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Analysis on Central and Distributed Architectures of Solar Powered DC Microgrids

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***Abstract*—In this work, central and distributed architectures of DC microgrids for rural electrification are analyzed under various operating conditions. In the proposed scheme, a single household consumer forms the atomic nanogrid unit which may integrate its resources in a scalable model with the community to form a microgrid, without dependence of the national grid. The flow of power between houses and the microgrid is implemented through a bidirectional flyback converter. The operation of proposed scheme for two different architectures, i.e. distributed generation distributed storage architecture (DGDSA) and centralized generation centralized storage architecture (CGCSA) is evaluated at various distribution voltage levels and conductor sizes. Modified Newton Raphson Method based analysis is performed for both architectures which show that distributed architecture has significant advantages over central architecture due to higher efficiency, low voltage drop and lower line losses. Further, the scalable nature with minimum installation cost for distributed architecture makes it more favorable for rural electrification applications in comparison to central architecture. The simulated results are also verified using a scaled down version of hardware implementation.**

***Index Terms*— Central Generation, DC Microgrids, Distributed Generation, Modified Newton Raphson Method, Rural Electrification**

I. INTRODUCTION

The ease of electricity access is one of the key indicators for economic standing of any community [1]. The substantial provision of electricity can contribute towards improved standards of living including better health, education, transport, agriculture and employment [1-3]. Around 1.3 billion people around the world that constitute 18 percent of the global population lack access to electricity [4, 5]. It is also estimated that around 85 percent of the people lacking access of electricity are the residents of rural areas [5].Therefore, rural electrification is the need of the hour to attain the social benefits associated with the easy access and reliable availability of electricity.

Decreasing costs of solar panels along with high insolation levels in most developing regions have resulted in wide deployments of solar technologies for rural electrification [6-9]. Further, the use of integrated microgrids containing local generation, distribution and utilization has its benefits compared to standalone systems. Several autonomous microgrid architectures have been discussed in literature [10]-[11]. DC microgrids with DC generation are generally more optimized due to efficient generation, distribution and storage of electrical energy due to absence of subsequent DC- AC conversion stages. It has been reported in [12, 13] that the overall efficiency of DC microgrids is higher i.e. around 80% (for DC loads) compared to AC microgrids which are less than 60% efficient.

In this paper, a DC microgrid is explicitly modeled to compare its operational efficiency for two of the proposed architectures i.e. DGDSA and CGCSA at different voltage levels and different conductor masses. As a test case, a typical rural community consisting of 40 households is considered for microgrid implementation. It has been shown in subsequent sections that DGDSA has advantages over CGCSA due to its distributed and resource sharing nature. Further, the higher operational efficiency, lower voltage drops and scalability makes DGDSA more favorable candidate for future microgrid implementations. Another key advantage of DGDSA, which makes its distinctive from CGCSA, is its flexible bi-directional power provisioning capability. Therefore, by adjusting the power allocations, communal load consisting of health care units, school and water pumping load may be derived without excessive dedicated generation units.

The paper is organized in the following sections. Section I describes the need for dc microgrids based rural electrification and brief introduction of proposed analysis. In Section II structural models of DGDSA and CGCSA are presented. Section III is dedicated for the formulation of modified Newton- Raphson based DC power flow analysis. Section IV discusses the analysis results of both of the proposed architectures for various power provisioning scenarios at different voltage levels and different conductor masses. Experimental results are also presented in section IV. The concluding remarks for the comparative analysis are delineated in section V.

II. MODEL OF DC MICROGRID

The proposed microgrid is an autonomous, self-sustaining system of electrical interconnections that is capable of generation, storage and distribution of electricity to the loads. PV panels are the primary sources of energy, however, the topology presented is universal in nature and any other generation source may be integrated with DC microgrid. For instance, a bio-fuel generator could be coupled with the microgrid using rectified generator output. However, for the current scope of the work, only the PV source is under consideration.

In solar panels, the non-linear output V-I and P-V characteristics requires a DC-DC converter ensuring maximum

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power point tracking (MPPT). This is employed in both of the architectures. Several MPPT methods for partial and uniform illumination conditions are presented in literature [14, 15]. However, in the proposed microgrid topology, Perturb and Observe (P&O) is used for MPPT due to relatively simpler design and fast convergence characteristics[16]. In order to provide necessary autonomy, batteries are used as storage system. For distributed architectures, smaller batteries at a nanogrid are available. For central architecture, batteries as well as panels are located at a central location. Typical load on each house is taken as 40W for lighting, fan and charging purposes. Village model is divided in five segments where each segment contains eight houses. Households and microgrid are interconnected via ring main scheme to ensure lower voltage drops, higher efficiency and effective reliability of distribution [17]. Both CGCSA and DGDSA are built on the interconnection model given in figure 1. The ring architecture provides necessary redundancy in case of an open conductor fault, therefore, enhances the reliability of the system. The ring main interconnection topology is shown in figure 1.

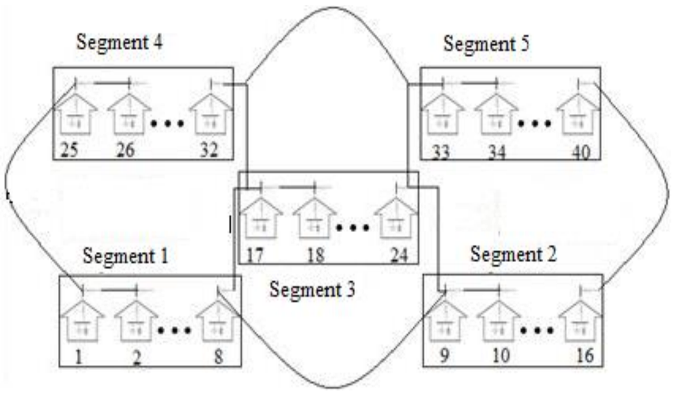

Fig. 1. Ring Main Scheme of Interconnection.

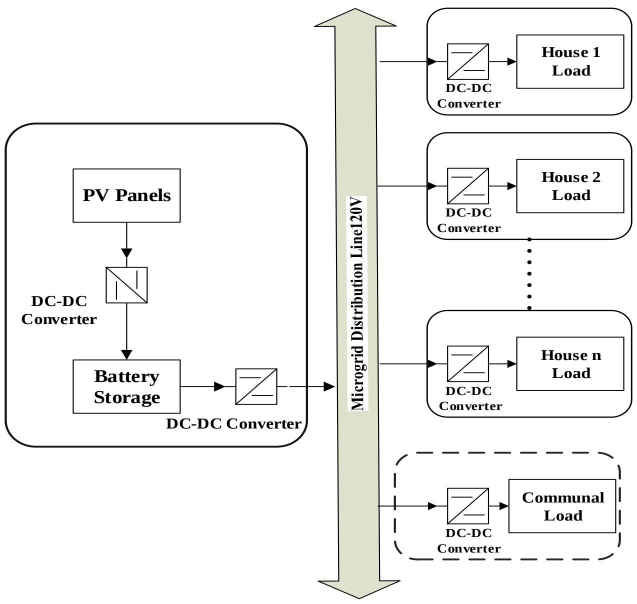

Fig. 2. Central Generation Central Storage Architecture

Following two independent architectures are presented in details.

A. *Central Storage Central Generation Architecture*

Figure 2 shows the topological diagram of CGCSA. CGCSA has central solar PV generation and central storage with a unidirectional flow of power to subscribing houses. The load for community center consisting of school computing or health care unit may also be derived from the central distribution line, however, generation capacity has to be designed as per over all load requirements. Since, there is unidirectional flow of power, so at generation end, only a single DC-DC boost converter is required for stepping up the voltage to microgrid distribution voltage level. MPPT is also achieved through the same DC-DC boost converter. At the consumer end another DC-DC converter is required to step down the microgrid voltage level to household devices level.

The household converter along with the load can by modeled by a resistor in this topology. Voltage level of DC microgrid is one of the key dimensions that need to be carefully selected. The optimal selection of voltage level for DC microgrid CGCSA will be discussed in later section IV. The placement of generation and battery storage unit is another key factor that needs to be optimized for minimum distribution losses and higher system efficiencies. Section IV also discusses the optimal placement of central generation and central storage units.

B. *Distributed Storage Distributed Generation Architecture*

In DGDSA, every house has its own solar panel mounted on the roof top and battery as shown in figure 3. Thus each house is capable of generation, storage and bi-directional flow of power, therefore, termed as nano-grid. DGDSA microgrid is formulated as a combination of 40 households (nano-grid) units that may share their resources to take the benefit of usage diversity and may even drive communal loads without excessive increase in the generation units.

An individual household nanogrid as shown in figure 3 can be modeled by a combination of solar panel, household load, battery, DC-DC boost converter and a bidirectional flyback converter. DC-DC boost converter is connected at the output of solar panel and it serves two purposes.

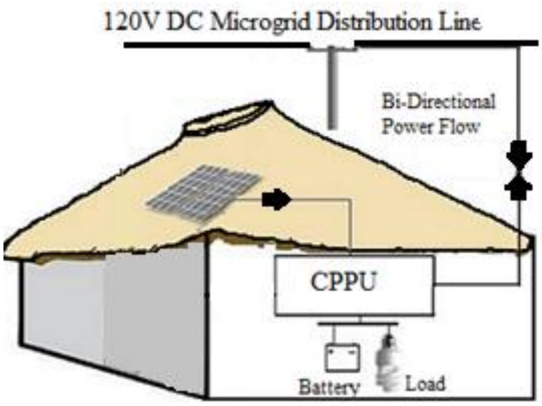

Fig. 3. Nanogrid Model of DGDSA

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Firstly, it produces voltage boost as per microgrid distribution voltage level to ensure homogenous grid integration. Secondly, it performs MPPT to extract the maximum out of incident solar energy. Depending upon the load requirements, bi- directional flyback converter effectively transforms the battery or load level voltage to the grid level voltage or vice versa [18]. Both the converters, along with an intelligent controller that is required to control the direction as well as amount of power flow are embedded in a central power processing unit (CPPU) as shown in figure 3.

Thus bidirectional flow of power imparts natural power provisioning flexibility to DGDSA. It can effectively derive the household load, charge the battery and dump the power directly on the grid as well indirectly through the charged batteries and bidirectional flyback converter. Various power provisioning scenarios for optimal selection of voltage level for DGDSA operation are discussed in section 4. The community load scenario for DGDSA is also presented and compared with CGCSA in terms of voltage drops and distribution efficiency.

III. Modified Newton- Raphson Method for Power Flow Analysis

Power flow analysis is performed to calculate optimal voltage level and conductor mass for DC microgrid operation. In conventional AC power systems, various methods such as Gauss-Seidel (GS), Newton-Raphson (NR) and Fast decouple are generally used for power flow analysis [19, 20]. In this paper, a modified Newton-Raphson method is presented for DC power flow analysis [21]. By using the presented method, many important system parameters such as Line Losses, efficiency and voltage drops are analyzed for various voltage levels and conductor sizes. The optimal placement of central generation and central storage units is another important parameter that is optimized via modified NR power flow analysis. Similarly for DGDSA, various power provisioning scenarios may be tested using the proposed analysis to ascertain the overall enhanced efficiency of the system.

The results of power flow analysis for various cases in DGDSA and CGCSA are discussed in section 4. Consider a power system in which bus 'i' is connected to bus 'j' where j may vary from 1 to n. g_{i1},g_{i2} and g_{in} are the respective value of the conductance between bus i and j. Using KVL , current in bus i 'I_i' may be calculated by (1)

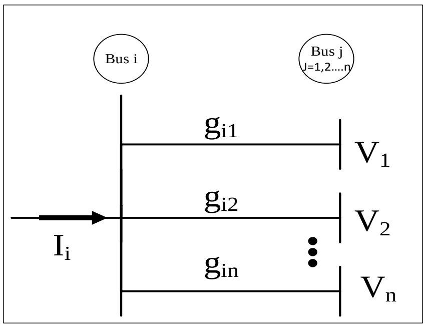

Fig. 4. A Typical Power System for Modified NR load flow analysis

$$I_i = \sum_{j=1}^{n} G_{ij} V_j \tag{1}$$

Where, 'G_{ij}' is the conductance matrix of the power system and is given in terms of individual conductance g_{ij} between bus i and j as given by (2).

$$Gij = \begin{cases} \sum_{j=1}^{n} g_{ij} & \text{for i} = j \\ -g_{ij} & \text{for i} \neq \text{j} \end{cases} \tag{2}$$

Power P_i at bus I may be calculated by (3)

$$P_i = V_i I_i \tag{3}$$

By putting (1) in (3) P_i may be written as

$$P_i = \sum_{j=1}^{n} V_i V_j G_{ij} \tag{4}$$

In a general analysis one of the generation bus generally, bus '1' is reserved for the balance of the power and is termed as slack bus. By expanding remaining terms of (4) using Taylor Series and neglecting higher order terms yields [19]

$$\begin{bmatrix} \Delta P_2^{(k)} \\ : \\ \Delta P_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial V_2} & .... & \frac{\partial P_2^{(k)}}{\partial V_n} \\ : & & : \\ \frac{\partial P_n^{(k)}}{\partial V_2} & .... & \frac{\partial P_n^{(k)}}{\partial V_n} \end{bmatrix} \begin{bmatrix} \Delta V_2^{(k)} \\ : \\ \Delta V_n^{(k)} \end{bmatrix} \tag{5}$$

Where, ΔP = difference in Scheduled Power P_{sch} and P_i calculated using (4) for k iterations.

Standard voltage is taken as reference for slack bus. Initial estimate of voltages for generator busses are slightly higher than reference voltage and for load busses these are assumed slightly lower than reference voltage. Using (5), the change in voltages ΔV and corresponding bus voltage V for k iterations are found until the difference between scheduled and calculated power becomes very close to zero. After convergence, bus voltage V is used to calculate the power of slack bus using (4). Using the converged value of voltage at each bus, associated line losses 'LL_g', percentage line losses '$\%LL_g$', voltage drop 'VD_g' percentage voltage drop '$\%VD_g$' and efficiency 'η_g' for the dc microgrid are calculated as

$$LL_g = \frac{1}{2} G_{ij} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(V_i (Vi - Vj) + V_j (Vj - Vi) \right) \tag{6}$$

$$\%LL_g = \frac{LL_g}{P_G} \tag{7}$$

$$\eta_g = 100 - \%LL_g \tag{8}$$

Where, $P_G = \sum_{i=1}^{n} (P_i > 0)$

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$$VD_g = V_{max} - V_{min} \quad (9)$$

$$\%VD_g = \frac{V_{max} - V_{min}}{V_{max}} * 100 \quad (10)$$

Where, V_{max} and V_{min} are the maximum and minimum values of voltage at any bus after k^{th} iteration.

IV. Results and Discussions

Modified NR analysis is applied on the proposed architectures to evaluate their efficiencies at various voltage levels and conductor masses. Different convenient dc voltage levels for dc microgrid operation are presented in [22]. In the presented analysis, the operation of grid is evaluated on 120V, 240V, 320V and 400V. The length of conductor between consecutive houses is assumed to be 20m. Similarly, the length of internal wiring of the house is also assumed 20m. Different cross sectional areas for conductors i.e. 0.2mm^2, 0.45mm^2, 2.5mm^2, 6mm^2 and 7.5mm^2 are evaluated. Using (7) (8) and (10), $\%LL_g$, $\%\eta$ and $\%VD_g$ are calculated for the following scenarios of CGCSA and DGDSA.

A. CGCSA without Communal load

In this scheme, peak load scenario is considered, where every house is demanding 40W power. The optimal placement for generation and storage units are found by running an iterative loop for all generation busses. System efficiency against each bus placement is recorded and bus with highest efficiency is selected.

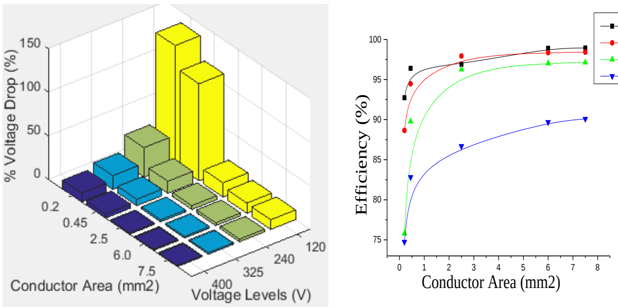

Fig. 5. Typical % Voltage drop and Efficiency for CGCSA with Peak Load and Far End Placement.

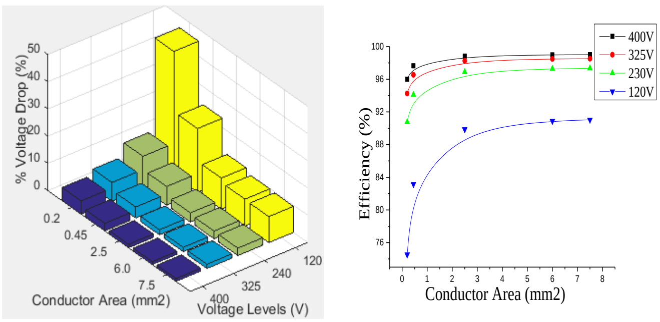

Fig. 6. Typical % Voltage Drop and Efficiency for CGCSA with Peak Load and Central Placement.

Figure 5 shows the results for %VDg and %η for different voltage levels and different mass produced conductors, when generation and storage units are placed at one of the starting or ending points of the corner segments i.e. segment 1, 2, 4 and 5 (Refer to figure 1). Figure 6 shows the results for $\%VD_g$ and %η, for different voltage levels and different mass produced conductors, when generation and storage units are placed at center of segment 3. From figure 6 it may be concluded that higher efficiencies and lower voltage drops are achieved by placing generation and storage unit at central location as compared to far end region placement.

B. CGCSA with Communal load

Figure 7 shows the results for %VDg and %η for communal load scenario, in which each of the houses is restricted to 30W, while 400W is supplied to communal load. This may be a typical scenario where during first half of a day, the power is allocated for computing school for children with limited power delivered to households. The optimal location for communal load on the microgird is found by running an iterative loop for placement at all possible load busses and comparing system efficiency. The bus with highest efficiency is selected which in our proposed case of CGCSA is located at the center of segment 3 and is shown in figure 7.

C. DGDSA without Communal Load

In this architecture, each house has a local generation through a solar panel, local battery storage and bidirectional flow of power to and from the grid in real time. Therefore flexible power provisioning is possible depending upon the load requirements in each house.

In a typical scenario, some of the houses are generating power more than their requirements, thus producing net power, while remaining houses would be consuming more power than their rated power, thus consuming net power from the grid. The microgrid acts as a bridge between houses that are generating net power and houses that are consuming net power. Thus, various thresholds for power sharing between the houses and microgrids may be defined according to the service level agreement or other practical constraints in the system .

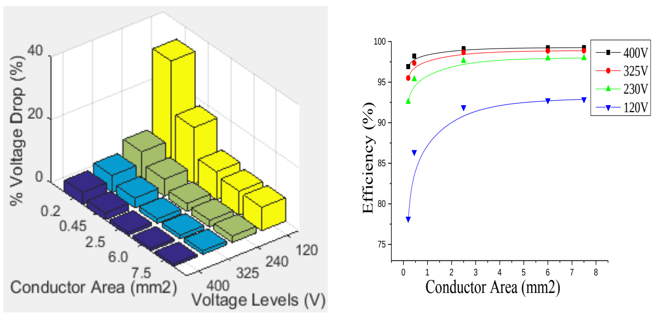

Fig. 7. %Voltage drop and Efficiency for CGCSA with Communal Load and Central Placement

Figure 8 shows a typical case of average power sharing where power sharing between houses and grid is taken as ±20% (a house can demand 20% more or supply 20% of its rated power). It can be seen from results that it is possible to achieve efficiency greater than 99% with almost all the proposed voltage levels and conductor masses.

Similarly, Figure 9 shows the peak power sharing scenario, where each house may supply 100% of its rated power or demand 100% more from its rated power. Thus power sharing limit is defined to be ±100%. Thus, results in figure 10 shows that despite of peak power sharing, higher efficiency is still achievable due mutual resources sharing and usage diversity factor. These results show that even with 120V microgrid distribution voltage and 2.5mm2 cross sectional area of conductor, the achievable system efficiency is greater than 99%. Since 120V is a safer voltage level than the typical LVDC standard of 380V, therefore the proposed scheme ensures a considerable balance between efficiency and safety at moderate voltage levels.

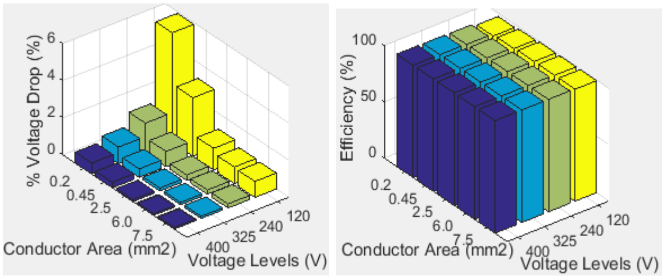

Fig. 8. %Voltage Drop and Efficiency for Average Power Sharing in DGDSA

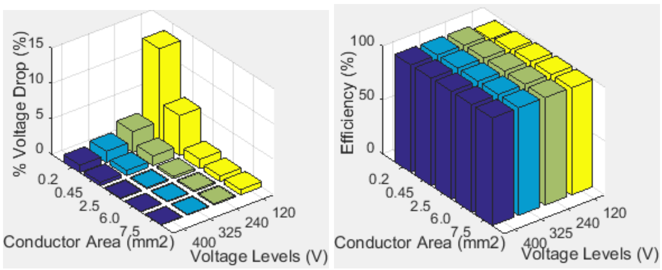

Fig. 9. %Voltage Drop and Efficiency for Peak Power Sharing in DGDSA

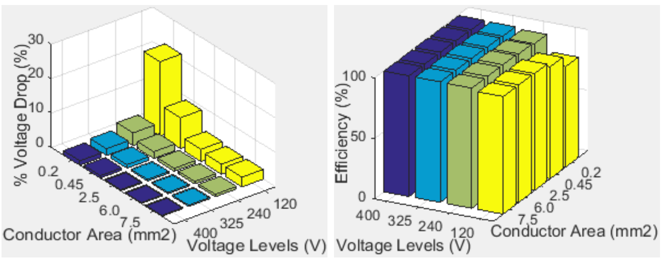

Fig. 10. %Voltage Drop and Efficiency for DGDSA with communal load

D. DGDSA with Communal Load

Now consider the case of communal load where each house is contributing 25% of its rated power to derive the communal load of 400W. This may be the typical scenario in a day where each house has been provisioned with 75 percent of its rated power i.e. 30W for its own house load requirements. Resulting percentage voltage drops and efficiencies for different voltage levels and mass produced conductors are plotted in figure 10.

E. Comparison Between CGCSA and DGDSA

In order to make a comparison between both the proposed architectures, they are compared on the same level of system loading. A typical conductor mass of 2.5 mm^2 cross section is selected. Table 1 show the comparison between the system parameters (Percentage line loss, Percentage voltage drop and efficiency) of CGCSA and DGDSA for communal load scenario, where 400W power is supplied to communal load.

TABLE I. COMMUNAL LOAD COMPARISON BETWEEN CGCSA AND DGDSA

Voltage Level (V)	**Cond. Area (mm^2)**	**CGCSA**			**DGDSA**		
		LL_g (%)	**VD_g (%)**	**η (%)**	**LL_g (%)**	**VD_g (%)**	**η (%)**
120	2.5	8.11	8.86	91.89	3.30	3.52	96.70
230	2.5	2.38	2.53	97.62	0.80	0.84	99.20
325	2.5	1.33	1.43	98.67	0.44	0.45	99.56
400	2.5	0.89	0.96	99.11	0.29	0.30	99.71

From the results of table 1, it may be concluded that for uniform system loading conditions, DGDSA has comparatively higher efficiencies in comparison to CGCSA due to usage diversity and mutual resource sharing capabilities.

F. Hardware Implementaion Results

The practical setup for the scaled down hardware implementation of DGDSA is shown in figure 11. In scaled down version, four houses are considered for power flow analysis. The net power generating house is modeled via a DC power supply, while the net power consuming house is modeled via resistive units.

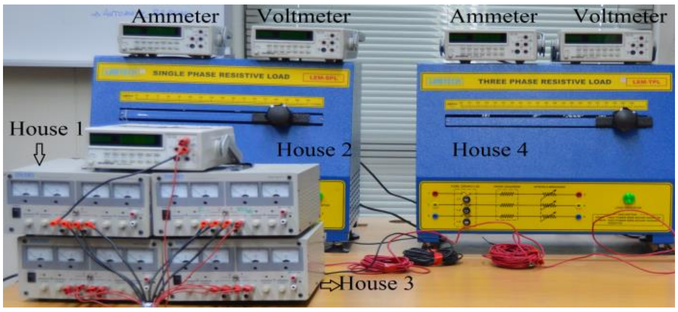

Fig. 11. Hardware Implementation of Scaled down version of DGDSA

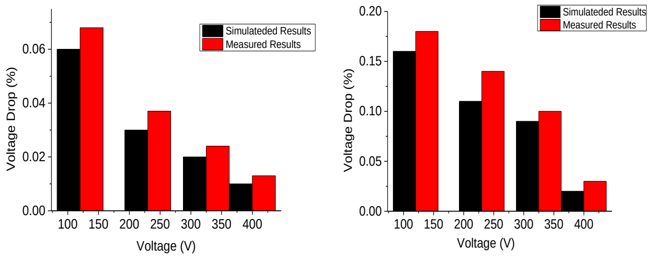

Fig. 12. Measured v/s Simulated %Voltage Drops Results at 120V, 230V, 325V and 400V for

a)DGDSA b)CGCSA

In case of DGDSA as show in figure 11, two houses are producing net power, while remaining two houses are consuming net power. Similar arrangement is made for CGCSA, where only one house generates net power and rest of three houses will consume power. Peak load operation for DGDSA and CGCSA is evaluated and measured results are found in agreement with the simulated results. The measured v/s simulated results of percentage voltage drops for CGCSA and DGDSA for scaled down version are shown in figure 12. Difference between simulated and measured results accounts for the excessive resistive losses at the joints and terminal points.

V. CONCLUSION

Analysis of central and distributed architectures of solar PV DC microgrids for Rural Electrification is presented in this paper. Modified Newton-Raphson technique for DC power flow analysis of CGCSA and DGDSA is applied to calculate the system parameters such as percentage voltage drops, percentage line losses and efficiency. Based upon the results of power flow analysis in CGCSA, optimal placement for generation and storage units as well as communal load is selected to ensure the minimum line losses. In order to extract the benefit of usage diversity, various scenarios of bi-directionally flexible power provisioning are evaluated. It has been concluded that for the same level of system loading, DGDSA has higher efficiency, lower line losses and less voltage drops as compared to CGCSA. In order to validate the proposed methodology, scaled down version of hardware is implemented and practical results are found in agreement with the simulation outcomes. Based upon the findings, it is concluded that DGDSA is the most promising choice for communal load based remote area electrification.

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