A mathematical model-based approach for DC multi-microgrid performance evaluations considering intermittent distributed energy resources, energy storage, multiple load classes, and system components variations

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Abstract

The efficiency of DC microgrid needs investigation from a smart grid perspective, since their spread has expected to prevail in comparison with AC counterparts. Furthermore, there is a need to address the limitations (majorly to cater the intermittency of distributed energy resources (DERs) as well as the time dependency of systematic parameters etc.) in previous model and propose a new mathematical model to evaluate system efficiency for given parameters and scenarios. The core focus of current study aims at formulation of an improved (composite) mathematical model, that is capable of bridging issues and serve as a tool to address requirements of future DC systems including microgrids (MGs) and multi-microgrids (MMGs). This research work offers such a mathematical model that consists of 3D matrices based on newly derived set of discrete time dependent equations, which evaluates the system efficiency of residential DC-MMGs. Each DC-MG is embedded with intermittent DERs, storage, components (with efficiency variations), and multi-class load (with discrete time dependency), for evaluation across worst, normal, and best scenarios. A comprehensive sensitivity analysis across various cases and respective scenarios are also presented to evaluate overall system performance. Also, the impacts of system parameters on various system variables, states, and overall system efficiency have presented in this paper.

KEYWORDS

DC microgrids, DC multi-microgrids, distributed energy resources, efficiency, smart grids

1 INTRODUCTION

In Ref. 1 the first era of electricity grid was DC and was replaced by AC grid due to advent of transformer that is capable of multi-level voltage transformation capability.2,3 Current AC grid structure is prone to various issues that has motivated transition toward smart grids. New distribution mechanisms, that is, microgrids (MG) and multi-microgrid
(MMG) enables consumer with better energy management options that were limited in the traditional grids. The AC system is still prevailed in MG as evident by various research efforts. However, DC distribution aiming MG concept has become a prominent research dimension in recent years.

In recent years, research community is inclined toward DC MGs due to high penetration of renewables, that is, solar photo-voltaic (PV) generation at distribution grid. Besides, PV generation contributes to DC level as an intermediate stage before converting into line frequency from different windfarms.4,5 Also, various PV as well as on/offshore windfarm generation-based control grids have been proposed.6-9 Successful DC power transfer via HVDC lines and growing DC natured VFD/VSD based loads at utilization side have motivated researchers to give their best efforts in this area.10,11 HVDC is more matured technology now a days since Siemens12 and ABB13 have provided vast solution for DC system spread. The advances in Power Electronics are accredited with SSTs and PECs; to attain multilevel DC voltage in grid and considers efficiency as key performance parameters.

On the utilization side, loads in commercial or residential buildings requires DC energy such as personal computers, laptops, battery-based devices. Main DC load contributor is light emitting diodes (LEDs)14,15 along with space heating/cooling.16 in homes and offices. The DC power/energy demand at the utilization side is expected to be prevalent in in future years. Thus, DC distribution must consider MG for future grid requirements.17-25

The research efforts in literature addresses various applications of DC distribution system with MG. The authors in Ref. 26 mainly focuses on DC MGs and its different contingencies. Authors in Ref. 22 made an effort to perform an analysis for the protection of smart DC MG with a ring topology, using a parameter estimation approach. Their efforts and references27-32 revealed that the field of DC MG, MMG and residential systems are still under-research with respect to energy management and cost effective solution. However, a proper mathematical model considering the distributed energy resource (DER) (wind-solar) intermittency was limited.

2 | LITERATURE REVIEW

2.1 | Reviewed works in literature

A comparative analysis is performed with radial topology for both AC-DC distribution test grids. The DC system is suitable and advocates need for proper mathematical model.33 An efficiency comparison in Ref. 34 for AC-DC distribution grids in commercial buildings. The study considers load side PEC losses, efficiency variation, conductor losses, DERs, storage, and load variation based on daytime. However, all loads are assumed unrealistically DC only. AC-DC system comparison work in Ref. 35 studies losses, load side PEC converter efficiency variation, DER, and storage, except SST efficiency variation.

A study in Ref. 16 offers a AC-DC residential building comparison, which is performed using simulation-based analysis considering US data with respective categorizations. The results show that AC is better than DC with higher efficiency of 2%. The estimation considers system losses, efficiency variations (of PEC converters and SST) with a variety in loads to evaluate the system efficiency. However, DER and storage is not included in evaluations. Contrary to, Ref. 16 authors in Ref. 36 demonstrates that DC system give more energy savings rather than AC system for US residential buildings. It is found that 5% and 14% of energy can be saved in PV-based residential buildings, with and without storage, respectively. Still, the study lacks a mathematical model for system efficiency evaluation with SST and DER.

The AC-DC efficiency comparison performed in Ref. 37 considers load side PEC losses, SSTs efficiency variation, and variety in loads. However, evaluations lack consideration of various PEC classes, storage, and DERs, to evaluate system efficiency. In Ref. 38, PEC losses and a variety of residential loads are suitable in presence of local DC source only. Although sensitivity-based analysis was offered, considering the worst-case scenario of system contingents, except evaluation on a proper mathematical model. The system evaluation in Ref. 17 counts fuel cell and load side PEC losses; and concludes LVDC system achieve higher efficiency than LVAC. However, SSTs and PEC efficiencies variation, DER generations, variety of loads and losses were not included in the evaluations. In Ref. 39, averaged efficiency of load side PECs and their losses are included to evaluate the system efficiency, which is improved by 1.3% with an energy storage and mix AC-DC distribution. However, variety of load classes and variations SSTs efficiency variations were not considered. In Refs 40,41, only distributed generation, PEC losses have taken into account to check the system performance.

In Ref. 42, an efficiency analysis is performed, for a DC residential distribution system comprising of modern homes and evaluated across simple power efficiency model. To check system efficiency, evaluation considers losses of PEC converters, conductor and in-building distribution. Results show smooth system efficiency during daytime and noticeably reduced at nighttime. However, the given model has limitations to deal with intermittency of DERs, energy storage, and variety of loads etc. An admirable work presented in Ref. 43 offers a detailed comparison regarding distribution efficiency of both AC and DC systems. The authors have pointed out their efforts regarding modeling to evaluate system efficiency. However, mathematical model is generic and does not address the energy storage, wind as DER, and discrete time dependency of load. This paper43 also provides the base work of our paper.
2.2 Limitations and originality of the paper

The proposed approach bridges various limitations in reviewed works, which is impetus of the proposed work. Most of the previous papers partially addressed various aspect of DC system applications and efficiency evaluation with simple models. However, an improved (composite) mathematical model, that is capable of bridging most of the addressed issues and serve as a tool to address future DC grid (MG and MMG) requirements, in limited in literature. Authors tried to the best of their knowledge, offers a comparison of recent work (point 1 to 3) and validating research effort from viewpoint of novelty and originality (point 4 to 6), shown as follows:

1. In response to limitations in Refs 33,34, proposed approach deals with the variety of loads with associated with respective category, for example, AC, DC, independent and VSD.
2. In response to limitations in Refs 16,17,35-41, offered approach deals with variations in SSTs and main grid efficiency, individual energy storage capacity and intermittency of DER generations, associated with each MG, variety of loads, and PECs and variation in efficiencies of PECs to compositely evaluate the system performance.
3. In response to limitations in Ref. 42,43, the proposed mathematical model will be a vital contribution, which addressed limitations in literature works and can deal with parameters, evaluate and check the system efficiency on different system variables and states. Also, model deals both DER intermittency and discrete time dependency.
4. This paper proposes the development of a novel mathematical model by considering all major system parameters, which were limited in previous works, that is, multi-level native categorical loads, efficiency of PECs, intermittent DERs, etc.
5. This research effort aims at objectives with the formulation of 3D matrices-based newly derived mathematical model to evaluate system efficiency by considering following assets like 1- discrete time dependent loads, 2- Intermittent DER generation, 3- storage, and 4- power exchanges. Moreover, sensitivity analysis will be performed to check the impacts of different system parameters on system performance.
6. The proposed model can be used for DC assets along with smart grid concepts (MG and MMG) and will serve as a valuable tool in future grid studies.

The paper is organized as follows: Section 1 gives a generic overview of issues and research dimensions. Section 2 is based on a literature review, shortcomings and framework to address limitations as novelty of this work. Section 3 shows the system topology and its components across centrally connected conceptual DC microgrid model. Section 4 presents the mathematical modeling consisting of a 3D matrices-based newly derived set of equations. Section 5 includes sensitivity analysis for system performance evaluation or various scenarios and states. Section 6 concludes the research work with future recommendations.

3 SYSTEM COMPONENTS

In this section, a conceptual system model and topology are proposed in which we tried to show all categorical loads, DERs including both solar and wind DERs, and storage.

3.1 System topology

A centrally connected grid topology is used, that is, each MG is connected to their neighboring MG as well as with main grid via SST as shown below in Figure 1. Power can flow bi-directionally in both cases, that is, MG to its neighboring MGs and MGs to Main grid.

3.2 Microgrid model

A MG presented in Figure 2 in which conventional electromagnetic induction-based transformers are replaced by SSTs, all categorical load, solar and wind DERs and storage is present. The components of the proposed MG model, consist of following:
3.2.1 | Load categories

MG loads are divided as Ref. 43 into four major categories shown as follows:

1. “A” Category: All loads inherently AC power based, for example, induction motor-based loads.
2. “D” Category: All types of loads are DC power-dependent, for example, electronic and lighting.
3. “I” Category: Loads independent of the nature of AC or DC power, for example, heating loads.
4. “VSD” Category: The VSD converter-based loads, for example, VSD-based air conditioners.

3.2.2 | Distributed energy resources

In the proposed system, both types of DERs have considered, that is, solar and wind Power. For the proposed model, the DERs, that is, a rooftop solar is present in the model which is attached to storage via MPPT based electronic converter that is linked with in-building distribution line through another DC-DC Boost Converter. Each MG has its own AC wind-based DER, which is converted to DC, to link with in-building distribution line via a PEC converter.

3.2.3 | Storage

Battery is attached to in-building distribution line from one end and with the solar panel via a PEC converter from the other end. It is considered that each MG has its own storage.

3.2.4 | In-building PEC converters

Powerstax F-Series based power electronic converters have used inside the MGs. Details of in-building PEC converters are given in Table S1 and shown as follows:

- Converters 1-3: F351-12-(12, 24, 48); Size: 350 W; Input 12 V; Output (12 V, 24 V, 48 V).
- Converters 3-6: F501-24-(12, 24, 48); Size: 500 W; Input 24 V; Output (12 V, 24 V, 48 V).
- Converters 7-9: F501-48-(12, 24, 48); Size: 500 W; Input 48 V; Output (12 V, 24 V, 48 V).

3.2.5 | Primary, secondary distribution feeder, and main grid

Only one phase is shown in model for primary distribution feeder from one SST to another SST. Likewise, one phase
is shown in model as secondary distribution feeder from one SST to another MG. Also, it is considered that the main grid is inherently DC in nature.

4 | SYSTEM MATHEMATICAL MODELING

System mathematical modeling for residential DC MGs includes power-based models of all categorical loads with ON or OFF states, DERs with intermittency, energy storage, in-building PECs, and SST. The model is formulated on a newly derived 3D matrices-based equations set that give total load of the system for the time of observation, input power from utility main DC Grid to the residential DC MGs or MMGs and overall system efficiency.

4.1 | Introduction to 3D matrices

The 3D matrices require three indices/coordinates or parameters to locate every entity. The three indices are presented by \( i, j, \) and \( s \) which represent the load, MG, and time sample numbers. To locate an entry into the 3D matrices, we must mention the \( i \)th load number present in \( j \)th MG at \( s \)th time of observation in which system efficiency needs to evaluate. Matrices are represented, that is, each matrix is a square matrix of the order of \( NTS \times 1 \). Where the \( x \)th number of loads can be present in \( y \)th, highest-numbered MG at the time \( ts \), having the highest number of samples “n” throughout the system. Thus, the “x” number of DC loads present in “y” MGs at time “ts” can be presented as (2) in compact form of a huge 3D matrix of the order of \( x \times y \) which depicts that each entity present in the matrix is itself a column matrix of the order of \( NTS \times 1 \).

\[
\begin{align*}
DC_{L,yMGs}(ts) & = \left[ p_{Dij}^{ts} \right]_{NTS \times 1}^{xy} \\
& = \left[ p_{D11}(ts) \right]_{NTS \times 1} \ldots \left[ p_{Diy}(ts) \right]_{NTS \times 1} \\
& \quad \quad \vdots \quad \quad \ddots \quad \quad \vdots \\
& \quad \quad \left[ p_{Dx1}(ts) \right]_{NTS \times 1} \ldots \left[ p_{Dxy}(ts) \right]_{NTS \times 1}
\end{align*}
\]

Here, \( \left[ p_{Dij}(ts) \right]_{NTS \times 1} \) is a column matrix (ie, first entity of \( DC_{L} \) \( (ts) \) matrix) which represents power of first DC load present in first MG at the time “ts,” expanded further as (3).

\[
\left[ p_{Dij}(ts) \right]_{NTS \times 1} = \begin{bmatrix} p_{Dij}(t_1) \\ p_{Dij}(t_2) \\ \vdots \\ p_{Dij}(t_n) \end{bmatrix}_{NTS \times 1}
\]

Similarly, 3D matrices can be formed for other categories, that is, \( A, I, \) and VSD, that is, \( A \) is given by (4), \( I \) categorical loads are shown as (5) and variable speed drive loads matrix is (6).

\[
AC_{L,yMGs}(ts) = \left[ p_{Aij}(ts) \right]_{NTS \times 1}^{xy}.
\]

\[
I_{L,yMGs}(ts) = \left[ p_{ij}(ts) \right]_{NTS \times 1}^{xy}.
\]

\[
VSD_{L,yMGs}(ts) = \left[ p_{VSDij}(ts) \right]_{NTS \times 1}^{xy}.
\]

4.2.2 | Mathematical modeling of in-building PECs

Referring to Section 3, worst case is considered for evaluations, that is, each load has its own converter or inverters in
case of AC loads in DC MGs. Each converter has its own rated power and efficiency. Thus, a matrix involving rated power of the converters connected to the corresponding loads and is given by (7).

\[
(\text{DC/DC})_{\text{rating}} (t_s) = \left[ p_{\text{DC}} (t_s) \right]_{\text{NTS} \times 1}.
\]

The converter efficiency can be evaluated as (8). The generalized form of the coefficients matrices is given by (9).

Finally, the efficiency-based 3D matrix can be presented as (10). Similarly, all the matrices would be formed for \( A \) and VSD loads-connected converters.

\[
\eta_{\text{DC/DC}} (t_s) = \left[ \eta_{\text{DC/DC}} (t_s) \right]_{\text{NTS} \times 1}.
\]

### 4.2.3 Mathematical modeling of DERs

#### Mathematical modeling of solar-based power generation

As each MG has its own solar power generation which is connected to the storage via a MPPT based PEC converter. MG-wise solar power can be presented as (11).

\[
p_{\text{MGs}} (t_s) = \left[ p_{\text{MGs}} (t_s) \right]_{\text{NTS} \times 1}.
\]

Attained solar power of all \( y \) MGs can be calculated as vector multiplication of matrices (12).

\[
p_{y} (t_s) = \left[ \beta (t_s) \right]_{y \times \text{NTS}} \left[ t_{\text{ms}} \cdots t_{\text{m0}} \right]_{\text{NTS} \times 1}.
\]

In (12), first matrix is conversion factor matrix (13), second matrix is of coefficients getting via curve fitting (14, 15) and last one is transposed time matrix (16) having some power.

\[
\lambda_{\text{SD}} (t_s) = \left[ \lambda_{\text{SD}} (t_s) \right]_{1 \times y}.
\]

\[
[\beta_j (t_s)]_{y \times \text{NTS}} = \left[ \beta_{j1} (t_s) \cdots \beta_{jn} (t_s) \right]_{y \times \text{NTS}},
\]

The intermittency of each PV at any time sample can be addressed by changing value of any variable in above equations. Accumulative solar power of all MGs can be evaluated as (17).

\[
p_{y} (t_s) = \sum_{j=1}^{y} \left[ \lambda_{\text{SD}} (t_s) \times \left( \beta_{j1} (t_s) + \cdots + \beta_{jn} (t_s) \right) \right].
\]

### Mathematical modeling of wind-based power generation

The worst case is considered to cater intermittency of DERs in proposed model, so other considerations are the air density, area of turbine and speed variation from MG to MG. The power extracted from wind is dependent on variables, that is, density and speed off the air, area of turbine and Betz limit, and are shown with respective matrices (18)-(20).

\[
\rho_j (t_s) = \begin{bmatrix} \rho_1 (t_s) \\ \rho_2 (t_s) \\ \vdots \\ \rho_y (t_s) \end{bmatrix} = \begin{bmatrix} \rho_1 (t_s) & \cdots & \rho_1 (t_n) \\ \vdots & \ddots & \vdots \\ \rho_y (t_s) & \cdots & \rho_y (t_n) \end{bmatrix},
\]

\[
A_j (t_s) = \begin{bmatrix} A_1 (t_s) & \cdots & A_y (t_s) \\ \vdots & \ddots & \vdots \\ A_1 (t_n) & \cdots & A_y (t_n) \end{bmatrix},
\]

\[
v_j (t_s) = \begin{bmatrix} v_1^j (t_s) \\ v_2^j (t_s) \\ \vdots \\ v_y^j (t_s) \end{bmatrix} = \begin{bmatrix} v_1^j (t_s) & \cdots & v_1^j (t_n) \\ \vdots & \ddots & \vdots \\ v_y^j (t_s) & \cdots & v_y^j (t_n) \end{bmatrix}.
\]

The accumulative wind-based power generation from MMGs must be normalized along time period, that is, cube of the number of time slots (ie, (NTS)3 in denominator) and shown in (21).

\[
p_w (t_s) = \frac{C_p}{2 (\text{NTS})^3 \times \eta_{Gj} \times \eta_{Tj}} \sum_{t_s = t_i}^{t_f} \left[ \rho_j (t_s) \right] A_j (t_s) v_j^3 (t_s).
\]
4.2.4 | Mathematical modeling of storage

Each MG has its own storage system in the form of batteries. So, the accumulative storage power is averaged power of all batteries present in all MGs and is given by (22).

$$p_{st,MGs}(t_s) = \frac{1}{NTS} \sum_{j=1}^{y} \sum_{t_s=t_1}^{t_s} p_{battery}(t_s).$$  \hspace{1cm} (22)

4.2.5 | Evaluation of total input power from main grid

To find out input power from main grid, we must find the accumulative input power for each categorical load of all MGs. The accumulative input powers for DC loads (i.e., averaged input power of all converters along No. of time slots) of all MGs are given by (23).

$$p_{DL,MGs}(t_s) = \sum_{j=1}^{y} \sum_{i=1}^{x} \sum_{t_i=t_1}^{t_i} \left\{ \frac{1}{NTS} \frac{p_{DL}(t_s)}{\eta_{DL}(t_s)} \right\}.$$  \hspace{1cm} (23)

The accumulative input power for AC loads is given by (24).

$$p_{AL,MGs}(t_s) = \sum_{j=1}^{y} \sum_{i=1}^{x} \sum_{t_i=t_1}^{t_i} \left\{ \frac{1}{NTS} \frac{p_{AL}(t_s)}{\eta_{AL}(t_s)} \right\}.$$  \hspace{1cm} (24)

The accumulative input power for independent loads is given by (25).

$$p_{IL,MGs}(t_s) = \sum_{j=1}^{y} \sum_{i=1}^{x} \sum_{t_i=t_1}^{t_i} \left\{ \frac{1}{NTS} (p_{IL}(t_s)) \right\}.$$  \hspace{1cm} (25)

For the case of VSD loads, the accumulative input power to MGs is given by (26).

$$p_{VSD,MGs}(t_s) = \sum_{j=1}^{y} \sum_{i=1}^{x} \sum_{t_i=t_1}^{t_i} \left\{ \frac{1}{NTS} (p_{VSD}(t_s)) \right\}.$$  \hspace{1cm} (26)

The (27) gives the total demand for all y MGs in the absence of DERs and storage.

$$p_{LD,MGs}(t_s) = \sum_{C \in DC, AC, \& VSD} p_{CL,MGs}(t_s).$$  \hspace{1cm} (27)

If the DERs and storage are present, then if the power from DERs is greater than that of demand then batteries would be charged, that is, act as a load, else will serve as a source. When the power from DERs is greater than that of demand is given by (28) under condition (29).

$$p_{De,MGs}(t_s) = p_{LD,MGs}(t_s) + p_{st,MGs}(t_s) - p_{st,MGs}(t_s) - p_{w,MGs}(t_s).$$  \hspace{1cm} (28)

$$p_{st,MGs}(t_s) + p_{w,MGs}(t_s) > p_{LD,MGs}(t_s).$$  \hspace{1cm} (29)

Total load demand when the power from DERs is less than that of demand in (30) s.t (31).

$$p_{De,MGs}(t_s) = p_{LD,MGs}(t_s) - p_{st,MGs}(t_s) - p_{st,MGs}(t_s) - p_{w,MGs}(t_s).$$  \hspace{1cm} (30)

$$p_{st,MGs}(t_s) + p_{w,MGs}(t_s) < p_{LD,MGs}(t_s).$$  \hspace{1cm} (31)

The total feeding power from SSTs to MGs must be the sum of demand for MGs and the secondary distribution losses (are used as function of output power of solid-state transformers) which are given by (32).

$$p_{SST,out}(t_s) = p_{De,MGs}(t_s) + p_{SST}(p_{SST,out}(t_s)).$$  \hspace{1cm} (32)

Input power from main grid is summation of power at input side of all SSTs (i.e., \(p_{SST, in}(t_s)\) is divided by efficiency of respective SST) and primary distribution losses (are used as function of input power form the Main Grid) are given by (33).

$$p_{in,MainGrid}(t_s) = \sum_{k=1}^{z} p_{SST, in}(t_s) \frac{\eta_{SST}}{\eta_{SST}} + p_{PD}(p_{in,MainGrid}(t_s)).$$  \hspace{1cm} (33)

4.2.6 | Evaluation of total load on main grid

The total load on main grid in the absence of DERs and storage is given by (34).

$$\text{Load}_{MGs}(t_s) = \sum_{C \in DC, AC, \& VSD} \{ C_{MGs}(t_s) \}.$$  \hspace{1cm} (34)

The storage will act as a load when the generation form DERs is greater than the demand; hence, the total load will increase such as in (35) under the condition given by (29).

$$\text{Load}_{MGs}(t_s) = \text{Load}_{MGs}(t_s) + p_{st,MGs}(t_s) - p_{st,MGs}(t_s) - p_{w,MGs}(t_s).$$  \hspace{1cm} (35)

The storage will act as a source when the local generation is less than that of load demand. Hence, total load on the main grid would be decreased as given in (35) s.t (31).
4.2.7 Evaluation of overall system efficiency

System efficiency can be found with total load on main grid (35) and demand or input power from main grid from (33), that is, system efficiency for a time sample is given by (36).

\[
\eta_{sys}(t_s) = \frac{TL_{\text{MGs}}(t_s)}{p_{\text{MainGrid}}(t_s)}.
\]

5 EVALUATION OF SYSTEM PERFORMANCE WITH SENSITIVITY ANALYSIS

5.1 Load data

The data are used for average monthly power consumption of for different US states and show that minimum consumption is 506 kWh for Hawaii and maximum is 1291 kWh for Louisiana state, the average daily consumption is calculated around 30 kWh energy and 1.25 kW as power. Then, US building split data for the year 2025 has been categorized and then changed into a pu system for the sake of simplification on the base of 1 kW. The load categorization and consumption data can be found in Table S2.

5.2 System states

The proposed system in Section 3 can have different states at any time. A state presents a set of variables on which system efficiency is to be evaluated. For a minute change in any of the variables will results in a different state hence, a different value of efficiency. Figure 3 is a conceptual state-to-state flow diagram in which only one variable is considered for the variation in the state. Here, “γ” is the increment or decrement in the efficiency of SSTs which causes the change in system state from one state to another state. Figure 4 is a conceptual diagram to present \( n \) different states, which are based on heptagons covered by the circles which include different levels for pu solar, wind and storage power, efficiency of SST, in-building PEC converter rated power, input and output voltages as variables. One can chose more than these systematic parameters similar or differently, but we chose these systematic parameters for system performance evaluation as they have greater influence on system performance evaluation that can be shown in the Section 5.4.

Here, \( s_1 \) is a state which reveals the system’s state where 0.375 pu for each solar and wind power, 0.5 pu power from storage, class D efficiency-based SSTs, 350W in-building converter having 12 V input and 24 V as output are present into the system. Each circle presents a state which has maximum efficiency than that of state beneath it. The classification of SSTs based on their efficiency ranges are 85%-87% for class-A, 88%-90% for class-B, 91%-93% for class-C and 94% and above for class-D, and shown in Table S3, respectively.

5.3 Simulations and results

All mathematical equations present in Section 4 have simulated in MatLab 2018Rb via .m coding file. For simulation, it is considered that there are 7 MGs that are connected to the main grid via individual SSTs. Each MG has a maximum 12 number of loads of each category. The number of MGs and number of loads can be changed in the same simulation. F-series based converters of Powerstax are used in a variety of states. Sensitivity analysis is performed by changing one variable at a time by keeping the others as constants to check the system efficiency. The number of states for system performance is evaluated, is given in (37).

\[
\text{No. of states} = \text{CT} \times \text{VL} \times \text{VIA} \times \text{EoS} = 2475
\]

Graphical representation is adopted to show the results. Moreover, to present the effect of individual variable on system performance, we chose a different state for each scenario.
mentioned below, that is, we considered that system is in different state whenever the impact of a system variable is desired to observe.

Figure 5 shows total load on main grid while considering all type of converter topologies individually and with varying ηSSTs, pDERs, and pstorage into system. It is found that total load on main grid is independent from SSTs efficiency, however, it varies as pu power from DERs and storage vary.

So, total load on main grid remains same for all converter topologies.

Figure 6 shows the input power from main grid for a specific converter case (F501-12-12 topology). For the total load on main grid, total input power from main grid to the system varies as it is dependent on SSTs efficiency, converter topology as well as on pu power from DERs and storage.

In Figure 7, the overall system efficiency corresponds to the above topology is presented. It can be concluded that system efficiency will be decreased by decreasing the SSTs efficiency and increasing the pDERs and pstorage and vice versa. In Figure 8, system behavior is also observed by considering same variations into the system as in above topology, however, converter topology considered (F351-12-24) is different. The total input power from main grid to the system for the concerned topology is shown in Figure 8. The overall system efficiency is shown in Figure 9.

The efficiency trend is same as in previous topology. For the converter F351-12-48 topology, the input power from main grid is given in Figure 10. The corresponding overall system efficiency is shown in Figure 11. System efficiency is in decreasing manner with the increase in pu powers from DERs and storage and decrease in SSTs efficiency.

For rest of six converter topologies (Section 3.2.4), the results have shown in tabular and graphical form in Appendix S1 with elongated ordinate to show minute change in input power from main grid and overall system efficiency.
The system is modeled in MatLab 2018Rb via .m-file and effect of different variables on total load on the main grid, total input from the main grid and at the end the efficiency of the system has been seen deeply. System performance is checked by sensitivity analysis.

5.4.1 Impacts of DERs on system efficiency

A state $s_2$ is chosen in which the accumulative power from storage present in all MGs is 0.25 pu, 350 W, 12 V input, and 24 V output voltages based in-building converters and from class A SSTs whose efficiency is 85%, has considered in test system at no loss and by varying accumulative power from all DERs. The system performance has shown in Table 1, that is, overall system efficiency will decrease by increasing DERs penetration into the system.

5.4.2 Impacts of storage on system efficiency

A state $s_3$ is chosen in which the accumulative power from all DERs present in all MGs is 0.5 pu, 500 W, 24 V input, and 12 V output voltages based in-building converters and from class A SSTs whose efficiency is 86% has considered at no losses (primary or secondary) into system and by varying accumulative power from storage, system performance is shown in Table 2. It is found that overall system efficiency is decreased by increasing the storage.
5.4.3 Impacts of SSTs efficiency on system performance

A state $s_4$ shown in (38), that is, system performance is analyzed, and sensitivity is observed. By changing the efficiency of SST’s system input power, total load, and system efficiency are evaluated in Table 3, that is, system efficiency is increases by increasing efficiency of SSTs.

$$s_4 = \begin{cases} P_{\text{sysMGs}} (t_s) = 0.375 \text{ pu} \\ P_{\text{wysMGs}} (t_s) = 0.375 \text{ pu} \\ P_{\text{stMGs}} (t_s) = 0.25 \text{ pu} \\ P_{\text{storage}} = 0 \text{ pu} \end{cases}$$

(38)

5.4.4 Impact of in-building PECs rated power

For a state $s_5$ shown in (39) below, system performance is evaluated. The corresponding system performance is shown in Table 4. System efficiency is in decreasing manner have been seen by increasing the rated power of in-building PECs.

$$s_5 = \begin{cases} P_{\text{sysMGs}} (t_s) = 0.375 \text{ pu} N_{\text{SST}} = 89 \% \\ P_{\text{wysMGs}} (t_s) = 0.375 \text{ pu} V_{\text{inPEC}} = 48 \text{ V} \\ P_{\text{stMGs}} (t_s) = 0.25 \text{ pu} V_{\text{oPEC}} = 12 \text{ V} \\ P_{\text{PDL}} = 0 \text{ pu} \\ P_{\text{SDL}} = 0 \text{ pu} \end{cases}$$

(39)
**FIGURE 10**  Input power from main grid to the system with varying SSTs efficiency, pDERs, and pstorage while considering F351-12-48 converter topology

**TABLE 1**  Impact of DERs on system efficiency ($s_2$)

| Power from DERs (pu) | System, pu results on the base of 1 kW | Total load | Sys. efficiency (%) |
|----------------------|---------------------------------------|------------|---------------------|
| 0                    | 11.803                                | 8.499      | 72.01               |
| 0.25                 | 11.509                                | 8.249      | 71.67               |
| 0.5                  | 11.215                                | 7.999      | 71.32               |
| 0.75                 | 10.921                                | 7.749      | 70.96               |
| 1                    | 10.627                                | 7.499      | 70.57               |

**TABLE 2**  Impact of storage on 1 kW test system ($s_3$)

| Power from storage (pu) | System, pu results on base of 1 kW | Total load | Sys. efficiency |
|-------------------------|-----------------------------------|------------|-----------------|
| 0                       | 13.338                            | 8.249      | 61.85           |
| 0.25                    | 13.047                            | 7.999      | 61.31           |
| 0.5                     | 12.756                            | 7.749      | 60.75           |
| 0.75                    | 12.466                            | 7.499      | 60.16           |
| 1                       | 12.175                            | 7.249      | 59.54           |
5.4.5 | Impact of in-building PECs input voltage

For state (s₆) in (40), the impact of input voltage from the viewpoint of variation is observed, that is, 12V to 24V and 24V to 48V. A trend is shown in Figure 12 which reveals that input voltage has a very drastic effect on system performance, that is, efficiency of the system decreases very fast and then remains almost constant.

\[
s_6 = \begin{cases} 
  p_{\text{sysMGs}} (t_s) = 0.375 \text{ pu} & p_{\text{t}} (t_s) = 0.5 \text{ pu} \\
  p_{\text{wsysMGs}} (t_s) = 0.375 \text{ pu} & \eta_{\text{SST}} = 89\% \\
  p_{\text{PDL}} = 0 \text{ pu} & p_{\text{SDL}} = 0 \text{ pu}
\end{cases}. \tag{40}
\]

5.4.6 | Impact of in-building PECs output voltage

For the state (s₇) shown in (41), the impact of input voltage is seen by changing it from 12 to 24 V and the 24 to 48 V. A trend is shown in Figure 13 which reveals that input voltage has a very drastic effect on system performance, that is, the efficiency of the system decreases very fast and then increases gradually as output voltage increases.

\[
s_7 = \begin{cases} 
  p_{\text{sysMGs}} (t_s) = 0.25 \text{ pu} & p_{\text{t}} (t_s) = 0.5 \text{ pu} \\
  p_{\text{wsysMGs}} (t_s) = 0.25 \text{ pu} & \eta_{\text{SST}} = 90\% \\
  p_{\text{PDL}} = 0 \text{ pu} & p_{\text{SDL}} = 0 \text{ pu}
\end{cases}. \tag{41}
\]

### TABLE 3 Impact of SST's efficiency on system performance (state s₄)

| η₅₅ (%) | System. pu results on the base of 1 kW |
|---------|-------------------------------------|
| pin_Main | Grid | Total load | Sys. efficiency (%) |
| 85-86   | 13.280-13.125 | 7.499 | 56.47-57.14 |
| 87-88   | 12.974-12.827 | 7.499 | 57.80-58.47 |
| 89-90   | 12.683-12.542 | 7.499 | 59.13-59.79 |
| 91-92   | 12.404-12.269 | 7.499 | 60.46-61.12 |
| 93-94   | 12.137-12.008 | 7.499 | 61.79-62.45 |
| 95      | 11.882     | 7.499 | 63.12     |

### TABLE 4 Impact of in-building PECs rated power on sys. performance (state s₅)

| PEC rated power (W) | System. pu results on the base of 1 kW | PEC rated power (W) | System. pu results on the base of 1 kW |
|---------------------|---------------------------------------|---------------------|---------------------------------------|
| pin_Main            | Grid | Total load | Sys. eff (%) | pin_Main | Total load | Sys. eff (%) |
| 100                 | 12.252 | 7.499 | 63.25 | 600 | 12.330 | 7.499 | 62.85 |
| 200                 | 12.298 | 7.499 | 63.01 | 700 | 12.332 | 7.499 | 62.84 |
| 300                 | 12.314 | 7.499 | 62.93 | 800 | 12.334 | 7.499 | 62.83 |
| 400                 | 12.322 | 7.499 | 62.89 | 900 | 12.335 | 7.499 | 62.82 |
| 500                 | 12.326 | 7.499 | 62.86 | 1000 | 12.336 | 7.499 | 62.82 |
TABLE 5  Impact of primary distribution losses (s_p)

| Power from DERs (pu) | pin_Main Grid | Total load | Sys. eff (%) |
|----------------------|---------------|------------|-------------|
| 0                    | 12.199        | 7.499      | 61.48       |
| 0.25                 | 12.449        | 7.499      | 60.24       |
| 0.5                  | 12.699        | 7.499      | 59.06       |
| 0.75                 | 12.949        | 7.499      | 57.92       |
| 1                    | 13.199        | 7.499      | 56.82       |

TABLE 6  Impact of secondary distribution losses (s_s)

| Power from storage (pu) | System, pu results on base of 1 kW |
|-------------------------|-----------------------------------|
|                         | pin_Main Grid | Total load | Sys. eff (%) |
| 0                       | 12.421        | 7.499      | 60.38       |
| 0.25                    | 12.699        | 7.499      | 59.06       |
| 0.5                     | 12.977        | 7.499      | 57.79       |
| 0.75                    | 13.254        | 7.499      | 56.58       |
| 1                       | 13.532        | 7.499      | 55.42       |

5.4.7  Impact of primary distribution losses
For state (s_p) given by (42), the system performance is evaluated to check the impact of primary distribution losses on system efficiency. The pu results have been presented in Table 5. Efficiency of the system will be decreased by increasing the primary distribution losses.

\[
s_p = \begin{cases} 
    p_{\text{sysMGs}}(t_i) = 0.375 \text{ pu } p_t (t_i) = 0.5 \text{ pu} \\
    p_{\text{wysMGs}}(t_i) = 0.375 \text{ pu } n_{\text{SST}} = 89\% \\
    p_{\text{wysMGs}}(t_i) = 0.25 \text{ pu } V_{\text{Spec}} = 12 \text{ V} \\
    p_{\text{SDL}} = 0.25 \text{ pu} 
\end{cases} \]  \quad (42)

5.4.8  Impact of secondary distribution losses
For state (s_s) given by (43), the system performance is evaluated to check the impact of secondary distribution losses on system efficiency.

\[
s_s = \begin{cases} 
    p_{\text{sysMGs}}(t_i) = 0.375 \text{ pu } p_t (t_i) = 0.5 \text{ pu} \\
    p_{\text{wysMGs}}(t_i) = 0.375 \text{ pu } n_{\text{SST}} = 89\% \\
    p_{\text{wysMGs}}(t_i) = 0.25 \text{ pu } V_{\text{Spec}} = 12 \text{ V} \\
    p_{\text{PSL}} = 0.5 \text{ pu} 
\end{cases} \]  \quad (43)

From Table 6, it can be observed that the secondary distribution losses have the same effect on system performance as of primary losses that is the system's efficiency decreases.

6  CONCLUSION AND FUTURE WORK

This paper has presented a mathematical modeling tool for DC microgrids or multi-microgrids aiming future prevalent requirements in smart grids. The proposed mathematical modeling bridges the limitations in previous works and offers a pathway to deal with a variety of loads with various types and discrete time dependency, and intermittency of DERs and storage. Besides, components variations have also incorporated into the model. The model consists of 3D matrices based on a newly derived set of equations and evaluates DC-MG based system and can also be used for AC-MG in future studies. Also, the proposed model deals with multiple aspects that were limited in previous work or addressed partially. A comprehensive sensitivity analysis is also performed and the trends of system efficiency for different states with varying system parameters have observed. In terms of impacts of system components verses system efficiency, it is found that with increasing DER and storages penetration decreases system efficiency. The system efficiency increases with increasing SSTs efficiency; however, it decreases with increasing the rated power of in-building PECs and system losses. In this paper, mathematical model is evaluated for the worst-case scenario. However, this model can be used while selecting any vital assumption to keep or replace with a real-world scenario having AC and DC nature of assets and respective microgrid topology.

NOMENCLATURE

A_j  area of jth MG-connected wind turbine
AC   alternating current
AC_L AC load matrix
C    load category
DC   direct current
DC_L DC load matrix
DERs distributed energy resources
HVDC high voltage direct DC
I, j and s indices used for ith load, jth MG and sth time sample
I_{IL} I load matrix
LVDC low voltage direct DC
Load_{MGs} pu load of MGs without DERs
MG, μG Micro grid/microgrid
MMG  multi-microgrid
pu   per unit
P_{Di}, P_A, P_t, & P_{PSL} pu powers of respective categorical loads
P_{SsysMGs} pu accumulative solar power of all MGs
P_{WsysMGs} pu accumulative wind power of all MGs
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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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