Power Loss Minimization in Smart Transformer Enabled Low Voltage Islanded Meshed Hybrid Microgrid

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\textbf{ABSTRACT} The smart transformer (ST) offers several features in a hybrid microgrid due to the presence of both ac and dc links while providing various power flow paths. For ST based meshed microgrid, continuous operation is highly important and one of the effective ways to achieve it is by minimizing line losses. This paper proposes a power loss minimization strategy which is specific for an ST based islanded meshed hybrid microgrid. In such an islanded system, a battery energy storage system (BESS) is used for maintaining the low voltage (LV) dc bus voltage of ST. The hybrid microgrid consists of renewable energy sources, electric vehicles (EV) charging stations, storage, etc. The minimization of total distribution line power loss is chosen as an objective function for optimization problem. The active power references of distributed generation converters and charge or discharge schedules of EVs are optimally controlled using genetic algorithm while satisfying the various constraints of the system. Further, a smart LV load shedding is also incorporated to the power management. This is activated on crossing the lower critical state of charge of the BESS. It is used as a final measure to increase BESS discharge time resulting in prolonged operation of the islanded system. Simulation and experimental results verify the performance of the proposed scheme. For the various cases considered, the proposed system is compared with conventional power management strategies. It was observed that while in a particular case, the conventional method incurred 1.337 kW losses, the proposed method was able to reduce the line losses to 1.0487 kW. This shows a 22\% reduction in line losses with proposed method as compared to conventional method.

\textbf{INDEX TERMS} Battery energy storage system (BESS), electric vehicle, islanding, meshed grid, smart transformer (ST).

\textbf{NOMENCLATURE}
\textbf{PARAMETERS}

- $V_{STLV}^{nom}$: Nominal LVac voltage.
- $n_{acl}$: Number of ac lines.
- $R_{ac}$: Resistance of ac line.
- $R_{dc}$: Resistance of dc line.
- $V_{min\,LVac}$: Minimum limit of load bus voltage magnitude specified by grid code.
- $V_{max\,LVac}$: Maximum limit of load bus voltage magnitude specified by grid code.
- $S_{rated\,DG\,Conv}$: Rating of DG converter.
- $SoC_{min\,EV_l}$: Minimum SOC limit of EV.

- $n_{dcl}$: Number of dc lines.
Several methods are proposed to obtain improved operation of ST in the distribution grid with such integrations [8], [9], [10]. In [11], stability assessment and voltage control mechanisms of ST in meshed and hybrid grids are discussed for healthy and faulty conditions in the grid. Meshed operation enables more power flow paths and provides the option to optimize losses in the system. This is explored in [20], where the DG converters are optimally controlled to incur lower losses and achieve an improved voltage profile. However, the islanded operation of the microgrid is not considered in this study.

The islanded operation of an ST based meshed hybrid microgrid is proposed in [21] and [22] during fault in medium voltage (MV) ac grid. During islanded operation, the energy stored in the LV grid needs to be controlled optimally to reduce losses and increase the operation time of LV grid. There are numerous studies in the literature which deal with optimization and loss reduction in distribution grids. In [23], the energy demand reduction is achieved through demand response with the help of optimal scheduling of DGs and EVs. The impact of the proposed method is tested on IEEE 24 bus transmission system. In [24], a new topology of distribution network is proposed in presence of renewable energy resources for minimizing the total cost of planning while considering the power loss cost. In [25], the optimal sizing of the DG capacity is performed for effective congestion management while considering the power loss reduction.

Moreover, aforementioned studies offer loss minimization in conventional microgrids. The loss minimization of islanded ST based meshed hybrid microgrid, utilizing the capabilities of ST and meshed operation is still unexplored.

To fill this research gap, in this paper, an optimal power management strategy is proposed to minimize the total line loss which results in increased operation time of LV grid.

\[ P_{ac,load}^i \] Load at the \( i^{th} \) LV ac bus.
\[ P_{dc,load}^i \] Load at the \( i^{th} \) LV dc bus.
\[ P_{DG} \] Power injected by the \( k^{th} \) DG plant.
\[ P_{EV} \] Power injected by the \( j^{th} \) EV.
\[ P_{BESS} \] Power injected by the \( l^{th} \) BESS.
\[ P_{DG,Conv}^0 \] Reference power for the \( k^{th} \) DG converter.
\[ I_{ac} \] Rms current flowing through ac line.
\[ I_{dc} \] Current flowing through dc line.
\[ V_{LVac}^i \] Magnitude of ac load voltage.
\[ V_{LVdc}^i \] Magnitude of dc load voltage.
\[ SoC_{EV} \] SoC of EV.
\[ SoC_{BESS} \] SoC of BESS.
\[ P_{EV}^{c_{min}}(t) \] Charging power of EV.
\[ P_{EV}^{c_{max}}(t) \] Discharging power of EV.
\[ P_{BESS}^{d_{min}}(t) \] Charging power of BESS.
\[ P_{BESS}^{d_{max}}(t) \] Discharging power of BESS.

I. INTRODUCTION

Recently, researchers have presented the smart transformer (ST) as an alternative to the conventional power transformer (CPT) [1]. As it is a power electronics based transformer with additional dc links and control functionalities, it can provide various ancillary services in addition to the functions of a CPT [2], [3]. Because of such features, researchers have conveyed ST as a smart device. Modern electric power systems are facing increasing integration of photovoltaic (PV) systems, wind systems, battery energy storage systems (BESS), electric vehicles (EVs), etc. [4], [5], [6], [7]. Thus, in such a scenario, the ST has been presented as a promising solution. Several methods are proposed to obtain improved operation of ST in the distribution grid with such integrations [8], [9], [10]. In [11], stability assessment and voltage control strategies have been investigated for ST fed distribution grids. Researchers have also explored various configurations of ST for improved integration of renewable sources into the grid.

In [12], a SiC based single stage ST is proposed with superior features like single stage operation, buffer port for active power decoupling, lightning protection, modular structure and soft switching capabilities. A semi-modular structure for ST is proposed in [13] which helps in reducing number of semiconductor devices in the overall ST.

The BESS integration to the grid with the help of ST is proposed in [14]. The peak load demand is reduced with the BESS through its proper sizing. It also helps to reduce the size of the ST converters. ST has also been used for formation and operation of microgrids. The power management for an ST based zonal microgrid is discussed in [15]. With the integration of BESS, the islanded operation of ST low voltage (LV) side is also proposed. However, the sizing of BESS or the power management based on state of charge (SoC) of the BESS is not analyzed.

When there is a parallel existence of both ac and dc grids, hybrid grids are generally formed by connecting ac and dc grids with the help of interlinking converters [16]. The extension of the ST LV dc bus in the distribution grid to connect the dc buses of distributed generation (DG) converters present on the LV side is proposed in [17] and [18]. Such a configuration forms a meshed hybrid grid which offers more power flow paths, lower distribution line losses, lower converter losses for reverse power flow, etc. In [19], various operation and control mechanisms of ST in meshed and hybrid grids are discussed for healthy and faulty conditions in the grid. Meshed operation enables more power flow paths and provides the option to optimize losses in the system. This is explored in [20], where the DG converters are optimally controlled to incur lower losses and achieve an improved voltage profile. However, the islanded operation of the microgrid is not considered in this study.
The proposed method is specific to islanded ST based meshed hybrid microgrid. The main contributions of the paper are summarized as follows:

- The multiple power flow paths offered by the meshed hybrid microgrid are exploited to achieve optimal power flow management in the islanded mode of operation.
- The proposed optimal power management algorithm considers the EVs connected to the grid along with their SoCs to further optimize the losses.
- A method of smart under voltage load shedding enabled by ST is also proposed to ensure longer operation time of critical loads in the system.
- Simulation and experimental validation is done to support the proposed scheme.

A comparison of the proposed work is done with the researches that are available in the literature. It is summarized in Table 1. The paper is organized as follows. Section II gives the description of the islanded meshed hybrid microgrid. Section III explains the centralized power management controller. The optimal power management strategy for the DG converters and EV schedules is discussed in Section IV. Section V elaborates the control strategies. The simulation and experimental results are explained in Section VI and VII respectively. The paper is concluded in Section VIII.

II. ISLANDED MESHER HYBRID MICROGRID

An ST based meshed hybrid microgrid is shown in Fig. 1. In such operation, the ST exchanges power from the MV side, the ST isolated dc-dc converter maintains the ST LVdc voltage and the ST LV converter maintains the ST LVac voltage. As LVdc bus is extended in the distribution line, the dc buses of the DG converters are connected to this line forming a mesh. For islanded mode of operation of such an LV meshed microgrid, the ST operates partially. The ST MV and isolated dc-dc converters are turned off and disconnected from the LV side with a breaker. Only the ST LV converter remains operational. The BESS converter operation changes to voltage control mode (VCM) to maintain the ST LVdc bus voltage. As the ST LVdc bus voltage is maintained constant, the ST LV converter operates undisturbed and maintains the LVac voltage. BESS as well as EVs are connected to the LVdc line of the system. The dc-dc converters of these systems operate in current control mode (CCM). The dc loads are also connected to the LVdc line at various points. The DG systems present in the distribution grid like PV and wind systems inject power to the LVac side with DG converters.

III. CENTRALIZED POWER MANAGEMENT CONTROLLER

A centralized power management controller is proposed which takes decisions based on the balance power of the system. In case the total load is higher than the total DG, the storage systems like the BESS and EVs support the loads. In case of surplus generation, the excess power is stored among the storage systems. The difference between the total load and the DG powers is the balance power of the microgrid.
A positive balance power means that the storage systems will be charged, while a negative value indicates power discharge by the storage systems. The balance power expression is given by

\[ P_{bal} = \sum_{i=1}^{m} P_{ac\_load_i} + \sum_{j=1}^{n} P_{dc\_load_j} - \sum_{k=1}^{o} P_{DG_k} \]  

where \( i, j \) and \( k \) are integers varying from 1 to \( m \), 1 to \( n \) and 1 to \( o \), respectively.

An optimization algorithm ensures that the power transfer from the DG converters and each of the EVs and storage systems are such that the losses are minimum. The controller manages the power in three stages - (a) primary, (b) secondary and (c) tertiary.

### A. PRIMARY POWER MANAGEMENT - SOURCE MANAGEMENT

In this stage, the power that has to be delivered or consumed by the BESS and EVs is computed. The LVac and LVdc buses at the ST LV converter are considered \( 0^{th} \) bus and the BESS maintaining the ST LVdc voltage is the \( 0^{th} \) BESS. The power transfer equation for this BESS is given by

\[ P_{BESS_0} = P_{bal} - \sum_{l=1}^{p} P_{EV_l} - \sum_{r=1}^{q} P_{BESS_r} \]  

\( l \) is an integer varying from 1 to \( p \) and \( r \) is an integer varying from 1 to \( q \).

The reference power for each of the EVs and BESS are obtained from the optimization algorithm which is explained in Section IV.

### B. SECONDARY POWER MANAGEMENT - DELIVERY MANAGEMENT

In the secondary power management, the DG converter reference powers are decided. Being a meshed hybrid microgrid, these converters draw power from the LVdc line and thus their power injection is not dependent on the availability of DG power. It is considered that the DG converters inject only active power to the LVac grid, and the reactive and harmonic powers are supplied by the ST. The reference powers for the DG converters are also obtained from the optimization algorithm. The amount of active power that the ST LV converter has to supply into the LVac side is given by

\[ P_{STLV} = \sum_{i=1}^{m} P_{ac\_load_i} - \sum_{k=1}^{o} P_{DG\_Conv_k} \]  

### C. TERTIARY POWER MANAGEMENT - LOAD SHEDDING

If there is a deficit of power and the SoC constraints tend towards the limiting value, then load is curtailed as a last resort. This is realized with the help of the ST by controlling the LVac voltage.

When the need for load curtailment arises, the centralized controller passes the information to the ST to lower the LVac voltage \( V_{STLV} \) to 0.95 p.u. This information is used to disconnect the non-critical loads from the LVac grid. This is the conventional under-voltage load shedding implemented by intentional lowering of LVac voltage [31]. A critical limit of SoC \( (\text{SoC}_{\text{critical}}_{\text{BESS}_0}) \) is defined to start this under voltage load shedding to ensure that the centralized BESS has a prolonged discharge time in order to supply critical loads in the system. Thus the voltage reference for the ST LV converter can be expressed as follows.

\[ V^*_{STLV} = \begin{cases} 0.95 V^\text{nom}_{STLV} & \text{if SoC}_{\text{BESS}_0} \leq \text{SoC}_{\text{critical}}_{\text{BESS}_0} \\ V^\text{nom}_{STLV} & \text{otherwise} \end{cases} \]  

The complete power management is shown in the flowchart given in Fig. 2.

### IV. PROPOSED OPTIMAL POWER MANAGEMENT SCHEME

This section explains the method of determination of optimal active power references of DG converters and charge or discharge schedules of EVs \( (P_{DG\_Conv_k} \text{ and } P_{EV_l}) \). The BESS systems in the distribution grid are similar to the EVs, i.e both
can act as storage systems which charge or discharge from the LVdc line working in CCM. Therefore, to simplify the analysis, only the EVs are considered.

A. OPTIMIZATION PROBLEM FORMULATION

The main goal of the proposed work is to increase the operation time of the isolated microgrid using battery energy storage and renewable energy sources present in the system. It is possible by minimizing the power losses in the distribution system. Therefore, the chosen problem is a single objective optimization problem. Accordingly, the objective function is chosen and implemented. An online optimal problem is formulated for determining \( P_{DG,\text{Conv}} \) and \( P_{EV} \). The objective function and constraints are given as follows.

\[
\text{minimize } f = P_{loss}(t) = \sum_{a=1}^{n_{ac}} (I_{ac}^a(t))^2 \times R_{ac}^a + \sum_{b=1}^{n_{dc}} (I_{dc}^b(t))^2 \times R_{dc}^b.
\] (5)

subjected to

1) Power balance constraint given in (1).
2) Bus voltages constraint
\[
V_{LVac}^{\text{min}} \leq V_{LVac}^l(t) \leq V_{LVac}^{\text{max}},
\]
\[
V_{LVdc}^{\text{min}} \leq V_{LVdc}^l(t) \leq V_{LVdc}^{\text{max}}.
\] (6)
3) DG converters rating constraint
\[
P_{DG,\text{Conv}}(t) \leq S_{\text{rated}}^{DG,\text{Conv}}.
\] (7)
4) SoC constraints of EVs
\[
SoC_{EV}^{\text{min}} \leq SoC_{EV}(t) \leq SoC_{EV}^{\text{max}}.
\] (8)
5) SoC constraints of BESS
\[
SoC_{BESS}^{\text{min}} \leq SoC_{BESS}(t) \leq SoC_{BESS}^{\text{max}}.
\] (9)
6) Charge/discharge power constraints of EVs
\[
P_{EV}(t) \leq P_{EV}^{\text{max}}, \quad P_{EV}^d(t) \leq P_{EV}^{\text{max}}.
\] (10)
7) Charge/discharge power constraints of BESS
\[
P_{BESS}^c(t) \leq P_{BESS}^{\text{max}}, \quad P_{BESS}^d(t) \leq P_{BESS}^{\text{max}}.
\] (11)

In (5), \( a \) and \( b \) are ac and dc line indices. \( V_{LVac}^{\text{min}} \) and \( V_{LVac}^{\text{max}} \) are chosen as 0.95 p.u. and 1.05 p.u., respectively [32].

B. SOLVING THE OPTIMIZATION PROBLEM

The considered fitness function is a non-linear function. Therefore, it is possible to solve the optimization problem with any non-linear optimization solver. The GA is a popular optimization technique used to solve the non-linear functions. Therefore, it is solved using GA solver in MATLAB [33]. The default values of GA solver are chosen for various parameters of GA, except for population size. The population size is tuned such that three different runs converges precisely to the same value and chosen as 40. The \( P_{DG,\text{Conv}} \) and \( SoC_{EV} \) are considered as control variables.

As per GA, firstly population initialization is done. Then calculation of fitness function is performed. This calculation is repeated through selection, crossover and mutation till the stop criteria is reached. This fitness function calculation requires power flow solution. For determining power flow solution, the type of buses and bus data in the distribution network are required. In the considered distribution network both LVac network and LVdc network are present. Since the ST LVac and LVdc bus voltages are maintained at 1 p.u., the ST LVac and LVdc buses are chosen as slack buses and the power flow equations are solved independently for LVac and LVdc networks. All the remaining buses are considered as load buses. The load bus power at each load bus in LVac network \( P_{lb,ac} \) is given in (12).

\[
P_{lb,ac} = P_{ac,load} - P_{DG,\text{Conv}}.
\] (12)
\[
Q_{lb,ac} = Q_{ac,load} - Q_{DG,\text{Conv}}.
\] (13)

The load bus power at each load bus in LVdc network \( P_{lb,dc} \) is given in (14).

\[
P_{lb,dc} = P_{dc,load} + P_{DG,\text{Conv}} - P_{DG}.
\] (14)

With the help of load powers the currents drawn by each load bus in LV ac and dc network \( I_{lb,ac} \) and \( I_{lb,dc} \) are calculated as given in (15) and (16), respectively.

\[
I_{lb,ac} = \frac{P_{lb,ac} - Q_{lb,ac}}{V_{vac}}.
\] (15)
\[
I_{lb,dc} = \frac{P_{lb,dc}}{V_{lvdc}}.
\] (16)

Using these load bus powers and currents, backward forward sweep power flow method is applied to both LVac and LVdc networks in order to obtain required power flow solution and thus, calculate the fitness function.

Once fitness function is calculated, GA checks certain stop criteria options such as maximum number of generations and function tolerance. If any one of these options is satisfied, the GA stops doing iterations and provides results.

V. CONTROL STRATEGIES

The power management algorithm in the centralized controller generates the power reference for the various converters in the system. Accordingly, the converters are controlled and operated to maintain the reference voltages and currents. The complete control diagram along with the simulation schematic considered for analysis is shown in Fig. 3. Two EV systems and two PV powered DG systems are considered. It is considered that \( EV_1 \) and \( DG_1 \) are at a distance of 250 m from the ST and the \( EV_2 \) and \( DG_2 \) are at a distance of 500 m from the ST. Both these points also have ac and dc loads connected. The control strategies consist of controlling the ST LV converter, the BESS dc-dc converters, EV dc-dc converters and the DG converters. In the grid connected mode, the ST MV converter draws power at unity power factor from the MVac side while maintaining the MVdc voltage and the dc-dc converter maintains the LVdc voltage [2]. These two converters are not operational in the islanded mode.
The control strategies of the converters operational during the islanded mode are discussed as follows.

A. **ST LV CONVERTER**
This converter is responsible for maintaining the LVac grid voltage. It draws power from the ST LVdc link and uses a proportional integral (PI) controller to follow the reference voltage \[^{230}\text{V}^*\text{per phase}\] at a frequency of 50 Hz is given.

B. **BESS DC-DC CONVERTER**
The BESS dc-dc converter is responsible for maintaining the LVdc voltage in the islanded mode. This also acts as the slack bus in the operation and maintains the power balance between demand and supply in the system. If the loads cannot be supplied by the DG sources and EVs, BESS supplies the remaining power. \(V_{LVdc}^*\) is considered as the reference output voltage of the converter. By comparing the actual LVdc voltage with this, the error is obtained and it is passed through a PI controller. The PI controller output is compared with a triangular signal to generate the switching pulses [35].

C. **EV DC-DC CONVERTERS**
These converters are similar to the BESS dc-dc converter. However, the mode of operation is CCM. Thus, instead of voltage reference, a current reference is given to these converters. The current references are obtained from power references which are generated by the optimal power management algorithm. The reference currents are compared with the actual currents and a PI controller is used to generate the firing pulses as per the error [35].

D. **DG CONVERTERS**
These converters work in CCM and maintain the reference power obtained from the optimal power management algorithm. The instantaneous symmetric component theory is used to generate the three phase current references from the reference power [36]. A PI controller is then used to maintain the actual currents of the DG converters as per the reference.

VI. **SIMULATION RESULTS**
The system is simulated in PSCAD software considering different scenarios. The simulation system details are given in Table 2. A total of six cases are considered for simulation. In the first two cases, loads higher than generation is considered. Here, the load change operation is shown from Case 1 to Case 2. In the next two cases, the scenario of surplus generation is considered and a load change operation...
TABLE 3. Summary of power flows in the system.

| Case | Load at LVac Bus 1 (kW) | Load at LVac Bus 2 (kW) | Load at LVdc Bus 1 (kW) | Load at LVdc Bus 2 (kW) | PV1 Power (kW) | PV2 Power (kW) | DG1 Power (kW) | DG2 Power (kW) | BEV1 Power (kW) | BEV2 Power (kW) |
|------|-------------------------|-------------------------|-------------------------|-------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1    | 15                      | 15                      | 5                       | 5                       | 14.5          | 16.5           | 14.8791        | 13.0399        | 5.308          | 1.608          |
| 2    | 25                      | 25                      | 5                       | 5                       | 14.5          | 18.5           | 15            | 20            | 5.552          | 6.444          |
| 3    | 0                       | 0                       | 0                       | 0                       | 7.2           | 9.3            | 0             | 0             | 0.0001         | -7.228         |
| 4    | 0                       | 0                       | 5                       | 5                       | 7.2           | 9.3            | 0             | 0             | -2.208         | -4.295         |
| 5    | 25                      | 15                      | 15                      | 10                      | 0             | 0             | 15            | 9.9107        | 0              | 0              |
| 6    | 15                      | 7.5                     | 15                      | 10                      | 0             | 0             | 9.0377        | 3.8578        | 0              | 0              |

FIGURE 5. Power flows in the system with BESS SoC within critical limits. (a) Total ac load power. (b) Total dc load power. (c) PV system 1 power. (d) PV system 2 power. (e) EV1 power. (f) BESS power. (g) DG converter 1 power injection. (h) DG converter 2 power injection. (i) ST LV converter power output.

FIGURE 6. Voltages and currents waveforms for transition from Case 1 to Case 2. (a) ST LVdc voltage. (b) ST LVac voltage. (c) LVac bus 1 load current. (d) LVac bus 2 load current. (e) DG converter 1 current. (f) DG converter 2 current. (g) The dc bus 1 and 2 voltages. (h) Storage system currents. (i) PV currents.

is shown in such a mode of operation. Finally, the scenario of under voltage load shedding is shown in the transition from Case 5 to Case 6. In each of the cases, the optimization algorithm which is implemented in MATLAB decides the reference powers for the EVs and the DG converters based on the system parameters. For example, in Case 1 the obtained best and mean fitness values plot of GA for this is shown in Fig. 4. The minimum value among the best fitness values i.e., 0.00824 W is the optimal power loss which is nearly zero. The obtained optimal values of $P_{DG, Conv}$ and $P_{EV}$ are given as inputs to the PSCAD simulation to verify the control aspects of ST based meshed hybrid microgrid and resulting battery power. This process is repeated while testing all the remaining cases. The power flows for these six cases are summarized in Table 3.

Fig. 5 shows the power flows during the system operation in the four cases from Case 1 to Case 4. In Cases 1 and 2 the PV powers are 14.5 kW and 18.5 kW for PV1 and PV2, respectively. These are reduced to 7.2 kW and 9.3 kW, respectively in Case 3 and Case 4. In the first two cases, the loads are higher than generation. Thus, it is seen that the EVs supply power. In the next two cases, the EVs are charged to consume
the surplus power. The DG converters follow the reference power as obtained from the optimal algorithm.

Fig. 6 shows the voltages and currents waveforms in the system for the transition from Case 1 to 2. The ST LVdc and ST LVac voltages are shown in Fig. 6(a) and (b), respectively. It can be observed that the power change does not affect these voltages. Fig. 6(c) and (d) shows the LVac bus 1 and LVac bus 2 loads, respectively. These are changed as per the data given in Table 3. The DG converters 1 and 2 inject currents according to the references obtained from the optimal power management algorithm and are shown in Fig. 6(e) and (f), respectively. The dc bus 1 and 2 voltages are shown in Fig. 6(g). These show minimum oscillations which do not affect the operation of the system. The battery and EV currents are shown in Fig. 6(h). These provide powers as per the given power references. The PV currents are kept constant as the PV powers are constant. These are shown in Fig. 6(i).

In Fig. 7 the currents in the system are shown for surplus generation. The transition is shown from Case 3 to Case 4. Here, ac loads are considered zero and the DG converters do not supply any power. The PV currents are shown in Fig. 7(a). These are constant as the PV powers are constant. The dc load currents are given in Fig. 7(b). Fig. 7(c) and (d) shows the EV currents and battery current, respectively. In case 3, the dc load is also kept zero. Thus, the entire PV power generated is used to charge the EVs. In Case 4, dc loads of 5 kW are added to both the dc buses. Therefore, reduced power is available for EV charging.

The proposed under-voltage load shedding is shown in Fig. 8. Fig. 8(a) shows the SoC of the BESS and Fig. 8(b) shows the ST LVdc voltage. When the SoC goes below 40%, the under voltage load shedding scheme is implemented and the LVac voltage is reduced to 0.95 p.u. This is seen in Fig. 8(c). This is detected at the LVac side load points and the non-critical loads are disconnected from the system. Accordingly, the LVac loads reduce as seen in Fig. 8(d) and (e).

To compare the performance of the proposed method with commonly used techniques, a loss comparison is done. A system is considered where power sharing by DG converters is done as per their individual ratings as considered in [17] and [37]. Moreover, EV power injection is also not considered. The loss comparison for such a system with the proposed system in the six cases considered is shown in Table 4.

| Case | Power Loss in the Conventional Method (kW) | Power Loss in the Proposed System (kW) | Power Loss Reduction (kW) |
|------|------------------------------------------|---------------------------------------|--------------------------|
| 1    | 0.0246                                   | 0                                     | 0.02459                  |
| 2    | 0.3186                                   | 0.2587                                | 0.0599                   |
| 3    | 0.1140                                   | 0                                     | 0.11399                  |
| 4    | 0.0194                                   | 0                                     | 0.0194                   |
| 5    | 1.3370                                   | 1.0483                                | 0.2883                   |
| 6    | 0.7874                                   | 0.5209                                | 0.2665                   |

VII. EXPERIMENTAL RESULTS

The block diagram of the complete experimental setup is shown in Fig. 9(a). To emulate the distribution line resistance, series resistances were added to both the ac and dc lines. The photographs of the ST LV converter, DG converter, BESS, EV system and PV system are shown in Fig. 9(b)-(f), respectively. The hardware parameters are given in Table 5.

Fig. 10 shows a load change operation when the system has surplus loads. The BESS maintains the ST LVdc voltage as shown in Fig. 10(a) and the ST LV converter maintains the ST LVac voltage as shown in Fig. 10(b). The LVdc load is kept constant at 100 W and the LVac load is increased from 140 W to 200 W. The corresponding LVac load currents are shown in Fig. 10(c). The optimization algorithm decides the power reference for the DG converter, and EV in these scenarios and the BESS supplies the balance power. In real-time, the optimal power management algorithm is implemented in centralized power management controller. The controller takes required inputs using communication infrastructure and provides optimal values to the respective controllers. However,
in this setup the optimal power references are given from a look up table as per the considered cases. Accordingly, in Case 1 to 2 the DG converter power changes from 128 W to 174 W and the corresponding currents are shown in Fig. 10(d). Fig. 10(e) shows the LVdc voltage at the DG converter and this remain unchanged throughout. With the
increase in load, the power drawn from the BESS increases. Thus, an increase in battery current is observed as shown in Fig. 10(f). The EV supplies power at rated value and the current is shown in Fig. 10(g). The PV and LVdc load currents are shown in Fig. 10(h) and (i). These do not change as the PV power and dc load are kept constant in this operation.

Fig. 11 shows a scenario of excess generation with load change operation. Only dc loads are used for this purpose. The PV source injects a constant power of 74 W. The corresponding current waveform is shown in Fig. 11(a). The dc load current waveform is shown in Fig. 11(b). Initially there is no load. Thus, the entire PV power is used to charge the EV. The EV current is shown in Fig. 11(c). The negative value depicts charging operation. The BESS is used to maintain the LVdc voltage only. Since no power is drawn from the BESS, the battery current is zero as shown in Fig. 11(d). The dc load is increased from 0 to 60 W. At this condition, the optimization algorithm ensures that the dc load draws the entire power requirement from the PV system and the balance power is fed to the EV. Therefore, there is a corresponding decrease in the EV charging current. As the BESS converter operates in grid forming mode, during the sudden load increase, the BESS supplies for the transients till the EV current settles to the new reference value. Once that condition is attained, the BESS current again settles to zero.

Fig. 12 shows the experimental results for under voltage load shedding. A scenario is considered where EV is absent and PV and BESS are the only sources. Total LVac load in the system is 160 W. When the BESS SoC goes below the critical value, the ST reduces the LVac voltage as shown in Fig. 12(b). This is detected at the load point and the non-critical load of 80 W is removed from the system. The optimization algorithm accordingly decides the reference current for the DG converter in the reduced load scenario. The battery current consequently reduces. As the power drawn from the battery is reduced, longer run-time of the islanded system is achieved.

VIII. CONCLUSION
An optimal power loss minimization scheme is proposed for an ST based islanded LV meshed hybrid microgrid. Such a microgrid offers different power flow paths between the
sources and loads. Based on the loading and DG power scenario, GA is used to optimally control the active power references of DG converters and charge or discharge schedules of EVs. This ensures minimum line losses in the system and helps to increase the system operation time. Moreover, an ST based smart under voltage load shedding is also incorporated into the optimization algorithm which triggers when the BESS SoC goes below the critical limit. Detailed simulation results are presented for the various possible scenarios along with load change operations. The obtained results were compared to a system where power to reduce losses. It was seen that for the six cases considered, the power loss reduction in the proposed system is shared as per the converter ratings, without the use of converter losses and reactive power loads in the minimization. It was seen that for the six cases considered, the power loss reduction in the proposed system is shared as per the converter ratings, without the use of converter losses and reactive power loads in the minimization.

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