
Optimal accommodation and management of high renewable penetration in distribution systems

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Abstract: The paper presents a new bi-level optimisation framework for optimal accommodation and operational management of wind power generation and battery energy storage system (BESS) simultaneously, aiming to maximise the renewable hosting capacity of distribution networks. A new objective function is suggested comprising of annual energy loss in feeders, reverse power flow into the grid, non-utilised BESS capacities, round-trip conversion losses of BESSs and node voltage deviation subjected to various system security constraints. An artificial-intelligence-based optimal management of BESS is proposed for effective control of high-renewable power generation. Due to the high investment and running costs of BESS, minimum storage capacity has been ensured in planning stage. In order to show the effectiveness of the proposed model, it is implemented on a benchmark test distribution system of 33-bus. Besides, various test cases are investigated and compared, which shows that the proposed optimisation model is promising.

1 Introduction

The global energy crisis, global warming, depleting conventional energy resources, inefficacy of traditional vertically integrated power system, deregulation policies etc. have led to the large-scale deployment of distributed energy resources (DERs) in distribution systems especially, renewables. The most popular DERs may include distributed generations (DGs), shunt/super capacitors, superconducting magnetic energy storage, battery energy storage system (BESS) etc. The recent advancement in electric cars is provided an option to utilise the electric vehicles (EVs) as an alternative DER technology. The quick growth of renewables in distribution networks, aiming to maximise various integration benefits may adversely affect the system performance and economics.

According to the standard offer programmes, the utilities have the right to curtail renewable power generation, if any operating constraint is violated [1]. The preventive action taken by utilities may lose a share of DG owner's revenue. Alternatively, the alarming green house gas (GHG) emission forced power system planners to increase the renewable penetration in distribution systems. The conflicting aspects of high renewable penetration may create many operational challenges for utilities. Moreover, without utilising the context of traditionally designed distribution systems, it is quite difficult to accommodate high penetration of renewables to achieve foreseen objectives of smart distribution systems. Therefore, the renewable-based DG integration problem needs to be strategically addressed, modelled and solved the issues precisely comprising the traditional context of existing distribution systems.

The optimally accommodated DERs may provide enormous benefits to distribution system operators, DER owners and customers such as minimised power/energy loss [2–6] and emission, improved bus voltage profile [4–9], reliability [10, 11] and voltage stability [6, 8], peak load shaving [5] etc. Considering optimal number, site, size, types of DERs etc., the optimal DER accommodation problem turns out to be a complex mixed-integer, non-convex and non-linear optimisation problem [6, 9]. Therefore, artificial intelligence (AI)-based optimisation methods may play a vital role to solve such complex optimisation problems.

In literature, various optimisation methods have been adopted to solve the complex DER accommodation problems in order to identify optimal nodes, sizes and types. These can be genetic algorithm (GA) [4, 5, 12, 13], second-order cone programming [14], particle swarm optimisation [2–4, 11, 15, 16], differential evolution [17], artificial bee colony [2, 11], biogeography-based optimisation [17], Taguchi method [8, 9], teaching-learning-based optimisation [17], grey wolf optimisation [11, 17], tabu-search [3, 17], improved elephant herd optimisation [6] etc.

Apart from optimisation methods, various strategies are also suggested in literature to mitigate the impact of high DG penetration and to improve the distribution systems performance. Some of these may be simultaneous and optimal accommodation of different DG technologies considering their pros and cons [4, 8], optimal accommodation of DGs in coordination with operational strategies such as network reconfiguration [4] and voltage regulators. The above discussed strategies certainly improve the system performance but may not be wise choice to manage the high penetration of renewables due to their intermittent and uncertain characteristics. With the recent advances in BESS, the simultaneous optimal accommodation of renewable-based DGs and BESS may be a viable strategy, to lessen the impact of DER integration, despite of being costly.

However, the problem of BESS accommodation is more complex than the DG accommodation problems since it behaves like load and generation with uncertain level of state of charge (SOC). Various estimation algorithms are also required to determine the instantaneous SOC of each BESS. Moreover, numerous charging and discharging constrains are also involved with BESS. Apart from these technical issues, the installation and operating cost of BESS is very high with relatively lesser lifetime as compared to average DER technologies. Due to high running costs of BESS, it may not be a wise choice to deploy BESS on large scale. Therefore, relatively small-sized BESS may be deployed to minimise the power/energy loss [5], variations of renewable power generation [10] and node voltages [5, 7] with minimum number of charging/discharging cycles of BESS [5, 7, 10]. Alternatively, the suboptimal accommodations may increase the cost, including system losses and installation of larger battery capacity [15]. Considering the

above discussed issues and challenges, the simultaneous optimal accommodation of renewables and BESS turns out to be a multi-level, complex mixed-integer, non-linear optimisation problem which may require multi-level optimisation model and framework to determine the optimal site and size of renewables and BESS simultaneously.

In literature, various BESS accommodation and operation management problems have been investigated to achieve numerous techno-economic benefits for passive [11, 12] and active [1, 5, 7, 10, 15–20] distribution networks. However, comparatively small amount of literature [2, 3] may be found which deal with simultaneous optimal accommodation of renewables and BESS. In [2], simultaneous optimal accommodation of dispatchable DGs and battery-switching stations are determined to minimise the system loss. In [3], a hybrid standalone power system is optimally designed using wind-solar-BESS to develop a trade-off between power reliability and cost. The optimal accommodation and management of distributed energy storages are achieved in [14] to alleviate detrimental impacts of high photovoltaic (PV) penetration in distribution systems.

In this paper, a new bi-level optimisation framework is developed for simultaneous optimal accommodation and management of high wind power generation and minimum BESS in distribution networks. The goal is to determine the optimal sites and sizes of predefined number of wind turbines (WTs) and BESS simultaneously.

To achieve this, new objectives and constraints are introduced to alleviate the effect of intense, variable power generation and load demand on system security such as annual energy loss in feeders, reverse power flow into the grid, non-utilised BESS capacities, round-trip conversion losses of installed BESSs and voltage deviation of distribution systems etc. An AI-based optimal energy storage management model is developed for optimal operation of distribution system. To explore the non-tangible benefits of BESSs integration with high renewable penetration, the problem is developed in a deterministic framework for various scenarios. An improved variant of GA has been adopted from [13] to solve the problem due to its ability to find the global or near global optima. The problem is solved for a benchmark 33-bus test distribution system and simulation results are found to be inspiring. The proposed model ensured the minimum BESS capacities and maximum utilisation of installed WT and BESS during system operations.

2 Problem formulation

During power delivery, power loss may be found at many stages, among these, maximum power losses are occurred in distribution systems which are significantly high as compared to transmission networks. The quick growth of AC/DC conversion devices has introduced many conversion losses in the system which needed to be minimised. Therefore, power loss minimisation may be an objective of distribution network operators to maximise the annual revenue. Moreover, node voltage regulation is also an important objective, which needs to be achieved for improved node voltage profile at customer nodes.

The above discussed objectives can be optimised if controllable energy sources/devices are present in the system; however, it may be difficult to optimise under high penetration of renewable energy sources. In light load hours, high renewable generation may cause reverse flow into the upstream grid which may create many protection issues. Therefore, reverse power flows should to be minimised and can be seen as an objective function. In order to minimise the different power losses, reverse power flow and node voltage deviation of the system under high wind power penetration, the simultaneous optimal accommodation of WT and BESS is achieved in this paper. It may be observed that the installation and running costs of BESS are very high with relatively lesser

timespan. Therefore, an optimal BESS nodes and capacities needed to be identified such that the above discussed issues are mitigated.

2.1 Objective function

Considering the above discussed facts, in this paper, various annual energy loss and node voltage deviation of the system is minimised subjected to various DG, BESS and system constraints. The following objective function is minimised using optimal accommodation and management of wind power generation and BESS simultaneously:

$$\min f = \phi \left(1 + \sum_{h=1}^{24} \Delta V^h \right) (1 + \Delta W_B) \times \sum_{h=1}^{24} (P_{\text{Del.}}^h + P_{\text{Rev.}}^h + P_{\text{Conv.}}^h) \quad (1)$$

where

$$\Delta V^h = \begin{cases} |V - V_i^h|, & \text{if } V_i^h < V \\ 0, & \text{if } V \leq V_i^h \leq \bar{V} \\ \text{a large number,} & \text{if } V_i^h > \bar{V} \end{cases} \quad (2)$$

$$\Delta W_B = \left| \sum_{h=1}^{24} P_{C_i}^h - \sum_{h=1}^{24} P_{D_i}^h \right| \quad \forall i \quad (3)$$

$$P_{\text{Del.}}^h = \sum_{i=1}^N \sum_{j=1}^N \alpha_{ij}^h (P_i^h P_j^h + Q_i^h Q_j^h) + \beta_{ij}^h (Q_i^h P_j^h - P_i^h Q_j^h) \quad (4)$$

$$\alpha_{ij}^h = \frac{r_{ij} \cos(\delta_i^h - \delta_j^h)}{V_i^h V_j^h} \quad \text{and} \quad \beta_{ij}^h = \frac{r_{ij} \sin(\delta_i^h - \delta_j^h)}{V_i^h V_j^h} \quad (5)$$

$$P_{\text{Rev.}}^h = \begin{cases} 0, & \text{if } I_G^h \geq I_{\text{Spc.}} \\ \text{Re}(V_G^h I_G^{h*}), & \text{if } I_G^h < I_{\text{Spc.}} \end{cases} \quad (6)$$

$$P_{\text{Conv.}}^h = (1 - \eta) P_{C/D_i}^h \quad \forall i \quad (7)$$

$$P_{C/D_i}^h = \begin{cases} 0, & \text{if } \text{SOC}_i^h = \overline{\text{SOC}} \text{ or } I_G^h \geq 0 \\ \bar{P}_B, & \text{if } \text{SOC}_i^h + \frac{\eta \bar{P}_B}{W_B^R} \leq \overline{\text{SOC}} \text{ \& } I_G^h < 0 \\ (\overline{\text{SOC}} - \text{SOC}_i^h) W_B^R, & \text{if } I_G^h < 0 \text{ \& } \\ \overline{\text{SOC}} - \text{SOC}_i^h < \frac{\eta \bar{P}_B}{W_B^R} \\ 0, & \text{if } \text{SOC}_i^h \leq \underline{\text{SOC}} \text{ or } I_G^h \leq 0 \\ -\bar{P}_B, & \text{if } \text{SOC}_i^h - \frac{\eta \bar{P}_B}{W_B^R} \geq \underline{\text{SOC}} \text{ \& } I_G^h > 0 \\ -(\text{SOC}_i^h - \underline{\text{SOC}}) W_B^R, & \text{if } I_G^h > 0 \text{ \& } \\ \text{SOC}_i^h - \underline{\text{SOC}} < \frac{\eta \bar{P}_B}{W_B^R} \end{cases} \quad (8)$$

Equations (2)–(4), (6) and (7) represent the node voltage deviation penalty function, under/over energy utilisation penalty of BESS, feeders power loss, amount of reverse power flow into the grid and BESS converter losses, respectively. Where, V_i^h , δ_i^h , P_i^h , Q_i^h , SOC_i^h and P_{C/D_i}^h are voltage magnitude and angle, real and reactive power injection, SOC status of BESS and charging/discharging dispatch of BESS at i th node in h th hour, respectively; V_G^h and I_G^h are the voltage and current magnitude in secondary winding of grid substation transformer, respectively. r_{ij} is the resistance of branch connecting node i and j . Further, η , ϕ , N , $I_{\text{Spc.}}$, \underline{V} and

\bar{V} , $\overline{\text{SOC}}$, $\overline{\text{SOC}}$, $\overline{P_B}$, $\overline{P_B}$ and W_B^R are charging/discharging efficiency of BESS, daily to annual conversion factor, total number of nodes in the system, specified reverse current limit into the grid, minimum and maximum allowable node voltage limits, minimum and maximum specified SOC limits of BESS, minimum and maximum allowable charging/discharging power limits of BESS and rated energy storage capacity of BESS, respectively.

2.2 Constraints

The objective function expressed in (1) is subjected to the following constraints:

Generation installation capacity limit constraint:

$$0 \leq P_{DG_i} \leq \overline{P_{DG}} \quad \forall i \quad (9)$$

BESS installation capacity limit constraint:

$$0 \leq W_{B_i} \leq \overline{W_B} \quad \forall i \quad (10)$$

BESS charging/discharging limit constraints:

$$\underline{P_B} \leq P_{C/D_i}^h \leq \overline{P_B} \quad \forall i, h \quad (11)$$

SOC limit constraints of BESS:

$$\underline{\text{SOC}} \leq \text{SOC}_i^h \leq \overline{\text{SOC}} \quad \forall i, h \quad (12)$$

Feeders thermal limit constraint:

$$I_{ij}^h \leq \overline{I_{ij}} \quad \forall i, j, h \quad (13)$$

Real and reactive nodal power balance constraints:

$$P_i^h = V_i^h \sum_{j=1}^N V_j^h Y_{ij} \cos(\theta_{ij} + \delta_j^h - \delta_i^h) \quad \forall i \quad (14)$$

$$Q_i^h = -V_i^h \sum_{j=1}^N V_j^h Y_{ij} \sin(\theta_{ij} + \delta_j^h - \delta_i^h) \quad \forall i \quad (15)$$

SOC balance constraint:

$$\text{SOC}_i^h = \text{SOC}_i^{h-1} + \frac{\eta P_{C/D_i}^h}{W_B^R} \quad \forall i, h \quad (16)$$

where P_{DG_i} , W_{B_i} , $\overline{P_{DG}}$ and $\overline{W_B}$ are real power generation of DG, energy dispatch of BESS, maximum power and energy generation limit of DG and BESS, respectively, at bus i . Similarly, θ_{ij} , Y_{ij} , I_{ij}^h and $\overline{I_{ij}}$ are impedance angle, element of Y-bus matrix, flow of current in h th hour and maximum thermal limit of line, respectively, connected between bus i and bus j .

2.3 Wind power generation modelling

The wind speed is highly uncertain which causes fluctuating power generations from WTs. The real power produced by WTs is the function of wind speed; therefore, wind speed is then combined with the WT parameters in order to evaluate the hourly electrical power generation. However, parameters such as pitch angle, swapping area etc. may assume to be constant except wind speed. If appropriate transformation is used, wind speed can be converted into the real power as a cubic function of wind speed as expressed as

$$P_{DG_i} = f(v^3) \quad (17)$$

using (17), the wind speed at bus ' i ' can be converted into real



Fig. 1 Chromosome structure of used in GA-1

power generation as

$$P_{DG_i} = \begin{cases} 0 & \text{if } v_i^h < v_{\text{cut in}} \text{ OR } v_i^h \geq v_{\text{cut out}} \\ \left(\frac{v_i^h}{v_r}\right)^3 \times P_{r,i} & \text{if } v_{\text{cut in}} \leq v_i^h < v_r \\ P_{r,i} & \text{if } v_r \leq v_i^h < v_{\text{cut out}} \end{cases} \quad (18)$$

where, v_i^h , $v_{\text{cut in}}$, $v_{\text{cut out}}$, v_r and $P_{r,i}$ are the wind speed in h hour at bus i , cut-in, cut-out, rated speed of WTs and rated power of WTs, respectively.

3 Optimal accommodation and management of high wind power generation

In this section, the proposed strategies and algorithm have been discussed and explained for optimal accommodation and management of high wind power generation in distribution systems. In order to solve the proposed mixed-integer, non-linear and non-convex optimisation problem formulated in Section 2, an improved variant of GA has been adopted from [13]. GA is a powerful meta-heuristic optimisation technique inspired from the process of natural selection. It is a population-based method which has the ability to explore global or near global optimal solution for complex power system optimisation problems [4, 5, 12, 13]. In this paper, two GAs are used to solve the optimal accommodation and management simultaneously: (i) simultaneous optimal accommodation of WTs and BESSs which will act as the main optimisation method (ii) optimal management of BESS which will be used as the subroutine technique to determine hourly optimal scheduling of BESS based on available SOC and update its SOC status. The chromosome structure used in main GA is shown in Fig. 1.

The chromosome structure for GA-2 will contain the BESS capacities only as the decision variables. The flow chart of basic steps of the proposed optimal accommodation and management strategies for WTs and BESS are shown in Fig. 2.

4 Simulation results

In order to validate the proposed simultaneous optimal accommodation of WTs and BESS, it is implemented on standard 33-bus test distribution system. It is a 12.66 kV distribution system with nominal real and reactive power demand of 3715 kW and 2300 kVAR, respectively. The other information of this system can be obtained from [21]. In the study, following test cases are investigated to shows its effectiveness: (i) Base case, (ii) optimal accommodation of WTs only, (iii) simultaneous optimal accommodation of WTs and BESSs. Further, the simulation parameters used in the study are summarised in Table 1.

The simulation results obtained using the proposed approach are presented in Table 2 for all investigated cases. The table contains optimal nodes and sizes of DGs/BESSs along with respective annual energy loss and DG penetration. The DG penetration is calculated as the fraction of system's peak demand which is assumed to be 1.6 times of nominal demand of the system. The table shows that case-III provides higher annual energy loss reduction as compared to case-II, even at high DG penetration while maintaining the system, generation and BESS security constraints. The loss shown in case-III has already included the round-trip conversion loss of BESSs but still, the power losses are 476.74 MWh lesser than the case-II. The simulation results of case-III show that BESS is installed at DG node or near to that node. It may be

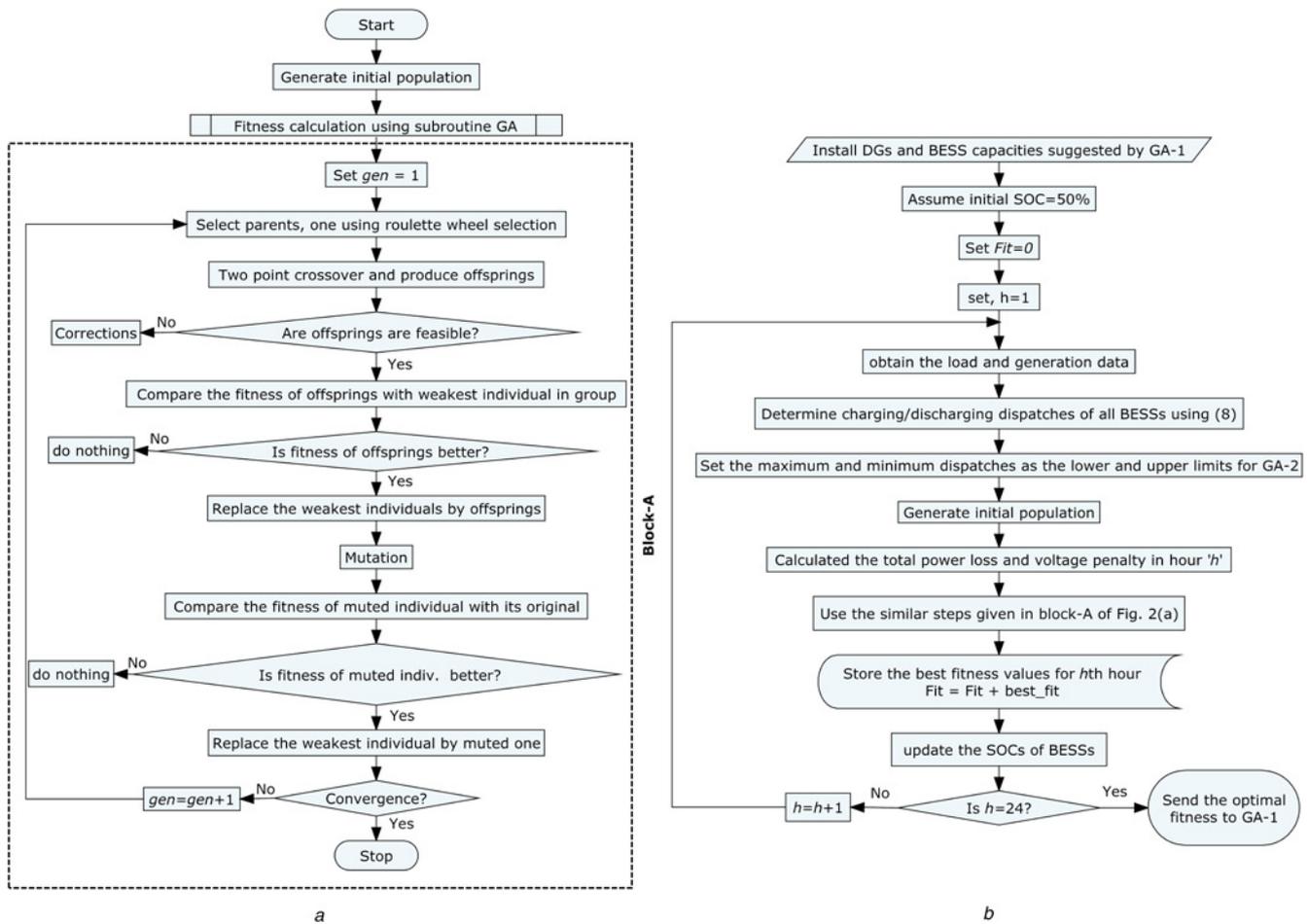


Fig. 2 Flow charts of proposed optimal accommodation and management of wind power generation
a Genetic algorithm 1 for optimal accommodation
b Genetic algorithm 2 for optimal management

Table 1 Simulation parameters used in the study

Parameter(s)	Value
ϕ	365
\underline{V}, \bar{V}	0.95 pu, 1.05 pu
I_{Spc}	5% of grid transformer rated current
η	85%
$\overline{P}_B, \underline{P}_B$	1 MW, 1 MW
$\overline{\text{SOC}}, \underline{\text{SOC}}$	0, 1
$\overline{P}_{\text{DG}}, \underline{W}_B$	2 MW, 5 MWh
$v_{\text{cut in}}, v_{\text{cut out}}, v_r$	4 m/s, 20 m/s, 15 m/s

Table 2 Simulation results obtained by proposed approach

Case (s)	Optimal nodes (sizes in kW) of WTs	Optimal nodes (sizes in kWh) of BESSs	DG penetration, %	Annual energy loss, MWh	Annual energy loss reduction, %
I	—	—	00.00	3493.27	00.00
II	14 (939) 17 (909) 32 (1651)	—	58.87	1887.54	45.97
III	11 (1539) 16 (719) 30 (1941)	10 (4494) 16 (2743) 30 (4411)	70.64	1410.80	59.61

installed to minimise the electrical distance between DGs and BESSs so that the energy transaction losses are minimum in charging/discharging cycles.

In Fig. 3, the hourly system demands are compared for all cases, which shows that BESS shifts the peak demand and reduced the variations in power imported from main grid even at higher DG penetration. The daily hourly power loss observed in all cases is shown in Fig. 4. The node voltage profiles for all cases are shown in Fig. 5, which ensures that node voltages are significantly improved in cases II and III and no node voltage violation is observed. Similarly, Fig. 6 shows the SOC status for all BESSs to minimise the hourly power loss and variability effect of WTs. It may be observed that the installed BESSs are fully utilised

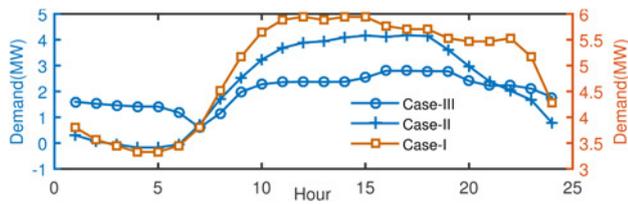


Fig. 3 System demand for all investigated cases

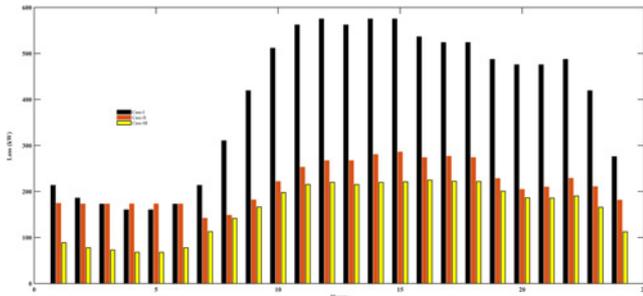


Fig. 4 Daily hourly power loss of the system for all investigated cases

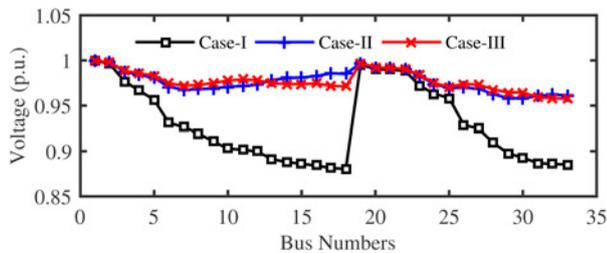


Fig. 5 Mean node voltage profiles of the system for all cases

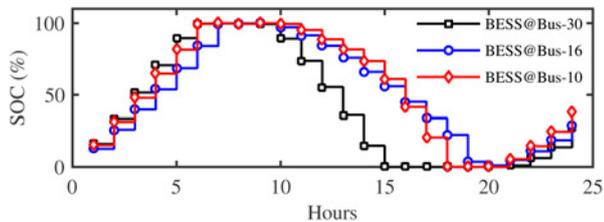


Fig. 6 SOC status of all BESSs

because SOC of all BESS are daily varying from '0' to '1'. It also indicates that minimum required amount of energy storage has been installed which is necessary to manage the system operations under high renewable penetration. It shows that all BESSs are charged during night hours (i.e. 21:00 to 7:00) when load demand is low and wind power generation is high.

5 Conclusions

In the paper, a bi-level optimisation framework is developed for optimal accommodation and management of WTs and BESS simultaneously considering various system constraints. In order to minimise the effect of intense WT penetration, new objectives and system security constraints are introduced such as minimisation of annual energy loss in feeders, reverse power flow into the grid, non-utilised BESS capacities, round-trip conversion losses of BESSs and voltage deviation of distribution systems. The proposed strategies effectively mitigated the reverse power flow problem due to high wind power penetration in distribution systems. It has been

observed that proposed approach shifts the system peak demand and the variability of power imported from main grid is alleviated. Moreover, the maximum utilisation of installed BESS has been ensured to optimise the necessary initial investment cost.

In future, the proposed work can be extended to investigate the techno-economic aspects of different renewable power generation considering stochastic behaviour of renewables and load demand.

6 References

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