Optimal Operation of a Converter Governed AC/DC Hybrid Distribution Network with DERs

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***Abstract*—Penetration of DC distributed energy resources (DERs) and development of different DC loads necessitate the integration of DC distribution networks with the existing AC networks by deploying power electronics converters. This paper designs a centralized mixed integer linear optimization portfolio for optimal operation of a grid tied AC/DC hybrid distribution network having DERs and voltage source converters (VSCs) by leveraging the benefit of load shifting process. Power flow equations due to the presence of VSCs are modelled in this article to achieve power balance in the network at lowest energy cost condition. Simulation process is carried out on a modified IEEE 33-bus AC/DC distribution network. The case study shows that energy cost is reduced significantly due to inclusion of the load shifting process.**

***Keywords*—AC/DC hybrid distribution network, distributed energy resources, energy cost, load shifting, mixed integer linear programming, voltage source converter.**

NOMENCLATURE

DN	Distribution network
DER	Distributed energy resources
VSC	Voltage source converter
MILP	Mixed integer linear programming
M	Modulation index of the VSC
Δx	Deviation variables
PV	Photovoltaic panel or solar panel
bat	Battery storage
grid	Main grid
L	Load demand
sh	Shifted demand
f	Forecasted demand
N	Total number of buses in DN indexed by i and j
T	Total number of time period indexed by t
ch, dch	Charging and discharging
P, Q, S	Active, reactive and apparent power in kW, kVaR and kVA
E	Energy in kWh
α	Binary status variable, 0- OFF, 1- ON
η	Efficiency
pf	Power factor
G_{ij}	Conductance in line connecting buses i and j in siemens
B_{ij}	Susceptance in line connecting buses i and j in siemens
$\|V\|, \theta$	Bus voltage magnitude and angle
$X^{+/-}$	Slack variables
$\bar{X}$	Upper limit of the decision variables
r_t^{grid}	Energy price in Rs./kWh

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I. INTRODUCTION

In the era of nineteenth century, the war between Thomas Edison and Nikola Tesla ended with the win of AC system due to numerous advantages of AC at that time period [1]. This reformed the power sector, from generation to transmission and distribution, as an AC network. However, since the last few decades, over exploitation of the fossil fuels by the power generation companies created global warming threat. Thus, to reduce the environmental degradation green energies are penetrating into the power sector as distributed energy resources (DERs). A large share in the renewable energy is owned by the solar powers, which is generated from the photovoltaic panels as DC power. Again, the intermittency present in the generated solar power is mitigated by the battery storages, which is also a DC equipment. These previously discussed DC energy resources and recent development in the DC loads (like DC computer, electric vehicles, LED lights etc.) bring back the DC system in the power sector. However, existing AC systems cannot be obsoleted completely. Therefore, to incorporate the advantageous attributes of the DC network with the benefits of conventional AC networks, concept of AC/DC hybrid distribution network is gaining popularity in present time [2]. These interconnections are made feasible by the development of different bidirectional power electronics converters. However, proper modelling of this converters and inclusion of those models in the optimal operation strategy of distribution network is a strenuous but crucial job. In this regard, this article proposes a centralized energy management portfolio for a converter dominated AC/DC hybrid distribution network.

Presently various research works are going on the AC/DC hybrid distribution systems for its successful deployment. Paul et al. [3] and Zhao et al. [4] proposed residential energy management process in an AC/DC microgrid. Murari et al. [5], [6] proposed graph theory based load flow solution process for AC/DC radial and weakly meshed distribution networks by utilizing the concept of linear algebra. Tylavsky et al. [7] implemented Newton-Raphson load flow strategy to AC/DC systems. Ahmed et al. [8] developed unified power flow model by modelling different power electronics converters. A genetic algorithm based planning approach for an AC/DC network was

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designed in [9]. The planning problem was designed as a two level nested problem, where upper level determines the configuration of the network and the lower level solved the optimal power flow problem. Lotfi et al. [10] investigated the size of the DERs in an AC/DC microgrid which could result lowest capital investment. Interaction between AC grids with one DC grid, connected through VSCs, was modelled by Qi et al. [11]. Authors propounded a decentralized iterative solution process to secure economic operation of the grids when working as individual or collaborative manner. A linear microgrid scheduling method was depicted in [12] by considering two AC and DC distribution grids connected through VSC. The economic impact of the AC/DC network configuration on the distribution network usage charge was assessed in [13]. Optimal power flow solution for grid tied and islanded AC/DC microgrid were explored by Qachchachi et al. [14]. Eajal et al. [15] proposed a bi-level centralized stochastic framework for optimal dispatch of two lumped AC and DC grids connected through a bi-directional AC-DC converter. The dispatch problem considered uncertainty in renewable generation, load profile and market energy price.

The above literatures mainly considered voltage source converters in their study as power electronic equipment. Power balance was achieved through VSC by considering only its efficiency. However, for a distribution network the voltage profile of the buses connected with the VSC also depends on its parameter setting, named modulation index. Again, the advantage of load shifting process in the optimal operation of AC/DC distribution networks is not explored in the previous literatures. In this regard, the current article proposes a centralized mixed integer linear optimization portfolio for optimal operation of AC/DC hybrid DN while leveraging the benefits of load shifting. Specific contributions of the current research work are listed below-

1. Elaborate modelling of distributed energy resources, loads and AC/DC distribution network with VSCs are provided.
2. The proposed optimization process derives the synergistic source-load-storage dispatch schedule of the network without fixing the modulation index values to a specific value unlike [5] and [7].
3. Load shifting process is included in the proposed optimization portfolio to achieve lowest energy cost over the entire time period by shifting the flexible demands from peak hours to off-peak hours.
4. The proposed method suggest possible solution process to avoid the occurrence of infeasible solution.
5. The entire optimization process is designed as mixed integer linear programming for its easy execution.

The article is organized as follows: Section II describes the modelling of different components present in the AC/DC network. The optimal operation strategy is elaborated in Section III with proper description on the optimization problem and its linear solution process. A case study on IEEE 33-bus AC/DC hybrid DN is showcased in Section IV. Finally Section V concludes the article.

II. Modelling of AC/DC Hybrid DN

This section describes analytical modelling of the different components present in the AC/DC hybrid network. Detailed modelling provides the insight about the power flow in different connections, active/reactive power supply/consumption from different DERs, load behaviors etc. The models are separately described in the following sub-sections-

A. DER Model

In this article, only solar generation and battery storage devices are considered as DERs. Though both are DC power sources but in the model it is considered they can be connected to both AC and DC buses. In case of DC buses they are connected through DC-DC converters, whereas an inverter is employed to connect them with the AC bus. Maximum active power output from solar panels at i^{th} bus at time t is expressed as,

$$\bar{P}_{i,t}^{PV} = \eta^{PV} A_i^{PV} I_t \left(1 - 0.005\left(T_t^{amb} - 25\right)\right) \quad (1)$$

Where, η^{PV}, A_i^{PV}, I_t and T_t^{amb} are efficiency of solar panel, area of the solar panel at i^{th} bus, solar irradiation and ambient temperature at time t respectively. Now, actual active power injected from the solar panel should be lesser than this maximum value as given below,

$$P_{i,t}^{PV} \le \bar{P}_{i,t}^{PV} \quad (2)$$

Now if the solar panel is connected with the ac bus then, reactive power can also be generated from the solar inverter by following the constraint (3).

$$\left(P_{i,t}^{PV}\right)^2 + \left(Q_{i,t}^{PV}\right)^2 \le \left(\bar{S}_i^{PV}\right)^2 \quad (3)$$

Equation (3) implies that the overall apparent power injection should be lower than the nameplate capacity of the inverters.

Battery storages are considered to be variable energy supplier and load depending on the available solar energy and the load demand. Energy level of the battery unit updates by following the equation (4). Active power and energy limits of the battery unit are denoted in equation (5). Constraint (6) prohibits simultaneous charging and discharging operations. To make each following day independent from the previous days constraint (7) is implemented. Now, same as the solar panel if the battery unit is installed at AC bus then the limits on the available apparent power are limited as per equation (8).

$$E_{i,t}^{bat} = E_{i,t-1}^{bat} + \left(\alpha_{i,t}^{ch}\eta^{bat} - \alpha_{i,t}^{dch}\big/\eta^{bat}\right) P_{i,t}^{bat}\Delta t \quad (4)$$

$$0 \le P_{i,t}^{bat} \le \bar{P}_i^{bat} \text{ and } E_{i,\min}^{bat} \le E_{i,t}^{bat} \le E_{i,\max}^{bat} \quad (5)$$

$$\alpha_{i,t}^{ch} + \alpha_{i,t}^{dch} \le 1 \quad (6)$$

$$\sum_{t\in T}\left(\left(\alpha_{i,t}^{ch}\eta^{bat} - \alpha_{i,t}^{dch}\big/\eta^{bat}\right) P_{i,t}^{bat}\right) = 0 \quad (7)$$

$$\left(P_{i,t}^{bat}\right)^2 + \left(Q_{i,t}^{bat}\right)^2 \le \left(\bar{S}_i^{bat}\right)^2 \quad (8)$$

B. Load Model

Load model is essential part for efficient and economic operation of the distribution network. Proper modelling of the active and reactive power demand help to shift the flexible demand from peak price hours to off-peak price and high renewable generation hours to avoid the chance of high energy cost and to maximize utilization of available renewable energy. Therefore, the load modelling at each bus is described in equations (9) to (11).

$$P_{i,t}^{L} = P_{i,t}^{f} + P_{i,t}^{sh} \text{ and } Q_{i,t}^{L} = P_{i,t}^{L}\sqrt{\left(1/pf_i^2\right) - 1} \quad (9)$$

$$P_{i,t}^{sh} \le \bar{P}_{i,t}^{sh} \quad (10)$$

$$\sum_{t\in T} P_{i,t}^{sh} = 0 \quad (11)$$

Equation (9) determines the active (for both ac and dc bus) and reactive (only for ac bus) power demand at each node. Equation (10) defines that total amount of load shifted

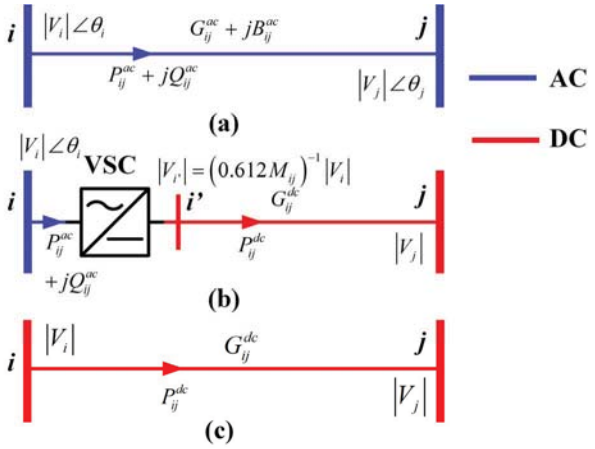

Fig. 1 Possible connections between buses in the DN

from/to a node at a particular time instant should be limited. To avoid load curtailment total load shifting should be zero over the time period as represented in equation (11).

C. Distribution Network Modelling with Converters

AC/DC distribution network is different from the commonly deployed AC distribution system due to integration of power electronics converters. Presence of these converters affects the power flow in the lines. Therefore, incorporation of their model to determine the line flows is necessary to maintain the active (for both ac and dc buses) and reactive (only for ac bus) power balance at each bus as expressed in equations (12) and (13),

$$P_{i,t}^{PV} + P_{i,t}^{grid} + \left(\alpha_{i,t}^{dch} - \alpha_{i,t}^{ch}\right) P_{i,t}^{bat} - P_{i,t}^{L} = \sum_{j \in J} P_{ij,t} \quad (12)$$

$$Q_{i,t}^{PV} + Q_{i,t}^{grid} + Q_{i,t}^{bat} - Q_{i,t}^{L} = \sum_{j \in J} Q_{ij,t} \quad (13)$$

Now the line flows depend on the buses on the either sides of the line and also on their connection types. Possible connections between two buses in the DN are shown in Fig. 1. Depending upon these connections the line flow models are described below sequentially.

1) AC-AC Connection

If a line is connecting two AC buses then active and reactive power flows in the corresponding line at time t are given by,

$$P_{ij,t}^{ac} = \left|V_{i,t}\right|^2 G_{ij}^{ac} - \left|V_{i,t}\right|\left|V_{j,t}\right|\left(G_{ij}^{ac}\cos\theta_{ij,t} + B_{ij}^{ac}\sin\theta_{ij,t}\right) \quad (14)$$

$$Q_{ij,t}^{ac} = -\left|V_{i,t}\right|^2 B_{ij}^{ac} - \left|V_{i,t}\right|\left|V_{j,t}\right|\left(G_{ij}^{ac}\sin\theta_{ij,t} - B_{ij}^{ac}\cos\theta_{ij,t}\right) \quad (15)$$

2) AC-DC Connection

If the buses at either sides are of two types, i.e. one is AC bus and another is DC, then they are connected through dc line and VSC as shown in Fig. 1(b). AC side voltage magnitude of the VSC in terms of the DC side voltage is given by [16],

$$\left|V_{i,t}\right| = 0.612 M_{ij,t} \left|V_{i',t}\right|$$

$$\Rightarrow \left|V_{i',t}\right| = \left(0.612 M_{ij,t}\right)^{-1} \left|V_{i,t}\right| \quad (16)$$

Where, $\left|V_{i'}\right|$ is the DC voltage just after VSC. Therefore, current flowing from *i'* to bus *j* is as follows,

$$I_{i'j,t} = G_{ij}^{dc}\left(\left|V_{i',t}\right| - \left|V_{j,t}\right|\right) \quad (17)$$

Therefore, active power fed from AC bus '*i*' to DC bus '*j*' when the VSC acts as a converter is,

$$P_{ij,t}^{ac} = \frac{P_{i'j,t}^{dc}}{\eta_{VSC}} = \frac{\left|V_{i',t}\right| I_{i'j,t}}{\eta_{VSC}}$$

$$\Rightarrow P_{ij,t}^{ac} = \frac{\left|V_{i',t}\right|}{\eta_{VSC}} G_{ij}^{dc}\left(\left|V_{i',t}\right| - \left|V_{j,t}\right|\right)$$

$$\Rightarrow P_{ij,t}^{ac} = \frac{G_{ij}^{dc}}{\eta_{VSC}}\left(\left|V_{i',t}\right|^2 - \left|V_{i',t}\right|\left|V_{j,t}\right|\right)$$

$$\Rightarrow P_{ij,t}^{ac} = \frac{G_{ij}^{dc}}{\eta_{VSC}}\left[\left(0.612 M_{ij,t}\right)^{-2}\left|V_{i,t}\right|^2 - \left(0.612 M_{ij,t}\right)^{-1}\left|V_{i,t}\right|\left|V_{j,t}\right|\right] \quad (18)$$

Now VSC can inject reactive power to the AC bus by following the below constraints same as the battery and solar inverter as discussed previously,

$$\left(P_{ij,t}^{ac}\right)^2 + \left(Q_{ij,t}^{ac}\right)^2 \le \left(S_{ij}^{VSC}\right)^2 \quad (19)$$

3) DC-DC Connection

Fig. 1(c) denotes the connection between two DC buses. It is accomplished by employing a DC line. The power flow in that line is given by,

$$P_{ij,t}^{dc} = G_{ij}^{dc}\left(\left|V_{i,t}\right|^2 - \left|V_{i,t}\right|\left|V_{j,t}\right|\right) \quad (20)$$

4) Other DN Constraints

Other than the power balance constraints described in equations (12) and (13), the specific operational constraints of the AC/DC hybrid distribution network are as follows,

$$\left|V^{\min}\right| \le \left|V_{i,t}\right| \le \left|V^{\max}\right| \quad (21)$$

$$\theta^{\min} \le \theta_{i,t} \le \theta^{\max} \text{ (only for AC buses)} \quad (22)$$

$$M^{\min} < M_{ij,t} < 1, \forall i, j, t \quad (23)$$

$$\left(P_{ij,t}^{ac/dc}\right)^2 + \left(Q_{ij,t}^{ac/dc}\right)^2 \le \left(S_{ij}\right)^2 \quad (24)$$

$$\left(P_{i,t}^{grid}\right)^2 + \left(Q_{i,t}^{grid}\right)^2 \le \left(S_{i}^{grid}\right)^2 \quad (25)$$

Equations (21) and (22) bound the bus voltage magnitude and angle within certain limits respectively. Modulation index of the VSCs are regulated at the boundary values by the constraint (23). Equation (24) defines the power flowing capacity of the distribution lines. Active and reactive power drawn from the main grid are limited by constraint (25).

III. Optimal Operation Strategy Design

A. Optimization Problem

Aim of the optimization process is to minimize the total energy cost of the AC/DC hybrid DN to get economic synergistic source-load-storage dispatch module. Again, the optimization process will also determine the exact voltage level of the buses and steady state operating conditions of the converters. Hence the entire optimization problem is given by,

$$\min_{\Omega} \quad C(\Omega) = \sum_{t \in T}\sum_{i \in N}\left(P_{i,t}^{grid} r_t^{grid} \Delta t\right) \quad (26)$$

Subject to, (2)-(25)

Where, decision variable set, $\Omega = \left[\Omega_t \middle| t \in T\right]$ and

$$\Omega_t = \begin{bmatrix} P_{i,t}^{L}, P_{i,t}^{sh}, Q_{i,t}^{L}, P_{i,t}^{PV}, Q_{i,t}^{PV}, \alpha_{i,t}^{ch}, \alpha_{i,t}^{dch}, P_{i,t}^{bat}, Q_{i,t}^{bat}, \\ P_{i,t}^{grid}, Q_{i,t}^{grid}, M_{ij,t}, \left|V_{i,t}\right|, \theta_{i,t} \end{bmatrix}, \forall i, j$$

B. Linearization Process

It is noted from the previously described problem formulation that it possesses several non-linearity as listed below in the proposed strategy,

1. Equations (4) and (7) is non-linear equality, which make the formulation non-convex, due to presence of multiplication of one binary and one continuous variables.
2. Active and reactive power balance equations (12) and (13) make the problem non-convex due to non-linear power flow equations (14), (15), (18) and (20).
3. Apparent power limiting constraints of VSC, solar and battery inverters and distribution lines are quadratic inequalities, equations (3), (8), (19), (24) and (25).

The above mentioned non-linear equality and inequality constraints make the solution process complex. Heuristic search techniques are quite efficient in this regard, however they may lead to local optimal solution instead of the global one. First convergence and global optimality can only be assured through classical optimization process, such as mixed integer linear programming (MILP) [17]. To solve the proposed strategy through MILP, necessitates linearization of the before mentioned non-linearity. Linearization processes are sequentially described as follows:

1) Linearization of Terms Having Multiplication of Binary and Continuous Variables:

Multiplication of binary and continuous variables takes the form as follows:

$$f = \delta x, x^{\min} \le x \le x^{\max} \tag{27}$$

Where, x is continuous and δ is binary variables respectively. The above equation is linearized by defining an auxiliary variable $g = \delta x$ subject to the following constraints,

$$x - x^{\max}(1-\delta) \le g \le x - x^{\min}(1-\delta) \tag{28}$$

$$x^{\min}\delta \le g \le x^{\max}\delta \tag{29}$$

Constraints (28) and (29) denote that if δ=1 then x=g and g has the same boundary values as x. Again if δ=0 then g=0.

2) Linearization of Power Flow Equations

For a distribution system following assumptions can be done-

a. voltage magnitude of any bus deviates from its nominal value and thus it can be represented as,

$$|V_{i,t}| = |V^{nom}| + |\Delta V_{i,t}| \tag{30}$$

Where, $|V^{nom}|$ is rated or nominal voltage of the bus and $|\Delta V_{i,t}|$ is the deviation in bus voltage from its nominal value.

b. voltage angle difference between two ac buses are very small, therefore

$$\sin\theta_{ij,t} = \theta_{ij,t} \text{ and } \cos\theta_{ij,t} = 1 \tag{31}$$

c. Modulation index (MI) of VSC converters are set close to unity. Therefore, $M_{ij,t} = 1 - \Delta M_{ij,t}$

Applying the above specified assumptions on the power flow equations (14), (15), (18) and (20) new linear line flow equations (32)-(35) are derived by neglecting the higher order terms and terms containing multiplication of two small deviation decision variables.

$$P^{ac}_{ij,t} = V^{nom}_{ac}\left(|\Delta V_{i,t}| - |\Delta V_{j,t}|\right)G^{ac}_{ij} - \left(V^{nom}_{ac}\right)^2 B^{ac}_{ij}\theta_{ij,t} \text{ (AC-AC)} \tag{32}$$

$$Q^{ac}_{ij,t} = -V^{nom}_{ac}\left(|\Delta V_{i,t}| - |\Delta V_{j,t}|\right)B^{ac}_{ij} - \left(V^{nom}_{ac}\right)^2 G^{ac}_{ij}\theta_{ij,t} \text{ (AC-AC)} \tag{33}$$

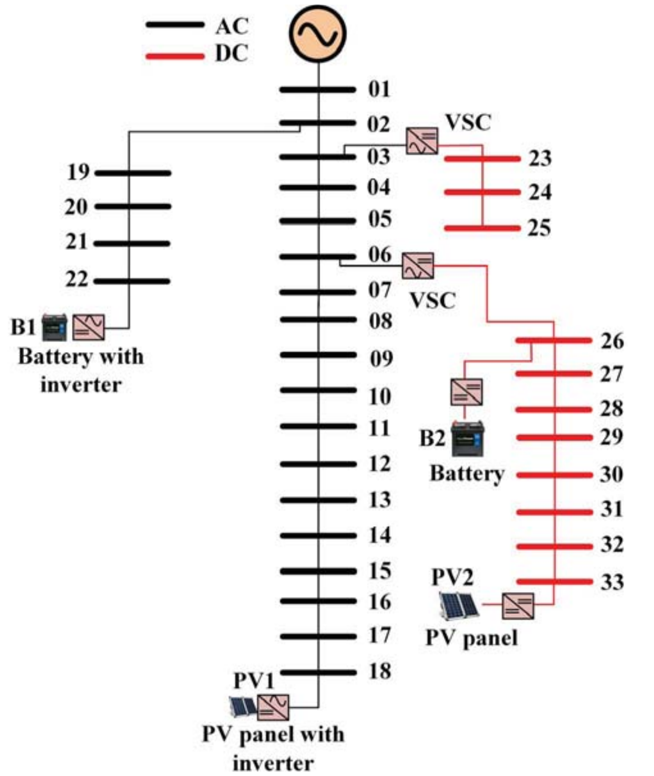

Fig. 2 Modified IEEE 33 bus system as AC/DC hybrid network

$$P^{ac}_{ij,t} = \frac{G^{dc}_{ij}}{\eta_{VSC}}\left[\begin{array}{l} 2.67\left(\left(V^{nom}_{ac}\right)^2 + 2V^{nom}_{ac}|\Delta V_{i,t}| + 2\left(V^{nom}_{ac}\right)^2 \Delta M_{ij,t}\right) \\ -1.634\left(\begin{array}{l} V^{nom}_{ac}V^{nom}_{dc} + V^{nom}_{ac}|\Delta V_{j,t}| + V^{nom}_{dc}|\Delta V_{i,t}| \\ +V^{nom}_{ac}V^{nom}_{dc}\Delta M_{ij,t} \end{array}\right) \end{array}\right] \text{ (AC-DC)} \tag{34}$$

$$P^{dc}_{ij,t} = G^{dc}_{ij}V^{nom}_{dc}\left(|\Delta V_{i,t}| - |\Delta V_{j,t}|\right) \text{ (DC-DC)} \tag{35}$$

$$\text{Here, } |\Delta V^{\min}| \le |\Delta V_{i,t}| \le |\Delta V^{\max}| \tag{36}$$

$$\text{And } \Delta M^{\min} \le \Delta M_{ij,t} \le \Delta M^{\max}, \forall i,j,t \tag{37}$$

3) Linearization of Quadratic In-equalities

The quadratic apparent power limiting in-equalities, equations (3), (8), (19), (24) and (25) are linearized using piecewise linearization process. The above equations are taking form of as follows,

$$P_t^2 + Q_t^2 \le S^2 \tag{38}$$

The left hand side terms of equation (38) can be represented as,

$$P_t^2 = \sum_{l=1}^{L} s_l P_{l,t} \text{ and } Q_t^2 = \sum_{l=1}^{L} w_l Q_{l,t} \tag{39}$$

Where, s_l and w_l are the slopes corresponding to the l^{th} segment and L is the total number of segments. Therefore, the linearized version of the quadratic constraints will be,

$$Lin\left(P_t^2, Q_t^2\right) = \sum_{l=1}^{L} s_l P_{l,t} + \sum_{l=1}^{L} w_l Q_{l,t} \le S^2 \tag{40}$$

By implementing the previously described linearization process, the problem formulation is converted to a perfectly mixed integer linear problem and that is easily solvable by any MILP commercial solver present in MATLAB, GAMS or any other simulation platforms.

C. Infeasibility Handling

Previously formulated problem may leads to an infeasible solution due to the violation of constraints (21), (24) and

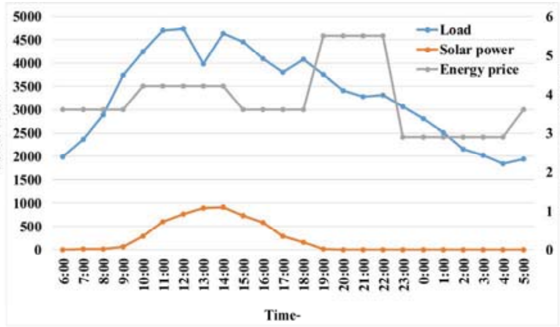

Fig. 3 Input load, solar generation and energy price data for simulation

(25). This infeasibility occurring is handled in this article by introducing slack variables for each constraints. To avoid large deviation from the preferable conditions the slack variables are added to the objective function to minimize them. Therefore, new optimization problem will be,

$$\min_{\Theta} F(\Theta) = C(\Omega) + C_{\varepsilon} \sum_{i\in N}\left(|V|_i^- + |V|_i^+\right) + C_{\upsilon} \sum_{i\in N} \sum_{\substack{j\in N \\ \neq i}} S_{ij}^+ + C_{\nu} \sum_{i\in N} S_i^+ \qquad (41)$$

Subject to, (2)-(13), (22), (32)-(37) and

$$\left|\Delta V^{\min}\right| - |\Delta V|_i^- \le \left|\Delta V_{i,t}\right| \le \left|\Delta V^{\max}\right| + |\Delta V|_i^+ \qquad (42)$$

$$Lin\left(\left(P_{ij,t}^{ac/dc}\right)^2, \left(Q_{ij,t}^{ac/dc}\right)^2\right) \le \left(S_{ij}\right)^2 + S_{ij}^+ \qquad (43)$$

$$Lin\left(\left(P_{i,t}^{grid}\right)^2, \left(Q_{i,t}^{grid}\right)^2\right) \le \left(S_i^{grid}\right)^2 + S_i^+ \qquad (44)$$

$$|V|_i^-, |V|_i^+, S_{ij}^+, S_i^+ \ge 0 \qquad (45)$$

Where, modified decision variable set $\Theta = \left[\Theta_t \middle| t \in T\right]$ or

$$\Theta = \left[\Omega, |V|_i^-, |V|_i^+, S_{ij}^+, S_i^+\right], \forall i, j$$

$C_{\varepsilon}, C_{\upsilon}$ and C_{ν} are the penalty cost for violation of the bus voltage, line flow and grid consumption constraints respectively.

IV. Case Study

The proposed centralized optimization process is implemented on a modified IEEE 33-bus AC/DC distribution network adopted shown in Fig. 2. Network base MVA, AC side base voltage and DC side base voltage are 10 MVA, 12.66 kV (ac) and 20.67 kV (dc) respectively. Solar panels are of 1 MW capacity each and every batteries are of 1 MWh- 0.5 MW rating, 100% efficient and can discharge up to 30% of its capacity. Initially batteries are at their 50% energy level. Solar generation from a practical PV panel is uplifted to the scale of 1 MW for simulation. Solar generation from each panel, 24 hour load curve of the entire network and the dynamic energy price data from literature [18] are protrayed in Fig. 3. Power factor of the AC buses are assumed to be remained same at each time interval as the base case power factor. It is assumed that per hour maximum 40% of the total demand at each bus can be shifted. Upper and lower bus voltage limits are 1.05 pu and 0.95 pu respectively. Efficiency of VSCs are 95%. Both solar and battery inverters are of 1.5 MVA ratings. Thermal limit of lines and capacity of VSCs are 4.5 MVA. The penalty costs for voltage violation, line flow violation and grid consumption violations are 20 times, 15 times and 10 times of the maximum day ahead energy cost for the entire time period.

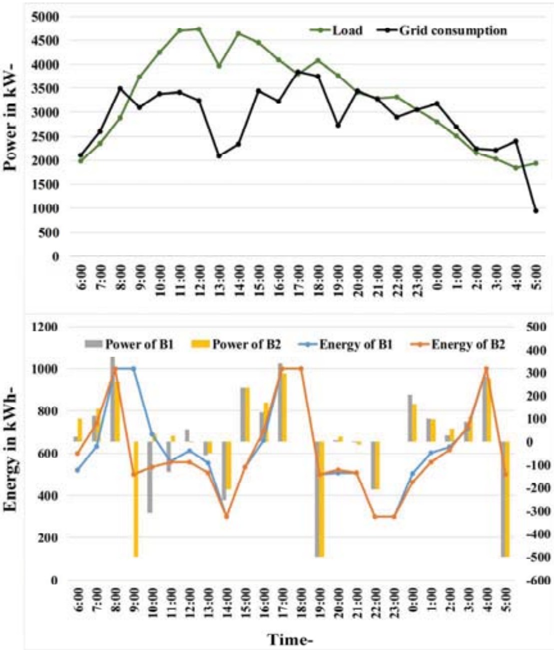

Fig. 4 Simulated output for case 1 showing grid power, battery power and energy status.

Proposed AC/DC distribution network energy managemnet strategy is simulated in a 3.4 GHz, 16 GB RAM personal computer using the MILP commercial solver present in MATLAB 2016b. The simulations are carried out for following two cases-

A. Case 1: Optimal Operation without Load Shifting

In this case, optimal operation of the AC/DC network is investigated without implementing load shifting process. The simulation results are depicted in Fig. 4. It is noted that the load demand is satisfied coordinately by solar panels, batteries and the main grid. During solar generation hours grid consumption reduced. The battery gets charged at off-peak price hours, that it can further discharge at peak price hours to lower the energy cost. With this centralized optimization approach peak demand of 4730.4 kW is met and the total energy cost for the entire time period is 269850.8 $ (Table I).

B. Case 2: Optimal Operation with Load Shifting

Case 2 is evaluated by utilizing the concept of load shifting. The simulation results are shown in Fig. 5. First figure of Fig. 5 shows that the load demand at peak and medium-peak price hours reduced significantly, whereas the demand at off-peak price hours increased. This signifies that the demand from peak hours is shifted to off-peak hours. Due to that the peak load reduced to 4528.9 kW (4.2% reduction as mentioned in Table I). Same as the previous case study batteries are charged at low price hours and discharged at peak price hours. Compared with the previous case study, due to implementation of load shifting, in this case the distribution network operator experiences 3.4% reduction in energy cost (reduced to 260588.3 $) as depicted in Table I.

Fig. 6 portrays the maximum voltage violation of the buses to meet the load demand over the entire period below the minimum allowed voltage level. It is noted that without load shifting process voltage limit violation is more compared to the condition when loads are shifted from peak

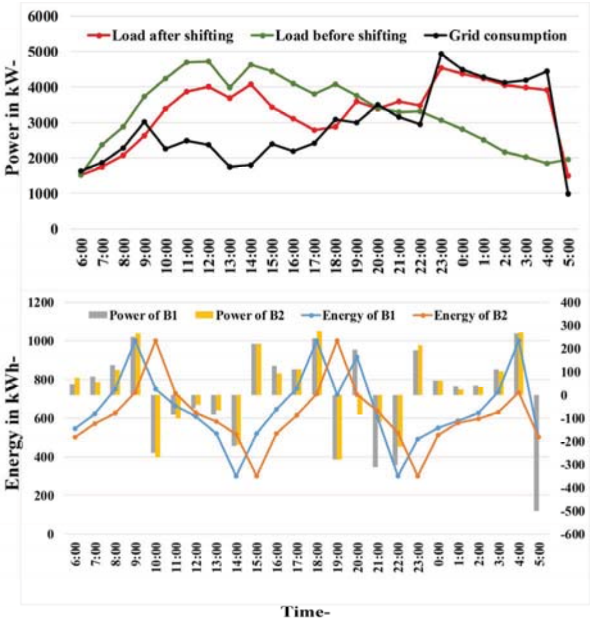

Fig. 5 Simulated output for case 2 showing the new load demand after applying load shifting, grid consumption, battery power and energy status

TABLE I
COMPARISON TABLE

Case	Case 1	Case 2	Percentage reduction (%)
Energy cost ($)	269850.8	260588.3	3.4%
Peak load (kW)	4730.4	4528.9	4.2%

to off-peak hours. This limit violation is more in case of leaf nodes or the buses which are far from the main sub-station.

V. Conclusions and Future Scopes

This paper aims to investigate optimal operation of an AC/DC hybrid distribution network under load shifting process. Voltage source converters present in the line connecting two AC and DC buses are modelled in this paper for successful implementation of the proposed strategy. The entire strategy is designed as a mixed integer linear programming problem and evaluated on modified IEEE 33 bus test system. Simulation results show that implementation of load shifting process can significantly reduce the energy cost and peak demand by 3.4% and 4.2% respectively.

In this article, a deterministic solution approach is presented to implement load shifting process in AC/DC radial distribution system. However, uncertainty present in the forecasted renewable generation and day ahead energy price data need upgradation of this formulation to design a robust energy management policy for both radial and meshed AC/DC distribution networks.

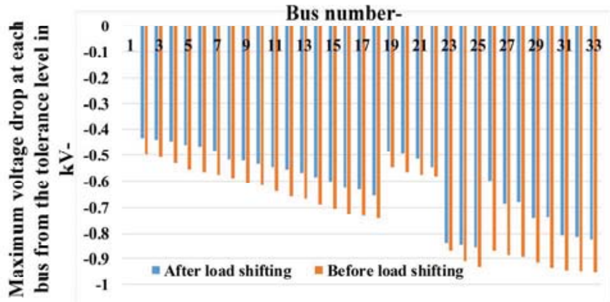

Fig. 6 Maximum voltage drop of each bus from the minimum tolerance level.

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