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Strategic Allocation and Energy Management of BESS for the Provision of Ancillary Services in Active Distribution Networks

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Abstract

The increased penetration of renewables has prompted the integration of battery energy storage systems (BESSs) in active distribution networks. The BESS not only act as backup power supply but also provides various ancillary services with extra degree of flexibility to distribution networks by changing its' role as generation and load. In this study, a new optimization framework is developed to optimally allocate the intense wind power generation units and BESSs considering its ancillary services in distribution systems. The BESSs are strategically allocated at two sites in coordination with the renewable generating source. One is installed at grid substation to participate in central ancillary services whereas; second will be used to participate in distributed ancillary services. The objective is to minimize the cost of annual energy loss while performing various ancillary services in distribution network. The proposed optimization framework is implemented on a real-life 108-bus Indian distribution system for different cases and solved using genetic algorithm. The comparison of simulation results show that the proposed optimization framework provides more energy loss reduction, improved system voltage and power factor at higher penetration of wind power generation units as compared to the cases in which ancillary services are not considered in planning.

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1. Introduction

The Distributed Energy Resources (DERs) have provided paradigm shift to the modern power industry. Some of the popular DERs may include Distributed Generations (DGs), Shunt Capacitors (SCs), super capacitors, Battery Energy Storage Systems (BESSs), Superconducting Magnetic Energy Sources (SMESs), electric vehicles, etc. The DGs may be dispatchable and non-dispatchable or intermittent. The prominent features of renewables and their contributions in lowering the GHG emissions have encouraged power system planners to increase the share of renewables in the modern power system. However, intermittent and uncertain characteristics of renewables are making their integration more challenging [1]. In order to alleviate some of the issues of high renewable penetration, it is recommended to integrate them optimally. On the other hand, the optimal allocated DERs can generate enormous techno-economic benefits for utility, DER owner, and customers. The commonly generated benefits of optimal DER integration may cover minimization of power/energy loss [2–5], operating cost [1], node voltage deviation [2–4], emission, feeder current stress [4], overloading of distribution transformers while maximizing the stability [2,3], reliability and power quality, etc. The optimal allocation of DERs turns out to be a complex, non-linear, mixed-integer and non-convex real-life optimization technique considering its node, size, and type.

In literature, the optimal allocation of DERs have been investigated by formulating single and multiobjective optimization problems, various optimization methods have been applied to get the optimal solution. The commonly known optimization methods may include genetic algorithm (GA) [1–2, 4–7], particle swarm optimization [2], harmony search optimization [5], teaching-learning based optimization [3], etc. In these formulations, different types of generation and load models have been considered e. g., single load level [2,3,4], multi-load levels [5] and variable load model [1,4]. Some of the researchers have been formulated the simultaneous DER integration problems by considering different DERs in order to provide the coordinated benefits. These can be DGs & network reconfiguration [5], DGs & SCs [6], DGs & voltage regulators [6], etc.

Conventionally, the ancillary services are delivered by the central power plants to operate power system in secure and stable states. The penetration of DGs is increasing in distribution systems whilst central power plants still needed to support in ancillary services which forced these plants to operate in a non-ideal mode, leading to reduced efficiency and increased costs [8]. The recent advances in battery storage technologies are encouraging the optimal integration of BESSs in the distribution systems along with the renewables [1,4], which can provide additional degree of flexibility to the system with its bidirectional power flow capability. It may be noticed that significant work has been done on BESS integration in distribution systems for different goal achievements. However, only a handful amount of work exists in literature based on ancillary services management in active distribution system with high renewable penetration along with BESSs. The dispatch of BESSs can be actively controlled by suitable energy management system to provide optimal voltage control, line congestion management, local load balance, aggregation and dispatching of local feeders, loss minimization, etc. [9]. The BESS services can be divided into three mainstreams namely; energy arbitrage, provision of ancillary services and objectives optimization of local distribution grids [10].

In this paper, a new optimization framework is proposed to allocate and operate the different DERs optimally while considering some ancillary services. Both central and distributed ancillary services have been considered which will be provided by BESSs & SCs installed in grid substation and one BESS in distribution system respectively. Generally, the central DERs are utilized to improve the Power Factor (PF) and to minimize variations in grid power transaction of distribution systems. The DERs are used to minimize power loss, node voltage deviation and hourly demand variations. The proposed optimization framework is implemented on a real-life Indian distribution system of 108 buses and GA is adopted from [7] to determine the optimal allocation solution and ancillary services management for different cases i.e., base case, WTs only and WTs with BESSs. The comparison of simulation results shows that the proposed model can generate more benefits such as enhanced node voltage and PF control, minimized annual energy loss by utilizing the ancillary services of installed DERs.

2. Proposed Optimization Framework

In this section, an optimization framework is developed for optimal energy management of BESSs simultaneously supporting some popular ancillary services in active distribution systems. The formulation considered annual energy

loss minimization as objective while maintaining various constraints. The objective function, constraints and ancillary services are discussed in following sub-sections.

2.1 Objective function

In daily practices, the utilities are trying to achieve various techno-economic benefits simultaneously. It can be observed that distribution systems are less efficient in power delivery as compared to transmission networks. The cost of annual energy loss found in distribution systems is considerably affecting the annual revenue of utilities. Therefore, the minimization of annual energy loss has always been an important concern for utilities. Following the facts, annual energy loss minimization is considered as an objective of proposed model, expressed as follows [4]:

$$F = \phi \sum_{h=1}^{24} \sum_{i=1}^N \sum_{j=1}^N \alpha_{ij,h} (P_{i,h} P_{j,h} + Q_{i,h} Q_{j,h}) + \beta_{ij,h} (Q_{i,h} P_{j,h} - P_{i,h} Q_{j,h}) \quad (1)$$

where, $\alpha_{ij,h} = \frac{R_{ij}}{V_{i,h} V_{j,h}} \cos(\delta_{i,h} - \delta_{j,h})$ & $\beta_{ij,h} = \frac{R_{ij}}{V_{i,h} V_{j,h}} \sin(\delta_{i,h} - \delta_{j,h})$

subject to

$$P_{i,h} = V_{i,h} \sum_{j=1}^N V_{j,h} Y_{ij} \cos(\theta_{ij} + \delta_{j,h} - \delta_{i,h}) \quad \forall i, h \quad (2)$$

$$Q_{i,h} = -V_{i,h} \sum_{j=1}^N V_{j,h} Y_{ij} \sin(\theta_{ij} + \delta_{j,h} - \delta_{i,h}) \quad \forall i, h \quad (3)$$

$$V_{\min} \leq V_{i,h} \leq V_{\max} \quad \forall i, h \quad (4)$$

$$\sum_{i=1}^N \sigma_i P_{DER_i} \leq P_D^{Peak} \quad \forall i \quad (5)$$

$$I_{ij,h} \leq I_{ij}^{Max} \quad \forall i, j, h \quad (6)$$

Equations (2)-(6) represent the nodal real & reactive power balance, node voltage limits, DER penetration and feeder current limit constraints respectively. $P_{i,h}$, $Q_{i,h}$, $V_{i,h}$, $\delta_{i,h}$, $I_{ij,h}$ are denoting the real & reactive power injections, node voltages & angle on bus i , and branch current between bus i and j for h^{th} hour respectively. Similarly, φ , N , R_{ij} , I_{ij}^{Max} , θ_{ij} , V_{\min} , V_{\max} , P_{DER_i} , P_D^{Peak} , σ_i represent daily to annual conversion factor, number of buses in the system, resistance, maximum current, impedance angle between bus i & j , minimum & maximum specified voltage limits, DER capacity to be deployed at bus i , peak demand of the system and binary decision variables for DER to be install at bus i respectively.

2.2 Wind Power Generation and Battery Energy Storage Systems

The wind speed is highly intermittent and uncertain by nature therefore; appropriate hourly modeling of wind power generation is adopted from [4]. The BESS is very different from DGs due to its changing role as backup generation or load. Furthermore, the availability of State of Charge (SOC) is also an issue for utilities. Therefore, the optimal network management considering BESSs may be essential to maintain their SOC levels and utilize it whenever needed. In this paper, it has been suggested that BESSs should be charged when reverse power flow is detected at grid substation generally observed during light load hours as it is expected to reduce the wind power curtailment and maintain the system security. The modeling and constraints of BESSs are adopted from [1,4].

2.3 Ancillary Services

The ancillary services are referred for the services which are generally provided by DERs other than the production of electricity and used to maintain the stability and security of power systems. From literature and discussions [11], it has been found that there is no uniform standardized categorization for ancillary services. According to Eurelectric [12], the control of frequency, voltage, stability and system restarting can be considered in ancillary services. The

CIGRE report on ancillary services includes frequency control, voltage control, network control and black start [13]. However, these practices are very common in transmission networks as compared to distribution systems. Though, the inclusion of various DERs in contemporary distribution system has augmented the importance of ancillary services in distribution systems. Nowadays, many ancillary services are popular in active distribution systems for demand side flexibility namely, fast frequency response, frequency curtailment reserve, replacement reserve, fast VAR support, slow voltage control, black start, islanding, stability, congestion management, power quality services, generation and load curtailment management etc. The inclusion of BESSs with high renewables has encouraged utilities to adopt various ancillary services in active distribution systems. In this paper, it has been assumed that the central services, i.e., Power Factor (PF) and demand variation, will be controlled by BESS present in grid substation whereas, the distributed services are managed by distributed wind turbines (WTs) and a BESS in the network. The basic configuration of proposed scheme is shown in Fig. 1.

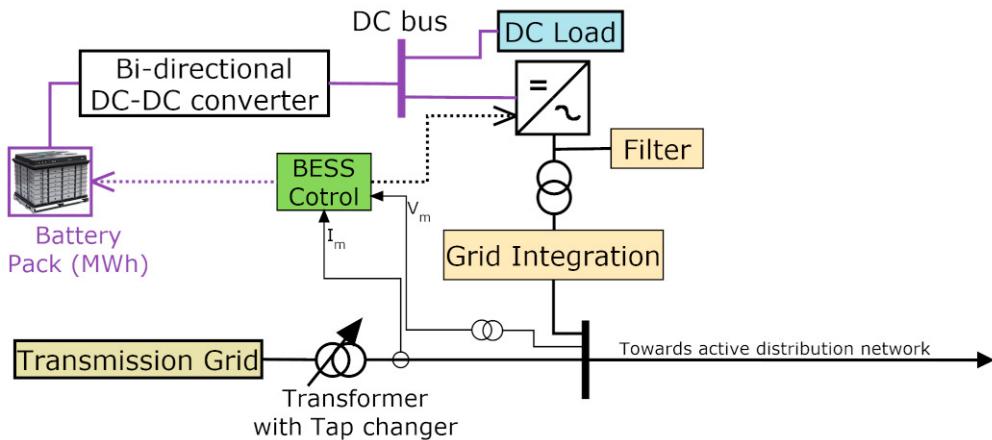


Fig. 1 Proposed energy management strategy to provide ancillary services in active distribution networks

3. Proposed Genetic Algorithm for Optimal DER Allocation

The proposed optimization framework is a complex mixed-integer, non-convex and non-linear optimization problem which requires an effective and powerful optimization method to obtain the competitive solution. Therefore, a nature inspired meta-heuristic optimization technique, i.e. Genetic Algorithm (GA) is adopted. The technique is inspired from the process of natural selection and proven its ability to solve diverse engineering optimization problems [1–2, 4–7]. An improved variant of GA, proposed in [7] is adopted except heuristic spark. The structure of individual or chromosome used in the GA is presented in Fig. 1.

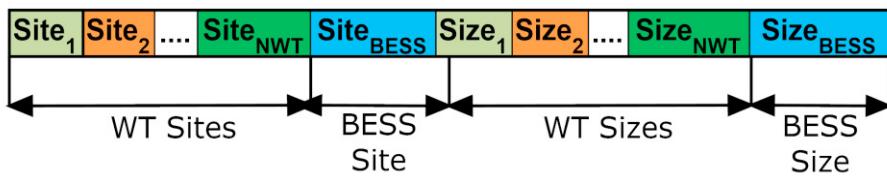


Fig. 2. Structure of individual used in proposed genetic algorithm

Suppose N_{WT} number of wind turbines is needed to install at N_{WT} different sites along with one BESS then the length of a chromosome will be $2(N_{WT} + 1)$. The flowchart of proposed GA and strategic optimal allocation and energy management of BESSs for the provision of ancillary services in active distribution networks is presented in Fig. 3.

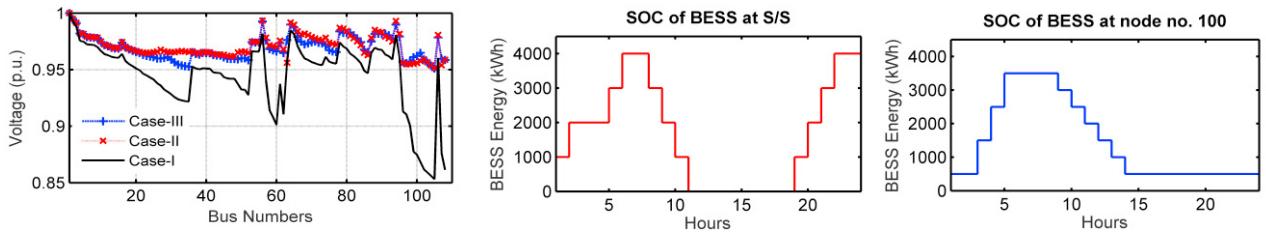
4. Case Studies

In order to demonstrate the effectiveness of proposed optimization model, a real-life 108-bus Indian distribution system is adopted from [6]. It is an 11 kV network with nominal real and reactive power demand of 12.132 MW and 9.099 MVar respectively. The real and reactive power losses determined for nominal loading are 645.02 kW and 359.416 kVAr respectively. In this modeling, the optimal allocation of seven WTs and two BESSs is determined to minimize annual energy loss expressed in (1) considering various ancillary services. The optimization problem is solved using the approach presented in section 3. Three different cases have been investigated to reveal the salient features of proposed planning and operation model: *I) base case, II) WTs only and III) WTs and BESSs under proposed strategies*. The simulation results obtained for these cases are presented in Table 1. The table shows the optimal nodes and sizes of WTs and BESSs, the values of DG penetration, annual energy loss, percentage annual energy loss reduction, minimum voltage with node and power factor of the system for all cases. The DG penetration is calculated as the percentage of systems' peak demand [6]. It can be observed that the proposed model, i.e. case-III has significantly improved the system performance in terms of PF improvement, voltage profile improvement and power loss reduction at higher DG or WTs penetration.

It is interesting to notice that WTs operating at unity PF deteriorates the system PF in comparison to base case, as system draws more reactive power from transmission grid. In proposed approach, the power factor control is provided by the central ancillary services thus it has been improved. Fig. 3(a) shows the mean node voltage profile of the system is significantly improved in case-II and III. The hourly SOC status of integrated BESSs is presented in Fig. 3(b) which shows that central BESS is charged and discharged slowly as compared to BESS deployed at node no. 100 as it is participating in energy loss minimization during peak load hours.

Table 1. Simulation results obtained by proposed optimization model for different cases

Case	Optimal nodes (sizes in MW) of WTs	Optimal node (size in MWh) of distributed BESS	Optimal size of central BESS (MWh)	DG penetration (%)	Annual energy loss (MWh)	Percentage Loss reduction (%)	Min $\langle V_{i,h} \rangle$ (p.u.)	Mean PF of the system
I	—	—	—	00.00	10996.91	—	0.82	0.80
II	27(2.668), 33(1.001), 60(2.935), 68(1.356), 79(3.113), 94(1.404), 102(2.328)	—	—	28.85	6301.86	42.69	0.89	0.45
III	21(1.400), 29(1.886), 60(2.283), 63(2.809), 71(0.372), 81(1.494), 101(1.870)	100(3.902)	1(4.000)	31.20	5602.66	49.05	0.89	0.90



(a) Mean voltage profile of the system

(b) SOC level of BESSs

Fig. 3 Various performance parameters of the system

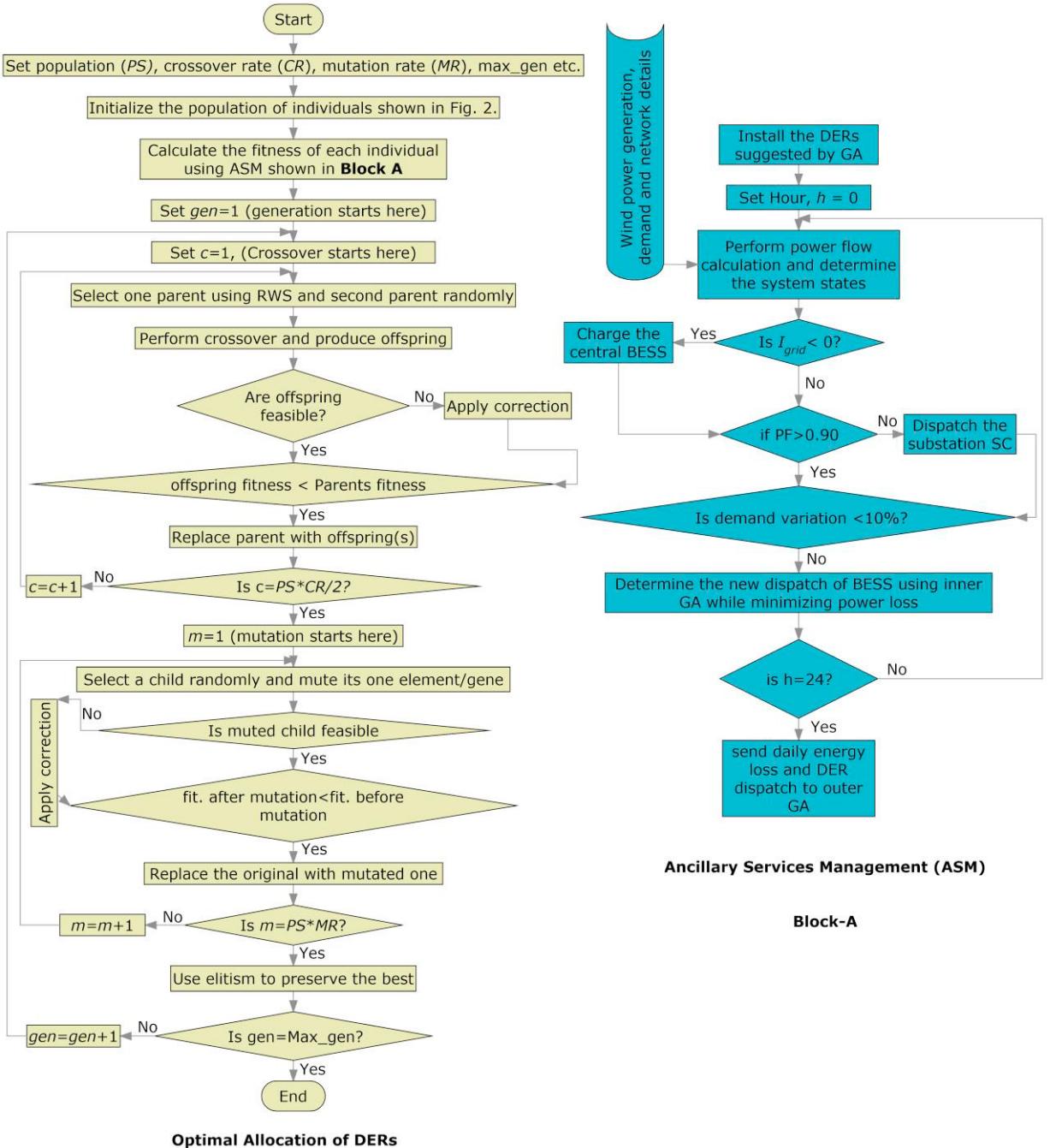


Fig. 4 Flowchart for optimal allocation of DERs considering ancillary services in distribution systems

5. Conclusions

The paper presents an optimization framework for strategic allocation and energy management of BESSs with the provision of ancillary services in active distribution networks. Annual energy loss minimization is the objective whilst improving node voltage profile & PF of the system. The effectiveness of model is tested on a real-life Indian

distribution system of 108 buses and its applicability is demonstrated by comparing the simulation results of different cases in which ancillary services are ignored. The comparison shows the proposed approach generates more benefits such as improved voltage profile, PF and reduced energy losses at higher DG penetration. The proposed strategy may play vital role to manage various services under higher DG penetration. In future, it can be extended for bi-level optimization framework to determine optimal energy management using inner layer optimization.

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