IMPACT OF CONSTRAINT HANDLING TECHNIQUES ON THE SOLUTION QUALITY OF MICROGRID SIZING & ENERGY MANAGEMENT SYSTEM OPTIMISATION

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Abstract

Constraint handling techniques (CHTs) are crucial in solving microgrid sizing and energy management system (MSEMS) problems. However, CHTs' use and impact on solution quality are not explored enough. Our study compares the solution quality of three CHTs (Deb's rules, a novel repair scheme and a novel hybrid CHT) in solving a MSEMS optimisation problem. While Deb's rules sort the best solution based on the fitness and constraint violations, the proposed repair scheme repairs the infeasible solutions and returns them to the feasible region or close to it. The proposed hybrid CHT directs feasible solutions straight to Deb's rules, and it uses the repair scheme to repair infeasible solutions before directing them to Deb's rules to filter the best solution. Two performance indices were developed to evaluate the solution quality: the feasibility ratio (FR) and the constraint violation monitoring mechanism. In this study, the MSEMS problem minimises the levelized cost of electricity, loss of power supply probability, and CO_2 emissions while satisfying power balance, battery, and generator constraints. The Predator-parasite algorithm is employed to solve the MSEMS problem simulated in MATLAB, validated using actual weather data and the demand profile of Westray Island in Scotland. The simulation outcomes demonstrate that the FR through Deb's rules is 67%, limiting its capacity to converge towards feasible solutions. Nevertheless, the repair scheme enhances solution quality by increasing FR to 86%, and the hybrid CHT further improves solution quality with a FR of 99%. This improvement is further visualised through the constraint violation monitoring mechanism. The findings demonstrate that Deb's rules approach is ineffective in solving MSEMS optimisation problems of this nature and highlight the importance of CHTs in achieving quality solutions. This study's implications are significant for the energy industry, especially in microgrid control architectures, where the quality of solutions is critical in real-world applications. Therefore, this study highlights the importance of CHTs in solving MSEMS optimisation problems and demonstrates a practical hybrid CHT for achieving quality solutions. Furthermore, the proposed hybrid CHT has the potential to be used in solving problems that involve multiple constraints, making it useful in various other applications.

Keywords: Constraint handling techniques, energy management system, microgrid, optimisation, renewable energy, sizing

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INTRODUCTION

Microgrids integrate renewable energy resources (RERs), conventional energy resources, and energy storage systems (ESSs) to meet varying electricity demands, operating in either grid-connected or islanded mode. While they offer reduced emissions, decentralised energy supply and other benefits, microgrids pose challenges such as high investment costs, reliability concerns, and intermittent RER management. Therefore, optimising microgrid sizing and energy management system (MSEMS) are critical to ensure cost-effective and efficient operation (Hirsch et al., 2018). However, these problems are non-convex, nonlinear, mixed-integer, and constrained optimisation problems with multiple local solutions (Rezaei et al., 2020). Therefore, scholars often use metaheuristic algorithms to solve these problems (Liu et al., 2021; Marocco et al., 2021; Zhou et al., 2020).

However, to navigate the feasible search space while satisfying constraints and increasing the likelihood of locating a globally optimum solution, constraint handling techniques (CHTs) must be incorporated into the algorithms. There are four main groups of CHTs found in research: penalty methods, separatist methods, repair methods, and hybrid methods (Jordehi, 2015; Yang et al., 2020; Yu et al., 2021).

Previous research has established that static (Ahmadi & Abdi, 2016; Askarzadeh, 2018; Gharavi et al., 2015; Lorestani et al., 2019; Nikmehr et al., 2017; Singh et al., 2020) and death penalty methods (Elgamal et al., 2020; Fathi et al., 2022; Javidsharifi et al., 2020; Rullo et al., 2019; Xie et al., 2021) are among the simplest and most straightforward CHTs to solve various microgrid optimisation problems. Nevertheless, they often lead to suboptimal solutions. Alternatively, some authors used the feasibility criteria (popularly known as Deb's rules) proposed by (Deb, 2000) to solve MSEMS problems (Beshr et al., 2018; Li & Xia, 2019). Several other CHTs have also been employed in some MSEMS optimisation studies in the past (An et al., 2021; Chen et al., 2022; Huang et al., 2021).

Scholars have mainly focused on developing or improving algorithms rather than exploring the impact of CHTs on solution quality in MSEMS optimisation. This paper addresses this gap by exploring the impacts of various CHTs on MSEMS optimisation simulation outcomes, and the results suggest the need for flexible and effective CHTs to obtain quality solutions. Thereby, the main contributions of this study are: (i) hybridising a novel repair scheme with Deb's rules, (ii) proposing performance indices to evaluate the solution quality, and (iii) comparing the quality of solutions of the hybridised CHT with the repair scheme and Deb's rules to showcase the superiority of the hybrid CHT.

METHODOLOGY

In this study, three CHTs were implemented in solving a MSEMS problem to analyse the impact of various CHTs on the solution quality. They are; Case A - the standard Deb's rules, Case B - a novel repair scheme proposed by (Amarawardhana et al., 2022), and Case C - a novel hybrid CHT. The proposed repair scheme calculates the difference between RER's generation and demand and distributes the gap among chosen generators to achieve the power balance. In addition, reinitialisation repair is used to fix the boundary violations. The proposed hybrid CHT (illustrated in Fig. 1**Error! Reference source not found.**) employs this repair scheme to fix infeasible solutions and bring them back into the feasible region or close to its boundary. The repaired solutions are then filtered based on Deb's rules to select the best solution.

Two performance indices were proposed to evaluate the solution quality: the feasibility ratio (FR) and the constraint violation monitoring mechanism (CVMM). FR is the ratio between the number of feasible runs to the total number of runs. CVMM monitors violations of each constraint throughout the iterations by comparing the gap from each concerned parameter from its' limit with zero.

A case study was carried out based on the Westray Island microgrid with a wind turbine (WT), a wave energy converter (WEC), solar photovoltaic (PV) panels, a diesel generator (DG) and a Lithium-ion battery. In addition, a dump load was utilised to manage any excess energy. The schematic of the microgrid is shown in Fig. 2. The hourly demand and weather profiles for 2013 were adopted from (Daniel Friedrich & George Lavidas, 2017). The MSEMS optimises solar panels and battery sizing, while the proposed energy management system (EMS) prioritises energy demand and determines excess/deficit levels at each time step. EMS uses any surplus energy to charge the battery. Alternatively, the battery serves as a backup power source in case of any energy deficit, while DG is utilised only if necessary. The EMS runs as a precursor in the model, enhancing system efficiency by proactively managing energy flows.

To optimise microgrid resources in the presence of RERs, battery storage (BS) and solar panel sizing must be optimal while minimising the use of DG reduces CO_2 emissions. However, microgrid design should also prioritise system reliability. Therefore, the multi-objective problem aims to minimise the levelized cost of electricity (LCOE), loss of power supply probability (LPSP), and CO_2 emissions, with decision variables including BS and solar panel sizes and charging/discharging power vectors. LCOE represents the total net present cost (NPC) per unit of energy consumed during a given period (Daniel Friedrich & George Lavidas, 2017; Perera et al., 2013), while LPSP calculates the energy deficit as a percentage of the total energy consumption during the study period (Das et al., 2022; Tarife et al., 2022). Burning one gallon (i.e., 3.78541 litres) of diesel produces approximately 0.010084 tonnes of CO_2 (El-Bidairi et al., 2018). CO_2 emissions are determined by multiplying this conversion factor by the total consumed diesel. The problem is subject to power balance constraint, power, energy and state of charge (SOC) limits of the BS and the generator operating limits.

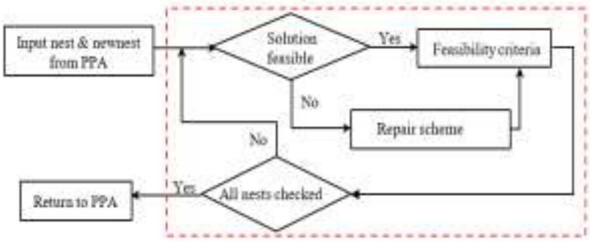

Fig. 1 Proposed novel hybrid repair-based feasibility CHT

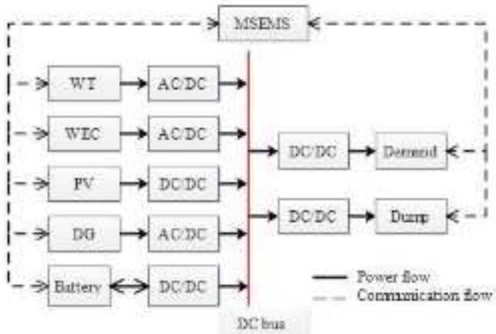

Fig. 2 Westray microgrid architecture

A hybrid parasitism-predation algorithm was employed in this study. Interested readers may consult (Mohamed et al., 2020) for more detailed implementation and algorithm parameters. Constraint violations were monitored using indices for each constraint to evaluate the quality of solutions. The generator specifications and cost details are used as in (Amarawardhana et al., 2022). Moreover, the lower and upper bounds of the decision variables are depicted in Table 1.

Table 1 Bounds of the decision variables

Decision variables	Lower bound	Upper bound
BS charging power	-300	0
BS discharging power	0	300
BS capacity	0	2000 kWh
PV panel area	0	10000 m^2

RESULTS AND DISCUSSION

Table 2 summarises a comparison of the optimised results obtained through the simulations. The results imply that Case A has the least LCOE, LPSP and CO_2 emissions. Nonetheless, when the FR and CVMM are compared, Case A presents the worst solutions and thus cannot be considered the best option. On the other hand, based on the solution quality (explained below), Case C outperforms the other two approaches.
As illustrated in Fig. 3, the simulation outcomes demonstrate that the FR through Deb's rules is 67%, limiting its capacity to converge towards feasible solutions. Nevertheless, the repair scheme (Case B) enhances solution quality by increasing FR to 86%, and the hybrid CHT (Case C) further improves solution quality with FR of 99%. These results demonstrate the substantial improvement in solution quality by implementing the proposed repair and hybrid CHTs.

Table 2 Comparison of optimised results using three CHTs

Description	CHT		
	Case A	**Case B**	**Case C**
LCOE (\$/kWh)	0.2798	0.2820	0.2828
LPSP	0.0185	0.0191	0.0186
CO_2 emissions (tonnes/kWh)	0.0792	0.0795	0.0799
Solar panel area (m^2)	175	9993	9998
BS capacity (kWh)	1028	1952	1775

Fig. 3 Feasibility ratio (FR) of three cases

This improvement is visualised through CVMM, as shown in Fig. 4. These verify the superiority of the proposed hybrid CHT (Case C). It is observed that the constraint violations are restricted only to power balance (PB), maximum BS size (C_{max}), maximum BS charge power ($P_{ch,max}$) and minimum BS discharge power ($P_{disch,min}$). In Fig. 4, blue dots represent no violations, while red dots indicate constraint violations over the iterations. As highlighted for PB constraint, the magnitude of constraint violations is highest in Case A and the lowest in Case C, similarly applicable to all other constraints.

Case A in Fig. 4 shows that Deb's rules alone cannot handle constraints in MSEMS problems of this nature. MSEMS are complex optimisation problems with scattered feasible regions due to dynamic constraints. Obtaining a feasible solution within these feasible regions is extremely difficult, and Deb's rules do not have a mechanism to locate them. Furthermore, microgrid conditions create dynamic constraint combinations that Deb's rules cannot identify, resulting in inferior results. Furthermore, constraints and objectives are interdependent, making it challenging to handle constraint violations effectively.

Case B in Fig. 4 illustrates that constraint violations in magnitude and number are reduced compared to Case A when using the proposed repair scheme. The limited violations are justified because the current solution selection method is based solely on the lowest fitness value. However, this may not provide the best outcome. Therefore, more comprehensive selection criteria based on fitness value and constraint violations are needed. Furthermore, finding the optimal solution within the feasible region remains challenging despite the repair process, which still needs rectification.

In contrast to cases A and B, Case C in Fig. 4 demonstrates the proposed hybrid CHT's effectiveness. In Case C, infeasible solutions are repaired before filtering through Deb's rules to select the best global solution. The repair process significantly reduces constraint violations by efficiently guiding the population to feasible regions or as close as possible to the boundary of the feasible region. Then, Deb's rules allow a fair comparison between feasible and infeasible solutions. By doing so, the proposed hybrid CHT quickly adapts to dynamic constraints, resulting in high-quality feasible solutions.

The correlation matrices for three cases were generated, as illustrated in Fig. 5, demonstrating the pair-wise relationships between the total fitness cost and the three objectives in each case. A strong negative correlation between LCOE and LPSP, and LPSP and CO_2 emissions are shown in all cases. In contrast, LCOE and CO_2 emissions have a strong positive correlation. These resulting correlation plots imply that the reduced CO_2 emissions correlate with lower LCOE and higher LPSP. The proposed EMS only operates the DG when RERs and BS cannot cater to the demand, effectively avoiding unnecessary diesel burning and reducing CO_2 emissions. The optimised sizes of the battery and solar panels also contribute to cost reductions.

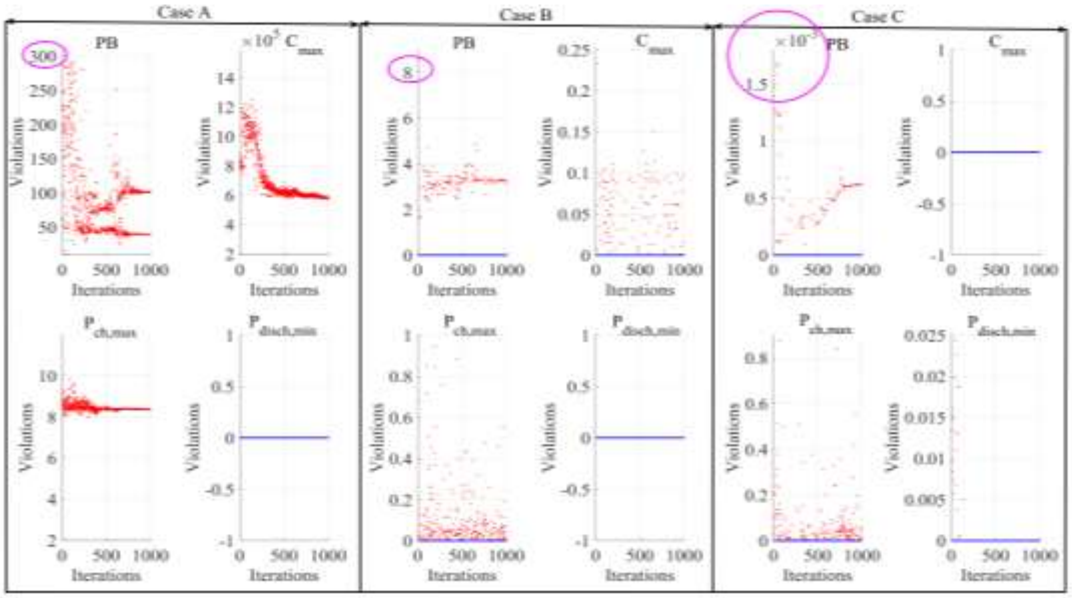

Fig. 4 Constraint violations through CVMM - Case A, B and C

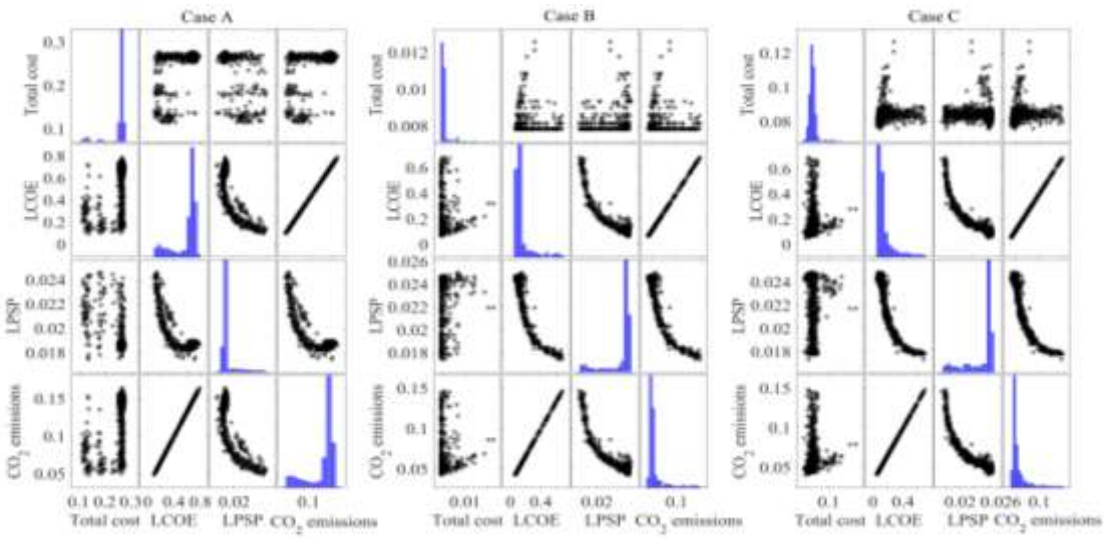

Fig. 5 Correlation of the total fitness function with three objectives

CONCLUSIONS/ RECOMMENDATIONS

This study proposes a novel hybrid repair-based feasibility CHT for solving MSEMS optimisation problems. This method uses a repair scheme to handle infeasible solutions by returning them to a feasible region or as close to it as possible before filtering them through Deb's rules, ensuring high-quality solutions without constraint violations. Simulation results demonstrate that this approach outperforms the used individual CHTs offering robustness and superior performance in handling multiple constraints. These findings have significant implications for the energy industry, especially in microgrid control architectures, where high-quality solutions are essential in real-world applications. Overall, this hybrid CHT has the potential to solve optimisation problems that involve multiple complex constraints, making it useful in various other applications beyond energy.

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