A Solution to the techno-economic generation expansion planning using Enhanced Dwarf Mongoose Optimization Algorithm

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***Abstract*— This paper proposes a hybrid metaheuristic algorithm to solve the decade Generation Expansion Planning (GEP)problem. In this proposed hybrid approach, the mutualism phase of Symbiotic Organism Search (SOS) is implemented in the Dwarf Mongoose Optimization Algorithm (DMOA) to improve the local search capability of the DMOA. In this hybrid algorithm, global search is taken care by the DMOA, and the local search is taken care by the mutualism phase SOS algorithm, which will help in solving nonlinear and nonconvex optimization problems. In recent decade every country aims to decarbonize its economy by implementing policies that increase the penetration of Renewable Energy Sources (RES) in its power generation capacity. This paper also presents a multidimensional framework of GEP based on the increasing penetration level of RES with the help of Enhanced Dwarf Mongoose Optimization Algorithm (EDMOA). The simulation results are discussed in the result section and compared with many previously published algorithms. The statistical study confirms the hybrid algorithm's effectiveness and resilience.**

Keywords— Generation Expansion Planning, Symbiotic Organism Search, Dwarf Mongoose Optimization Algorithm, Renewable Energy Sources

I. INTRODUCTION

In order to combat climate change, the majority of the world's governments ratified the Paris Agreement in 2015. These countries committed to drastically reducing their greenhouse gas (GHG) emissions in order to keep human climate change to a minimum of 1.5 degrees Celsius [1]. As a result, the European Union established a goal of reducing GHG emissions by 80-95 percent by 2050 in comparison to 1990. However, the major reductions in GHG emissions will necessitate a significant increase in the usage of renewable energy sources (RES). This results in a paradigm shift toward a fossil-based energy system in which supply follows demand. The timing and magnitude of these fluctuations vary depending on the technology.

The power system is probably the most complex physical system in the world due to its huge physical dimensions, integration at the international levels, geographical growth, and their compliance with legislation. In the other hand, electricity companies have to provide secure and cost-effective energy supplied with wide range of consumers with varying needs which is known as power system expansion planning. The expansion plan is suggested since the present network equipment is insufficient to fulfill the expanding customer demand.

GEP provides information about the amount of capacity to be added, where to site, and when to contribute to the load demand while satisfying the reported equality and inequality constraints. GEP is subdivided into Static GEP (SGEP) and Dynamic GEP (DGEP) [2]. In DGEP all the required objectives such as deciding the location, quantity, and the time when new resources construction is needed to be done. On the other hand, the time is considered to be the unknown parameters in the case of SGEP.

In recent years, extensive research on the expansion of the power systems has been performed. Optimization algorithms are found to be the best method to design optimal mathematical modelling for GEP. The GEP is deeply investigated based on the variability of RES and the required load demand in [3]. In which a metaheuristic algorithm is used to identify an acceptable solution to the problems posed by uncertainty. In [4], a complementary GEP model is described. The computationally difficult Simulation Model based on Operational Cost is solved in this paper utilizing the meta-model aided evolutionary method (MAEA). In [5] a long-term GEP framework has been developed. To overcome this problem, a generic mixed integer linear programming (MILP) is adopted in this study. A robust optimization methodology for the generation and transmission expansion planning challenge with uncertainties such as demand increase, fuel cost, and unpredictable renewable energy output are discussed in [6]. In this work, an off-line Lattice Monte Carlo simulation approach is used to address this issue. Rodgers et al. created an optimization model with the aim of reducing societal costs and included the harm done to human health by the power sector in the GEP in [7]. This work uses a Metamodel-Based Simulation Optimization (MBSO) to deal with this problem. A novel whale optimization algorithm (WOA) with a penalty factor strategy framework is created in [8] to handle a nonlinear, dynamic, discrete, extremely complicated, substantially restricted GEP problem, and robustness is evaluated using an equivalent energy function technique. In [9] gravitational search algorithm (GSA) is used to solve the renewable-conventional GEP optimization problem.

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This paper presents an optimized model for GEP that takes into account distributed generation sources as well as central power generating sources. The suggested model focuses on minimizing the total cost of generation. This model offers an ideal GEP model that boosts the effect of DG resources while improving technical, economic, and environmental indices. The model is also designed to handle different load levels to continuously supply the load demand.

The rest of the paper is structured as follows. Section II discusses problem formulation, while Sections III and IV address the DMOA and SOS approaches, respectively. Sections V and VI discuss EDMOA and the outcome analysis, respectively, and Section VII draws conclusions.

II. Problem Formulation

The proposed objective function improves the reliability and flexibility index when developing power systems. This section covers all the terms used in the objective function.

A. *Load model with uncertainty*

This study takes into account three linear load levels: peak load, average load, and base load condition [10]. Utilizing probabilistic models and each feeder's historical power consumption data is one method for analyzing and estimating how the system will behave. Therefore, using these two methodologies, a suitable horizon of dynamic load performance may be generated [11]. The power needed at each level in terms of power generating units is given by:

$$Load_i = \sum_{i=1}^{NF} CC_{i,f} \times P_{Peak_{i,f}}$$

Where NF represents number of feeders, $CC_{i.f}$ represents Coefficient of coincidence and $P_{Peaki.f}$ Peak power of ith feeder.

The stochastic character of load forecasting may be described using the probabilistic distribution function (PDF) which is expressed by:

$$f(x) = \frac{1}{\sigma_{load}\sqrt{2\pi}} \exp\left(\frac{-(x-E_{load})^2}{2\sigma_{load}^2}\right)$$

Where σ_{load} represents standard deviation of each node (i.e.10% of average load in this study), E_{load} represents the average value of the base load.

B. *Economic model of the demand response (DR)*

DR systems are intended to improve consumers' sensitivity to changes in market prices. To find out consumers involvement a model is needed to be developed that defines the pattern of demand profiles as well as customer profits and losses in associated with the energy pricing [12]. the load to price fluctuations can be can be mathematically formulated as:

$$E = \frac{\rho_0}{d_0}\frac{\partial d}{\partial \rho}$$

Where ρ_0 and ρ represents the electricity price before and after load reduction respectively, d_0 and d represents the initial and instantaneous load respectively.

C. *DR program model based on single-period*

The single-period price-based model while taking into account the incentive parameter (I) for lower demand and the penalties (λ) for higher load demand can be mathematically formulated as:

$$\frac{d(i)}{d_0} = 1 + \frac{E\times[\rho-\rho_0+I-\lambda]}{\rho_0}$$

D. *Objective function*

The objective function of this work can be mathematically formulated by considering Investing cost, emission cost, fuel cost, operational cost, maintenance cost, extra cost due to transmission and distribution loss, cost due to insufficient energy supply, and cost due to DR program execution [11]. It can be mathematically formulated as:

- GEP Cost in the Primary Generation Sector

$$PGEC = \left(\frac{z(1+z)^N}{(1+z)^N - 1}\right) \times APGEC \times PGECcap \times DMD$$

Where z and N represent annual profit rate and total lifespan of the fuel-based power plant, APGEC represents the average cost of the generation capacity expansion in ($/MW), PGECcap represents the capacity of the generation required for upstream network and the planning horizons decision-making duration is represented by Decision Making Duration (DMD).

Unit Commitment (UC) and Economic Load Dispatch (ELD) are considered to be useful for deriving the power demands and scheduling.

$$P_{net} = \sum_{i=1}^{F}(P_{Li} - P_{DGi})$$

Where F represents the number of load feeder, P_{net} represents the total load demand, P_{Li} represents the load demand at ith feeder and P_{DGi} represents the distributed generation of ith feeder.

The PGFC can be mathematically formulated as:

$$PGFC = \sum_{i=1}^{NL}\sum_{g=1}^{G} S_{gi} \times FC_g \times P_{Gi}$$

Where NL represents the number of load levels, S_{Gi} represents the on or off status of generating units, FC_G represents the cost function of each generating unit and P_{Gi} represents the power generation of ith DG.

The cost function of GHG emission can be mathematically formulated as:

$$\sum_{i=1}^{NL} PEMC_i = E_g \times M_{gi}$$

$$E_g = \sum_{g=1}^{G} F_{CO2g} \times CF_{CO2g} + F_{NOxg} \times CF_{NOxg}$$

$$M_{gi} = \sum_{g=1}^{G}\sum_{i=1}^{NL} S_{gi} \times P_{gi} \times T_i$$

Where F_{CO2g} and F_{NOxg} represents the CO2 and NOx factor respectively, CF_{CO2g} and CF_{NOxg} represents the cost factor of CO2 and NOx respectively and Ti represents the duration time.

The operational and maintenance (O & M) cost of GEP can be mathematically formulated as:

$$PGOMC = \sum_{g=1}^{G}\sum_{i=1}^{NL} S_{gi} \times P_{gi} \times T_i \times OMC_g$$

Where OMCg represents average DG O & M costs

- Costs of GEP in the Secondary Generation Sector

The cost functions arising from the growth of RES, as well as fuel costs, GHG, and O & M expenses are expressed in that section.

$$SGEC=\left(\frac{z(1+z)^{N}}{(1+z)^{N}-1}\right)\left(GE_{DGfi}+LC_{DGfi}\right)\times PI_{fi}\times DMD$$

Where GE_{DGfi} represents Annual Investment Cost of DG connected to ith feeder, LC_{DGfi} represents Annual Land Cost of DG connected to ith feeder and PI_{fi} represents Power injection in ith feeder.

The fuel cost of DG units in GEP can be mathematically formulated as:

$$SGFC=\sum_{i=1}^{NL}\sum_{f=1}^{F}FC\times\frac{[P_{DGfi}\times T_{i}\times 0.0034]}{\eta}$$

Where P_{DGfi} represents the power generation of ith feeder DG and η represents the efficiency of DG.

The emission cost based on DG units can be mathematically formulated as:

$$SEMC=\sum_{i=1}^{NL}\sum_{f=1}^{F}\frac{\left[E\times\left[P_{DGfi}\times T_{i}\right]\right]}{\eta}$$

$$E=F_{CO2}\times CF_{CO2}+F_{NOx}\times CF_{NOx}$$

Where E represents the self-load elasticity.

The O & M cost related to DGs can be mathematically formulated as:

$$SGOMC=\sum_{i=1}^{NL}\sum_{f=1}^{F}P_{DGfi}\times T_{i}\times OMC_{g}$$

- Lack of Power Consumption Cost

Modeling the budgets of not delivering electricity to consumers and the charges of power outages is an essential aspect in GEP of power systems.

$$NSLC=DTL_{f}\times e_{Lf}\times r_{Lf}\times NetP_{Lf}-D_{f}\times AIC_{f}$$

$$D_{f}=\left(\frac{DT_{Lf}\left(DTL_{f}-1\right)}{2}\times\sum_{s=1}^{DTL_{f}}e_{Lf}\times r_{Lf}\times NetP_{Lf}\right)$$

$$AIC_{f}=\frac{(I_{Rf}\times P_{Rf})+(I_{Cf}\times P_{Cf})+(I_{If}\times P_{If})+(I_{Gf}\times P_{Gf})+(I_{Of}\times P_{Of})+(I_{Af}\times P_{Af})}{PP_{f}}$$

Where I_{Rf}, I_{Cf}, I_{If}, I_{Gf}, I_{Of} and I_{Af} represents the investment cost related to residential, commercial, industrial, governmental, official and agricultural load. P_{Rf}, P_{Cf}, P_{If}, P_{Gf}, P_{Of} and P_{Af} represents the load demand related to residential, commercial, industrial, governmental, official and agricultural load.

- Cost due to Distribution Losses

$$GLCD=R_{puf}\times\frac{LF_{f}}{NDT_{f}}\times\sum_{i=1}^{NL}\sum_{f=1}^{F}T\times\left(\frac{P_{TDfi}-P_{TDGfi}}{LVT\times\cos\varphi}\right)^{2}$$

$$T=\frac{(NDT_{f}+1)(NDT_{f}+2)(2NDT_{f}+3)}{6}$$

Where NDT_f represents Number of Distribution Transformers of each feeder, P_{TDfi} represents the power demand from all the distribution transformer on ith feeder, P_{TDGfi} represents total DG power of ith feeder and LVT represents the line voltage of transformer.

- Costs due to active Power loss in Transmission Lines

To compute power loss, first acquire the power plant schedule using a unit commitment program. The power loss may then be determined using economic dispatch. Power loss is calculated on lines that use DG units, which have a higher cost of power production. The total cost due to transmission loss can be mathematically formulated as:

$$TGLC=\sum_{i=1}^{NL}P_{LTi}\times FC$$

Where P_{LTi} represents the active power loss in transmission line and FC represents the fuel cost.

Cost due to DR

The DR cost can be mathematically formulated as:

$$DRC_{i}=\sum_{t\in T}\omega_{t}\times -d_{0}\times\frac{I^{2}\times E}{\rho_{0}}$$

Where ω_t represents the coefficient of participation in the DR program.

E. Constraint

- Transmission Planning constraint

Availability of constructed transmission line should be more than the required transmission line and the number of the line should be restricted to its maximum limit [13]–[15].

$$u_{l(t+1)}\geq u_{l(t)}$$

$$0\leq nij(t)\leq n^{\max}$$

Where $u_{l(t)}$ represents the currently existing transmission line, $u_{l(t+1)}$ represents the constructed transmission line, nij(t) represents the transmission line connected between ith and jth bus and n^{max} represents maximum transmission line.

- Constraints Related to GEP

Construction of generating units should be restricted to their maximum limit [11].

$$0\leq\sum_{n\in N_{j}}U_{nt}\leq U^{\max}$$

Where U_{nt} and U^{max} represents the construction of generating units and maximum construction of generating unit.

- Annual cumulative generation limit

$$8760\times uf_{nt}^{\min}\leq g_{nt}\leq 8760\times uf_{nt}^{\max}$$

Where uf_{nt}^{min} and uf_{nt}^{max} represents the hourly cumulative generation minimum and maximum limit.

Power Network Constraints

- Power balance equation

$$P_{Gi}-P_{Li}=\sum_{j=1}^{NB}V_{i}V_{j}G_{ij}\cos\left(\delta_{i}-\delta_{j}\right)+V_{i}V_{j}G_{ij}B_{ij}\sin\left(\delta_{i}-\delta_{j}\right)]$$

$$Q_{Gi}-Q_{Li}=\sum_{j=1}^{NB}V_{i}V_{j}G_{ij}\cos\left(\delta_{i}-\delta_{j}\right)-V_{i}V_{j}B_{ij}\sin\left(\delta_{i}-\delta_{j}\right)]$$

Where PGi and QGi are the generator bus active and reactive power respectively. PLi and QLi are the load bus active and reactive power respectively. NB is the total Number of buses. Gij and Bij are the transfer conductance and transfer susceptance between ith & jth bus respectively. Vi & Vj are the voltage magnitude of ith and jth buses respectively. δi & δj are the voltage angle of ith and jth buses respectively [16].

- Limitations on transmission limits power

$$S_{li} \le S_{li}^{\max}$$

Where Slimax is the upper limits of transmission line. Sli is the absolute value of line power flow.

- Limitations on bus bars voltage amplitude

$$V_{GENi}^{\min} \le V_{GENi} \le V_{GENi}^{\max}$$

Where V_{GENi}^{min} and V_{GENi}^{max} are the lower and upper limits of generator bus voltages (V_G).

$$V_{LOADi}^{\min} \le V_{LOADi} \le V_{LOADi}^{\max}$$

Where V_{LOADi}^{min} and V_{LOADi}^{max} are the lower and upper limits of load bus voltage (V_{Li}).

III. DWARF MONGOOSE OPTIMIZATION ALGORITHM

In 2022 Jeffrey O. Agushaka developed a novel metaheuristic algorithm namely Dwarf Mongoose Optimization Algorithm (DMOA) [17]. This algorithm is based on the foraging behavior of dwarf mongoose. The mongoose's compensatory behavioral adaptations include target size, space use, group size, and food availability. The suggested algorithm employs three dwarf mongoose social groups: the alpha group, babysitters, and scouts. The DMOA stages are detailed in the section below.

Step1: Initialization of DMOA
In this part, the mongoose population and babysitter are initialized.

Step 2: Calculation objective function
In this step the fitness of each mongoose are calculated.

Step 3: Find out current best solution
In this step, the current best solution can be calculated by using the formula

$$\alpha = \frac{fit_i}{\sum_{i=1}^{n} fit_i}, \varphi = \frac{\sum_{i=1}^{n} sm_i}{n}, M = \sum_{i=1}^{n} \frac{S_i \times sm_i}{S_i}$$

$$sm_i = \frac{fit_{i+1} - fit_i}{\max(fit_{i+1}, fit_i)}$$

Where fit_i represents fitness value of ith iteration, S_i represents the food position
Step 4: Position update

In this stage, each mongoose strives toward a better solution by comparing themselves by the equation

$$S_{i+1} = \begin{cases} S_i - CF \times rand \times [X_i - M], if\, \varphi_{i+1} \ge \varphi_i \\ S_i + CF \times rand \times [X_i - M], else \end{cases}$$

$$CF = \left(1 - \frac{t}{T}\right)^{\frac{2t}{T}}$$

Where rand represents a random number between -1 and 1, and t and T represents the current and maximum iteration number respectively.

Step 5: Limit checking

After updating the position of all the mongoose, it should be checked that the position should not violet its lower and upper limit.

Step 6: Stopping criteria

Check whether the number of iterations has reached its maximum value.

Step 7: Display results

The mongoose with the best fitness is declared as the final result.

IV. SYMBIOTIC ORGANISMS SEARCH

M. Y. Cheng and D. Prayogo introduced a novel nature-inspired algorithm called Symbiotic Organisms Search (SOS) algorithm in 2014 best known for its exploitation properties [18]. SOS is based on the behavior of symbiotic interaction of different creatures to live in any ecosystem. Mutualism is a symbiotic relationship between two individuals produce a new individual having the advantage of both parent individuals. The mutualism process is formulated as:

$$S_{inew} = S_i + a \times (S_{best} - M \times A)$$

$$S_{jnew} = S_j + b \times (S_{best} - M \times B)$$

$$M = \frac{S_i + S_j}{2}$$

Where S_i and S_j are two randomly selected individuals in the swarm. a and b represent two uniformly distributed random numbers between 0 and 1, S_{best} is the individual having the best fitness in the swarm, and A and B represent the benefit factor randomly chosen as 1 or 2.

V. PROPOSED ALGORITHM

Balanced exploration and exploitation in any algorithm perform a significant job for its performance [19-20]. In this section, the DMOA is hybridized with SOS, which will enhance the performance of DMOA. In this proposed algorithm, the mutualism part of the SOS is implemented after both stages of updating the process for improving the exploitation process of this algorithm. The steps below give a brief explanation of the algorithm and its execution.

Step1: Initialization of EDMOA

In this part, the mongoose population and babysitter are initialized.
Step 2: Calculation objective function

In this step the fitness of each mongoose are calculated by equation given below.
Step 3: Find out current best solution

In this step, the current best solution can be calculated by using the formula

$$\alpha = \frac{fit_i}{\sum_{i=1}^{n} fit_i}, \varphi = \frac{\sum_{i=1}^{n} sm_i}{n}, M = \sum_{i=1}^{n} \frac{S_i \times sm_i}{S_i}$$

$$sm_i = \frac{fit_{i+1} - fit_i}{\max(fit_{i+1}, fit_i)}$$

Step 4: Position update

In this stage, each mongoose strives toward a better solution by comparing themselves by the equation

$$S_{i+1} = \begin{cases} S_i - CF \times rand \times [X_i - M], if\, \varphi_{i+1} \ge \varphi_i \\ S_i + CF \times rand \times [X_i - M], else \end{cases}$$

$$CF = \left(1 - \frac{t}{T}\right)^{\frac{2t}{T}}$$

Step 5: Call for SOS mutualism process

When an inadequate solution is identified or the solution does not improve for 3 consecutive iterations, the mutualism phase of SOS is invoked, and if the solution is better than the original solution then, the result is substituted, and the original algorithm is permitted to proceed further.

Step 6: Position update

In this stage, each mongoose strives toward a better solution by comparing themselves by the equation.

Step 7: Limit checking

After updating the position of all the mongoose, it should be checked that the position should not violet its lower and upper limit.

Step 8: Stopping criteria

Check whether the number of iterations has reached its maximum value.

Step 9: Display results

Calculate the techno-economic and environmental costs of both primary and secondary sectors. In addition, calculate the cost of transmission line loss in the primary sector and costs associated with the distribution network for different scenarios.

VI. RESULTS AND DISCUSSIONS

To verify the suggested approach, the proposed approach is tested and evaluated on a six-bus test system having distribution network [11]. Three scenarios are presented in this study to handle this problem. In scenario 1 a gas power plant is used to supply the 80 MW power in primary sector. In scenario 2 and scenario 3 conventional units in primary sector and DG units in secondary aector simultaneously generate 80 MW.

TABLE I. TABLE TYPE STYLES

SCENARIO	Capital cost	Total fuel cost	Total emission cost	Total O&M cost	Total Power loss cost	Total NSLC	Total cost
1	20.000.000	86.640.000	122.130.000	30.040.000	32.332.210	4.012.231	295.154.441
2	68.733.779	59.101.939	50.702.346	42.182.287	11.456.647	2.365.835	234.542.833
3	25.217.531	81.832.259	120.672.941	30.711.586	28.874.361	2.304.965	289.613.643

TABLE II. TABLE TYPE STYLES

Scenario/Method	GA [11]	HBMO [11]	GSA [11]	PSO [11]	APSO [11]	DMOA	EDMOA
1	307,169,237	306,703,967	303,850,747	304,437,228	295,021,126	303,951,275	294,972,845
2	246,850,174	246,092,637	247,745,665	245,209,694	234,167,002	242,295,162	234,105,179
3	318,460,060	311,662,042	303,965,902	303,741,657	289,212,408	302,913,624	289,057,839

TABLE III. TABLE TYPE STYLES

Scenario 1	**Best result**	**Worst result**	**Mean**	**Standard deviation**
DMOA	303,951,275	304,372,125	304,014,317	41762
EDMOA	294,972,845	295,214,527	295,103,467	18219
Scenario 2	**Best result**	**Worst result**	**Mean**	**Standard deviation**
DMOA	242,295,162	242,835,293	242,482,972	26867
EDMOA	234,105,179	234,612,458	234,394,576	8351
Scenario 3	**Best result**	**Worst result**	**Mean**	**Standard deviation**
DMOA	302,913,624	303,438,572	304,126,201	49073
EDMOA	289,057,839	290,532,931	289,580,417	24864

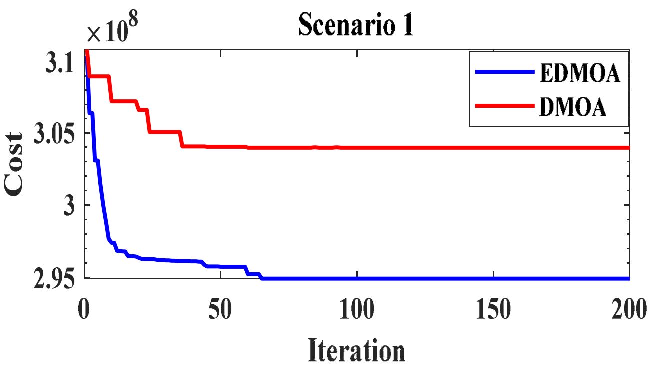

Fig. 1. Convergence plots for Scenario-1

Result of scenario 1: It can be observed that due to low efficiency of thermal power plant and higher line losses in transmission and distribution line the GEP will suffer with significant expenses. From Table. it can be seen that the proposed algorithm gives better result from all the other algorithm. From fig.1 it can be seen that the convergence curve of EDMOA is smoother and faster, which indicates that the exploration and exploitation in the proposed algorithm is properly balanced.

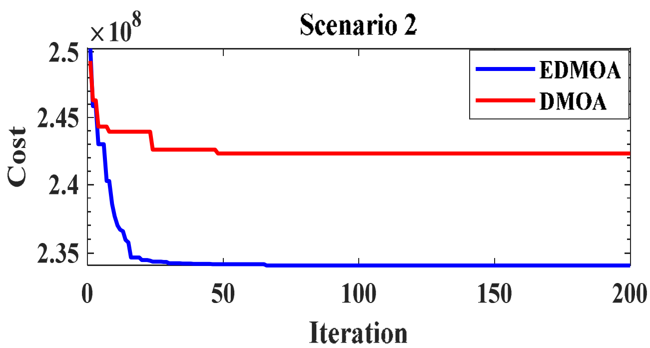

Fig. 2. Convergence plots for Scenario-2

Result of scenario 2: It can be observed that the implementation of DG units lowers the expenses associated with environmental pollution and transmission and distribution line losses. Table shows that the proposed algorithm outperformed several previously published algorithms and the statistical analysis in table confirms the efficiency and robustness of the proposed algorithm.

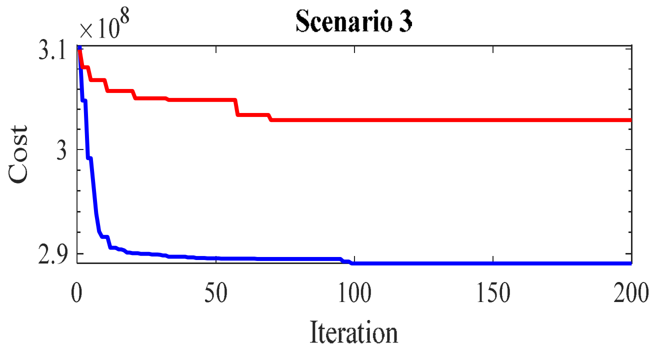

Fig. 3. Convergence plots for Scenario-3

Result of scenario 3: In scenario 3 when the network is subjected to the peak load demand, the network operators have to pay more cost. Under these situations, conventional units with low efficiency are connected to the grid. Not only are these units expensive, but their use also raises environmental concerns. It can be seen that scenario 3 required more cost as compared to scenario 2. In Fig. 3, it can be seen that the convergence curve of EDMOA is improved from the original algorithm. The efficiency and robustness is verified by statistical analysis in Table VI.

VII. Conclusion

In this paper, the extension of the power system has been investigated from several perspectives. Three case studies have been used to evaluate the proposed paradigm at two different levels. The first section covers both large-scale generating units and RES, while the second section includes non-probabilistic DG units. In the first case study, GEP is solely accomplished by primary sectors and using resources from conventional power plants. The second and third case studies involve distributed generation with base load and peak demand. In this paper, a novel hybrid algorithm namely Enhanced Dwarf Mongoose Optimization Algorithm is developed to handle the problem associated with nonconvergent hybrid and mixed-integer optimization. The convergence criteria of the novel algorithm perform better than the other published algorithm. The result shows the DR program enhances the performance of the power system and helps in increasing the amount of nonrenewable and renewable distributed generation implementation. This approach works well and may be used for various power systems.

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