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Multi-Dimensional Energy Management Based on an Optimal Allocation of Hybrid Wind Turbine Distributed Generation and Battery Energy Storage System in a Flexible Interconnected Distribution Network Considering Seasonal Uncertainties †

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Abstract: In recent years, the incorporation of wind turbine distributed generation (WTDG) in addition to a battery energy storage system (BESS) into an electrical distribution network (EDN) has developed into a beneficial solution for ensuring a satisfying balance between energy generation and consumption. The principal approaches used to locate and size multiple WTDG and BESS units inside an EDN are described in this article. To optimize overall multi-objective functions, this research investigates the optimal planning of multiple hybrid WTDG and BESS units in an EDN. In the first scenario, injecting active power into the EDN is accomplished by installing WTDG. In contrast, in the second scenario, hybrid WTDG and BESS units are deployed concurrently to provide the EDN, taking into consideration the seasonal uncertainty of load–source power variation in order to approach the practical case, where there are many parameters to be optimized, considering different constraints, during the uncertain times and variable data of a load and power generator. The suggested work's originality is in completely designing a novel multi-objective function (MOF) based on the sum of three technical metrics of the active power loss (APL), voltage deviation (VD), and operating time of the overcurrent relay (OTR). The proposed MOF is validated on the standard IEEE 69-bus distribution network by applying a new, recently published meta-heuristic algorithm called the Light Spectrum Optimizer (LSO) algorithm. The optimized outcomes revealed that the LSO showed good behavior in minimizing each parameter included in the MOF during the year season.

Keywords: optimal allocation; seasonal uncertainties; wind turbine distributed generation; battery energy storage system; electrical distribution network; multi-objective functions

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1. Introduction

Currently, power network load variation and energy flow are becoming more unstable, owing to the sporadic production of renewable resources (RERs). Consequently, electrical grids are undergoing an interval of transition caused by an array of issues that require some solutions, such as the growth in power system reliability and development, enhanced energy quality, increased load management, renewable energy penetration, and lower emissions of greenhouse gases.

Wind turbines are often employed in distribution systems, as they offer clean energy that is reliant on renewable sources with an elevated state of inertia. Using wind turbines (WTs), we can convert kinetic energy into an EDS system. In recent years, there has been a rapid increase in the use of RERs in electrical distribution systems (EDSs), such as wind turbine distributed generators (WTDGs) [1]. However, the inconsistency of WTDG output power has caused a number of issues for distribution networks. A battery energy storage system (BESS) is used in conjunction with WTDGs to seamlessly inject output power into the grid [2]. The BESS, with its separate charging and discharging abilities, provides an efficient method of minimizing RER output fluctuations and improving EDS interactions.

The RES may have significant benefits if properly deployed. A variety of methods of optimization, involving conventional and artificial intelligence approaches, were recently examined and compared in [3]. This study proposes a practical method for best placing hybrid WTDG and BESS units in an EDS to minimize overall system losses and improve voltage profiles [4]. Recently, a number of researchers studied the most effective WTDG and BESS location in the EDS via a number of algorithms and methods to minimize the total costs including uncertainty of WTDG [5].

Additionally, the marine predator algorithm was used to optimize a multi-objective function included power losses, voltage deviation, and relay operating time indices [6]. Modified African buffalo optimization was used to minimize the daily energy losses [7], and novel inherited competitive swarm optimization was employed to reduce the annual energy loss cost [8]. A variety of proposed chaotic grey wolf optimization techniques to minimize a novel multi-objective function included a total of three techno parameters [9], and a crow search algorithm to minimize the annual and flicker emission costs produced by WTDG units [10].

Recently, researchers utilized new metaheuristic algorithms that involved a unique chaotic student psychology-based optimization including load models and the hourly load profile average [11]. The search group algorithm was used with the aim of maximizing the technological, economic, and environmental objectives [12], as well as a hybrid multi-objective algorithm that incorporated the GA-PSO algorithms in order to optimize a simultaneous total cost for BESS and power loss [13].

The practical objectives are diametrically opposed. As a consequence, deciding where to put the hybrid WTDG and BESS is a difficult multi-objective function (MOF) problem that has to be resolved while optimizing several competing goals. In this study, a hybrid WTDG-BESS system allocation problem is intended to minimize the MOF, which can be resolved by using a new recent meta-heuristic algorithm identified as the light spectrum optimizer (LSO) algorithm and examined using the IEEE 69-bus standard [14].

2. Problem Formulation

This article is considered to optimally locate and size the hybrid WTDG and BESS sources into EDN by simultaneously reducing the technical parameters of total active power loss (*TAPL*), total voltage deviation (*TVD*), and total operation time (*TOT*) of relays.

$$MOF = Minimize \sum_{i=1}^{N_{Bus}} \sum_{j=2}^{N_{Bus}} \sum_{i=1}^{N_{Relay}} TAPL_{i,j} + TVD_j + TOT_i \tag{1}$$

We start with the *TAPL* of the distribution line, which can be expressed by [13].

$$TAPL_{i,\, j} = \sum_{i=1}^{N_{Bus}} \sum_{j=2}^{N_{Bus}} \alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}\left(Q_i P_j + P_i Q_j\right) \tag{2}$$

$$\alpha_{ij} = \frac{R_{ij}}{V_i V_j} \cos\left(\delta_i - \delta_j\right),\ \beta_{ij} = \frac{R_{ij}}{V_i V_j} \sin\left(\delta_i - \delta_j\right) \tag{3}$$

where R_{ij} is the line resistance. (δ_i, δ_j) and (V_i, V_j) are angles and voltages, respectively. (P_i, P_j) and (Q_i, Q_j) demonstrate active and reactive powers, respectively. The second term is the *TVD*, which is defined as [15].

$$TVD_{\,j} = \sum_{j=2}^{N_{Bus}} \left|1 - V_j\right| \tag{4}$$

The final term, the *TOT* of overcurrent relays, is defined as [16].

$$TOT_{\,i} = \sum_{i=1}^{N_{Relay}} OT_i \tag{5}$$

$$OT_{\,i} = TDS_i \left(\frac{A}{M_i^B - 1} \right) \tag{6}$$

where T_i is the operation time of the relay, *TDS* is the time dial setting, *M* is the multiple of the pickup current. *A* and *B* are relay constants set to 0.14 and 0.02, respectively. N_{Relay} is the number of overcurrent relays.

3. Application and Results

The algorithm used in this study has been verified on the standard IEEE 69-bus EDN, which is depicted in Figure 1 as a single-line diagram. The test network has a baseline voltage of 12.66 kV, a total active load of 3790.00 kW, and a reactive load of 2690.00 kVar. Each bus of the tested network would be secured via an overcurrent relay (OCR) and backed up by another OCR, with a coordination time interval (CTI) set above 0.2 s.

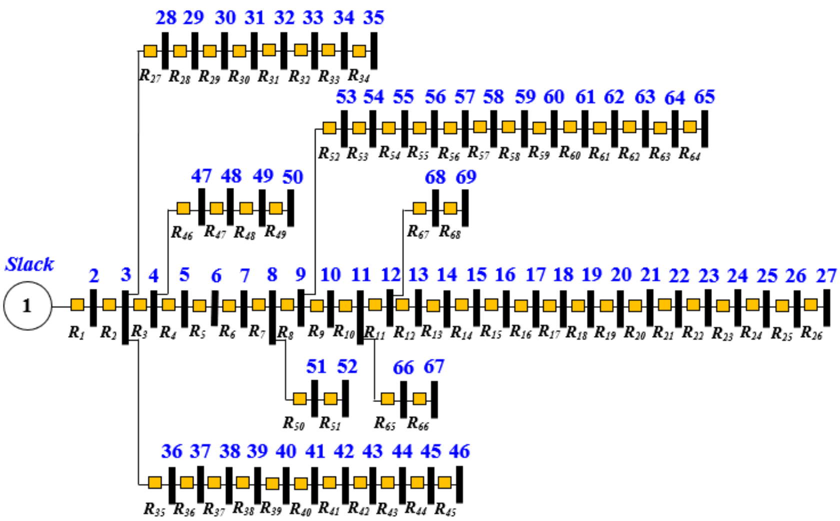

Figure 1. Single-line diagram of the IEEE 69 bus EDN.

Figure 2 represents the convergence curves while minimizing the MOF using the applied LSO algorithm for all integrated cases into the IEEE 69-bus EDN.

For a maximum number of iterations equaling 100, involving an average population size of 10, we demonstrated the LSO algorithm's superiority while generating the most effective outcomes and remedies for the established problem. The case of hybrid WTDG-BESS was the best one that provided the minimum MOF results, and also with a fast convergence characteristic, which settles down at around 90 iterations.

Table 1 stated the outcomes of optimization utilizing the LSO algorithm, contrasting the studied integrated cases into IEEE 69-bus EDNs.

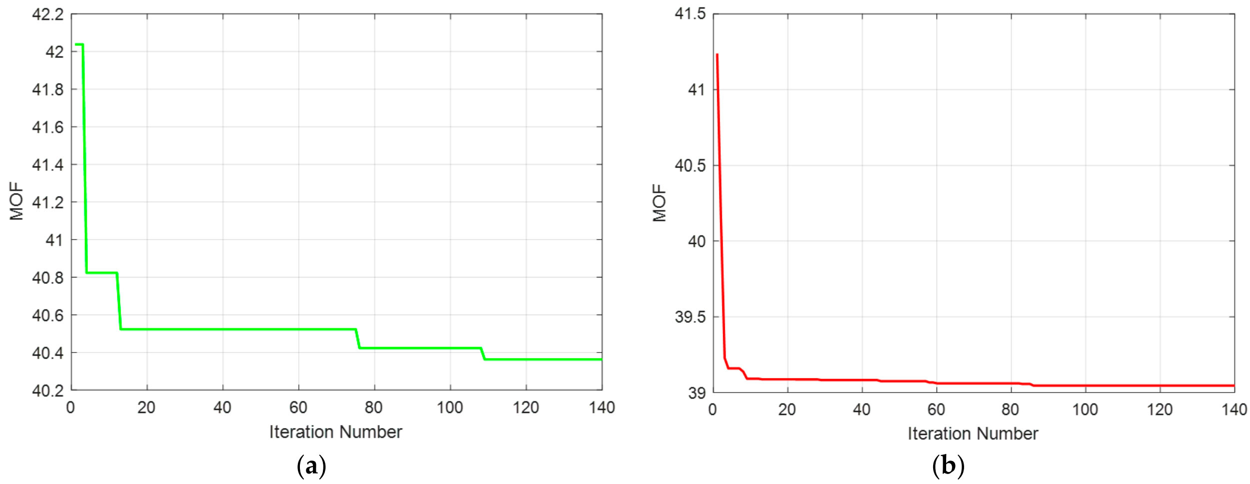

Figure 2. Convergence curves of the applied LSO algorithm for various case studies: (**a**) WTDG case; (**b**) hybrid WTDG-BESS case.

Table 1. Optimal results for all the studied cases integrated into the IEEE 69-bus EDN.

Case Studies	**WTDG**			**BESS**		***TAPL* (MW)**	***TVD* (p.u.)**	***TOT* (s)**	***MOF***
	Bus	**P_{WTDG} (MW)**	**Q_{WTDG} (MVar)**	**Bus**	**P_{BESS} (MW)**				
With WTDG	6 29 58	1.0131 1.5902 0.9019	0.9809 0.7091 0.4111	....	....	76.30	0.973	38.62	40.36
With WTDG and BESS	3 7 56	0.9830 1.7390 0.9211	0.3989 0.6964 0.7309	22 44 61	0.5460 0.3718 1.2233	65.58	0.630	38.46	39.04

The outcomes of optimization displayed in Table 1 indicate the LSO algorithm's advantage and effectiveness in producing the most effective results reflected as the minimum of MOF across all studied cases. Another point to mention is that hybrid WTDG-BESS units were the best option for providing the least number of results for EDNs at the same time until 39.04, including the minimum values of TAPL with 65.58 MW, TVD with 0.43 p.u., and TOT with 38.46 s.

Figure 3 depicts the seasonal variation in active power loss variation displayed in 96 h, for all studied cases integrated in the IEEE 69-bus.

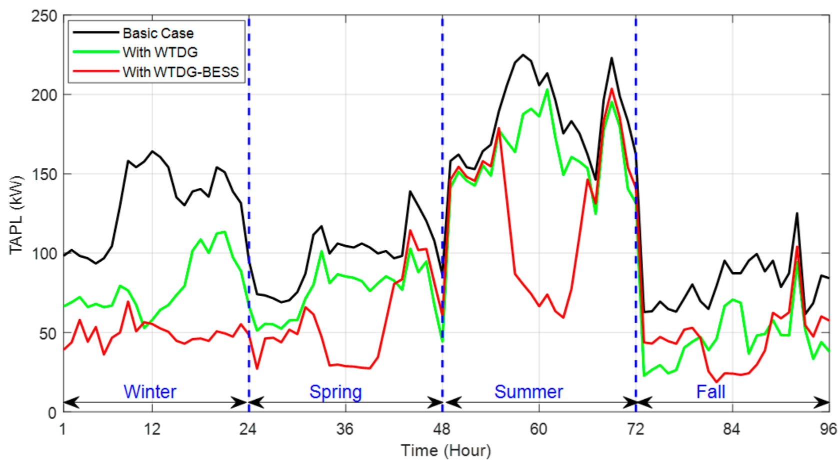

Figure 3. Seasonal active power loss variation.

The seasonal total active losses decreased substantially for the test system EDNs, following the optimum setup of all the studied cases, with greater efficiency and reduction stipulated from the case of hybrid WTDG-BESS units, from an overall value of 11.84 MWh to 6.72 MWh for the test system EDN, with a minimization rate of 56.76%. Because the hybrid WTDG-BESS units incorporate two power sources that produce both active and reactive power, the supply is guaranteed and ongoing throughout the year, almost without disruption.

Figure 4 represents the seasonal variations in total voltage deviation in the test system EDN displayed over 96 h for all the studied integrated cases. The illustrations in Figure 4 show that the optimal inclusion of all the studied cases, using the LSO algorithm, significantly influenced and lowered the seasonal voltage deviation in the test system EDN. The hybrid WTDG-BESS unit case was deemed to be the most suitable choice between the studied cases because it effectively ensured the lowest and best results in terms of seasonal voltage deviation, going from an overall value of 131.20 p.u. to 92.71 p.u. including a minimization rate of 70.6%.

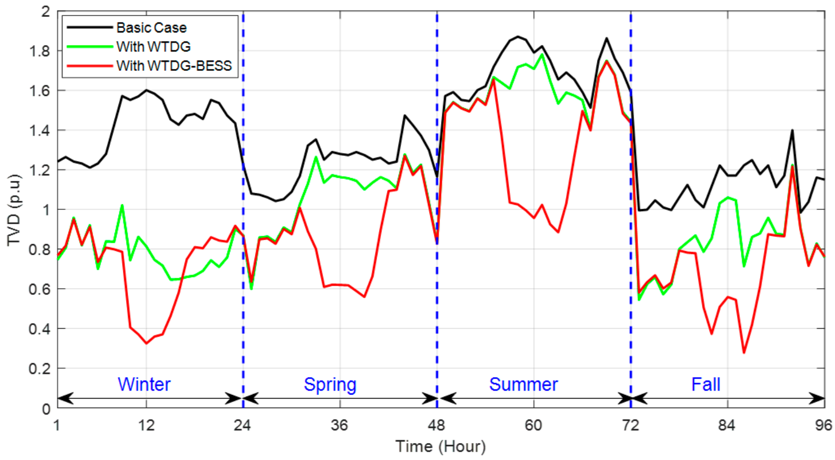

Figure 4. Seasonal variation in total voltage deviation.

Figure 5 represents the seasonal variation in the total operating times of overcurrent relays in the test system EDN, which displayed over 96 h for all the studied integrated cases.

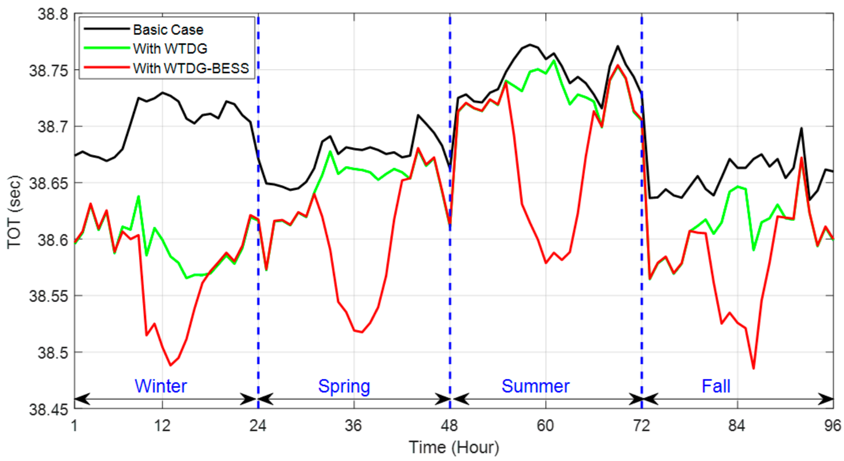

Figure 5. Seasonal variation in the total operation of overcurrent relays.

Overcurrent relays are dedicated to identifying and correcting the fault current. Reducing their operating time is favorable for many aspects, such as system protection, continuity of service, and extending the lifetime of equipment. Using the LSO algorithm obviously led to the mitigation of the seasonal operation time of the overcurrent relays in the EDN, with superior results to the case of WTDG-BESS units, with a minimizing of the TOT to 38.46 s.

4. Conclusions

This research was devoted to applying a new optimization algorithm called the LSO to optimally locate and size the hybrid WTDG-BESS into an IEEE 33-bus EDN, considering the seasonal uncertainties of load–source power variation. The purpose of that implemented optimization was to enhance the performance of the tested network while reducing an MOF comprising the technical parameters of TAPL, TVD, and TOT. The outcomes revealed the effectiveness of the LSO algorithm in optimizing and solving the formulated problem; also, clearly, the case of WTDG-BESS was the best choice that provided the best results to the distribution network as long as the active/reactive power was provided during all seasons.

Future research will concentrate on proposing a complex MOF that may comprise different techno-economic issues, as well as focusing on the topic of EVCS as a load to better improve the performance of the distribution network.

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