed optimization framework therefore, enables the optimal selection of conductor size based upon the trade-off between cost of the conductor and its relative cost of distribution (see Fig. 11).

From the comparison of Fig. 6 and Fig. 11 it can be seen that with the higher power provision, the optimal conductor selection has been shifted to lower gauge size (thicker conductor). For instance, the optimal conductor sizes for 5W operation (Fig. 6) are 10, 12, 12 and 16 AWG for C-24, O-24, C-48 and O-48 configurations respectively. While for 10W provision, the gauge sizes are reduced to 6, 10, 10 and 12 AWG for C-24, O-24, C-48 and O-48 configurations respectively. Therefore, the proposed optimization framework has adjusted the conductor size such that overall cost of the losses has been compensated by the selection of a thicker conductor while keeping the overall cost of the system as minimum. Fig. 12 shows the overall system optimal cost for various regions (with reference to their PSH). It is important to note that due to the planning flexibility in the current framework, the overall cost of the system in high power provision follows the same trend with relatively higher values in comparison to case 1. Further it has been observed that the overall panel and battery requirements for case 2 also follow a similar trend as compared with case 1 (results for case 2 are not shown here).

VI. CONCLUSION

A methodology for optimal planning and design of PV based DC microgrids is formulated. The proposed framework allows optimal selection of 1) solar panel sizing, 2) storage size and 3) conductor size for optimal cost solution. The dependence of region specific temperature and variations in irradiance pattern on optimal system sizing is observed through analysis of multiple locations in India. The quantification of system performance with distribution of generation and storage units at the two ends of the system (O-architecture) shows considerable improvement on distribution efficiency (10% or higher in most cases). In particular, C-48V (C-architecture with 48V distribution) and O-24V (O-architecture with 24V distribution) show remarkable similarity in terms of optimal system costs.

The selection of distribution voltage (24V or 48V) and the distributed architecture (C or O) is ultimately the choice for the microgrid installers/planners and is influenced by power converter preferences and financial models. But, importantly, the framework established in this work for optimal system topology (in multiple constraint scenarios) will be highly useful in planning for new optimal low-voltage systems along with efficiency enhancements of many existing systems by retrofitting distribution architectures.

REFERENCES


