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A Hybrid Algorithm Based on HBMO and Fuzzy Set for Multi-Objective Distribution Feeder Reconfiguration

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Abstract: This paper presents an efficient hybrid algorithm for multi-objective distribution feeder reconfiguration based on Honey Bee Mating Optimization (HBMO) and fuzzy multi-objective approach. The objective functions are to minimize real power losses; deviation of nodes voltage; the number of switching operation and to balance the loads on the feeders. Due to the objectives are different and no commensurable, it is difficult to solve this problem by conventional approaches that optimize a single objective. In the proposed algorithm, these objective functions are first modeled with fuzzy sets to evaluate their imprecise nature and then the HBMO algorithm is used to determine the optimal solution. The feasibility of the proposed optimization algorithm is demonstrated and compared with the solutions obtained by other approaches over different distribution test systems.

Key words: Distribution feeder reconfiguration . fuzzy set . Honey Bee Mating Optimization (HBMO) . Multi-objective function

INTRODUCTION

Distribution networks are built as interconnected mesh networks; however, they are arranged to be radial in operation. The distribution feeder reconfiguration is to find a radial operating structure that optimizes network performance while satisfying operating constraints. The change in the network configuration is performed by opening sectionalizing (normally closed) and closing tie (normally opened) switches of the network. These switches are changed in such away that radiality of networks is maintained, all of loads are energized, power loss is reduced, power quality is enhanced and system security is increased. Distribution feeder reconfiguration is a complex nonlinear combinatorial problem since the status of the switches is non-differentiable [1, 2]. Generally, distribution feeder reconfiguration is defined as altering the topological structure of the distribution feeders by changing the open/close states of sectionalizing and tie switches so that the objective function is minimized and the constraints are met [1, 2].

The first publication about the reconfiguration problem was presented by Merlin and Back [1]. In the paper, the global minimum is calculated starting from a meshed network. This method was later modified by Shirmohammadi and Hong in [3], where they reduced computation time by applying an efficient load flow. Civanlar and Grainger in [4] have derived a formula to estimate loss reduction using an algorithm called, branch interchange. Chen and Cho have presented an optimal switching criteria using binary integer programming with a branch-and-bound technique for network reconfiguration to achieve energy loss minimization for short-term and long-term operation of distribution systems [5]. Taleski and Rajicic have proposed a method to determine the configuration with minimum energy losses for a given period [6]. Nara *et al.* [7] have presented an implementation using a genetic algorithm (GA) to look for the minimum loss configuration. In [8, 9], the authors have suggested to employ a power flow method-based heuristic algorithm for determining the minimum loss configuration of radial distribution networks. In [10, 11], the authors proposed a solution procedure employing simulated annealing (SA) to search an acceptable no inferior solution. In [13], the authors have been to outline and validate a methodology for optimization of MV distribution networks operation. In [14], the authors had considered time-varying load analysis to reduce loss. In [15], the authors have approached bidirectional feeder models to simplify calculation for distribution systems. In [16], fuzzy theory and evolutionary programming have employed to solve feeder reconfiguration systems.

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Although this problem had been solved by the above methods, either its optimality is not guaranteed or it has to spend much of computation time. In [16], Debaprya has combined the optimization techniques with heuristic rules and fuzzy logic for higher efficiency and robust performance. A methodology that combines two heuristic procedures to determine the group of switches to be open in order to minimize the total power losses in distribution systems has been described in [17]. McDermott *et al.* [18], have proposed a heuristic constructive algorithm that starts with all maneuverable switches open and at each step, the switch that results in the least increase in the objective function is closed. The objective function has been defined as the incremental losses divided by incremental load served. In [2, 18-20], the authors have investigated the impact of distributed generators on the distribution feeder reconfiguration.

In the light of the above developments, the present work considers the network reconfiguration problem as a multiple objectives problem subject to operational and electric constraints. The problem formulation proposed herein considers four different objectives related to:

- Minimizing of the power losses;
- Minimizing the deviation of the bus voltage;
- Minimizing switching operation;
- Balancing loads among feeders.

At the same time, a radial network structure must remain after network reconfiguration in which all loads must be energized.

Since the objective functions of the distribution feeder reconfiguration are not the same and commensurable, it is difficult to solve this class of problem by conventional approaches that are utilized to optimize single objective problems. Therefore, the proposed algorithm first models the multiple objectives using fuzzy sets to evaluate their imprecise nature and for ease of integration. Then, the HBMO algorithm is presented to solve the multiple objective problems. The control variables are the status of the tie switches. Since the configuration of the distribution systems should remain radial, while there are numerous switches, control variables are defined so that when a tie switch is closed, one sectionalizing switch that forms a loop must be opened.

PROBLEM FORMULATION

This section proposes four objective functions, practical constraints and fuzzy modeling of the objective functions for the network reconfiguration problem.

A) Objective function

1) Minimization of the power losses: Minimizing the real power loss of the feeders is selected as the first objective function for the feeder reconfiguration because reducing the real power loss of the distribution feeders is an important purpose in feeder reconfiguration. The minimization of the total real power losses arising from feeders can be calculated as follows:

$$f_1(X) = \sum_{i=1}^{N_{br}} R_i \times |I_i|^2 \qquad (1)$$

$$X = [Tie_1, Tie_2, \ldots, Tie_{N_{tie}}]$$

where R_i and I_i are resistance and actual current of the i^{th} branch, respectively. N_{br} is the number of the branches. X is the control variables vector. Tie_i is the state of the i^{th} tie switch (0 = open and 1=close).

2) Minimizing the deviation of the bus voltage: Bus voltage is one the most significant security and service quality indices, which can be described as follows:

$$f_2(X) = \max_i |V_i - V_{rate}|, \qquad i = 1,2,3,\ldots N_{bus} \qquad (2)$$

where N_{bus} is total number of the buses. V_i and V_{rate} are the real and rated voltages on the i^{th} bus, respectively.

3) Minimizing switching operation: Minimizing the number of switching operations can be modeled as follows:

$$f_3(X) = \sum_{i=1}^{N_s} |S_i - S_{oi}| \qquad (3)$$

where S_i and $S_{o,i}$ are the new and original states of the switch *i*, respectively. N_s is the number of the switches.

4) Feeder load balancing: The load balancing is one of the major objectives of the feeder reconfiguration. An effective strategy to increase the loading margin of heavily loaded feeders is to transfer part of their loads to lightly loaded feeders. Feeder load balancing can be described as follows:

$$f_4(X) = -\min_i |I_{i,rate} - I_i|, i = 1,2,3,\ldots,N_{br} \qquad (4)$$

where I_i and $I_{i,\ rate}$ are the actual loading current and rated current of the i^{th} branch, respectively.

B) Fuzzy modeling of objective functions: The mentioned objective functions are formulated as fuzzy

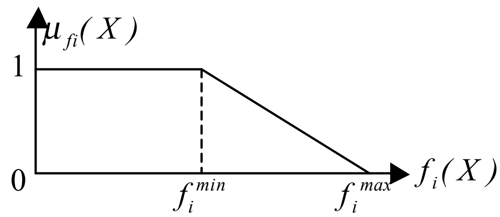

Fig. 1: A membership function for objective functions

sets since they are imprecise. A fuzzy set is typically represented by a membership function $\mu_{fi}(X)$. A higher membership function implies greater satisfaction with the solution. The membership function consists of lower and upper boundaries, together with a strictly monotonically decreasing and continuous function. Fig. 1 plots a possible curve of a strictly monotonically decreasing membership function. The lower and upper bounds, f_i^{min} and f_i^{max}, of each objective function under the given constraints are established to elicit a membership function $\mu_{fi}(X)$ for each objective function, $f_i(X)$. A membership function of a minimizing problem can be defined as:

$$\mu_{fi}(X) = \begin{cases} 1 & \text{for } f_i(X) \le f_i^{min} \\ 0 & \text{for } f_i(X) \ge f_i^{max} \\ \dfrac{f_i^{max} - f_i(X)}{f_i^{max} - f_i^{min}} & f_i^{min} \le f_i(X) \le f_i^{max} \end{cases} \quad (5)$$

C: Constraints: The constraints can be listed as follows:

- Distribution line limits

$$\left|P_{ij}^{Line}\right| < P_{ij,max}^{Line} \quad (6)$$

$\left|P_{ij}^{Line}\right|$ and $P_{ij,max}^{Line}$ are the absolute power flowing over the distribution lines and the maximum power transmitted between the nodes *i* and *j*, respectively.

- Distribution power flow equations

$$\begin{aligned} P_i &= \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \\ Q_i &= \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) \end{aligned} \quad (7)$$

where, P_i and Q_i are the net injected active and reactive powers at the i^{th} bus. V_i and δ_i are the amplitude and angle of the voltage at the i^{th} bus, respectively. And Y_{ij} and θ_{ij} are the amplitude and angle of the branch admittance between the i^{th} and j^{th} buses.

- Radial structure of the network

$$M = N - N_f \quad (8)$$

Where M is the number of branches, N is the number of nodes and N_f is the number of sources.

ORIGINAL HBMO ALGORITHM

The honey bee is a social insect that can survive only as a member of a community, or colony. The colony inhabits an enclosed cavity. The honey bee community consists of three structurally different forms-the queen (reproductive female), the drone (male) and the worker (no reproductive female). These castes are associated with different functions in the colony; each caste possesses its own special instincts geared to the needs of the colony. The HBMO Algorithm combines a number of different procedures [21-23]. Each of them corresponds to a different phase of the mating process of the honey bee. A drone mates with a queen probabilistically using an annealing function as follows [21-23]:

$$Prob(D) = \exp(-\Delta(f)/S(t)) \quad (9)$$

where *Prob(D)* is the probability of adding the sperm of drone *D* to the spermatheca of the queen (that is, the probability of a successful mating), *Δ(f)* is the absolute difference between the fitness of *D* and the fitness of the queen (for complete description of the calculation of the fitness function see below) and *S(t)* is the speed of the queen at time *t*. The probability of mating is high when the queen is with the high speed level, or when the fitness of the drone is as good as the queen's. After each transition in space, the queen's speed decreases according to the following equations:

$$S(t+1) = \alpha \times S(t) \quad (10)$$

where α is a factor $\in (0,1)$ and is the amount of speed and energy reduction after each transition and each step. Initially, the speed of the queen is generated at random. A number of mating flights are realized. At the start of a mating flight drones are generated randomly and the queen selects a drone using the probabilistic rule in Eq. 9. If the mating is successful (i.e., the drone passes the probabilistic decision rule), the drone's sperm is stored in the queen's spermatheca. By using the crossover of the drone's and the queen's genotypes, a new brood (trial solution) is generated, which can be improved later by employing workers to conduct local search. One of the major differences of the HBMO algorithm from the classic evolutionary algorithms is that since the queen stores a number of different drone's sperm in her spermatheca, she can use parts of the genotype of different drones to create a new solution which gives the possibility to have fittest broods more. In real life, the role of the workers is restricted to brood care and for this reason the workers are not separate members of the population and they are used as local search procedures in order to improve the broods produced by the mating flight of the queen. If the new brood is better than the current queen, it takes the place of the queen. If the brood fails to replace the queen, then in the next mating flight of the queen this brood will be one of the drones.

SOLUTION OF MULT-OBJECTIVE DISTRIBUTION FEEDER RECONFIGURATION

This section presents the proposed hybrid algorithm based on combination of HBMO and fuzzy sets for multi-objective distribution feeder reconfiguration. Due to the objective functions of the problem are not the same, in the proposed algorithm the objective functions are first modeled as fuzzy sets. One solution methodology for the multi-objective optimization in fuzzy framework is based on the max-min principle as used in this paper. To apply the proposed algorithm in the distribution feeder reconfiguration problem, the following steps have to be taken:

Step 1: Define the input data: In this step, the input data including the network configuration, line impedance and status of switches, f_i^{min}, f_i^{max}, the speed of queen at the start of a mating flight (S_{max}), the speed of queen at the end of a mating flight (S_{min}), the speed reduction schema (α), the number of iteration, the number of workers (N_{Worker}), the number of drones (N_{Dreone}), the size of the queen's spermatheca (N_{Sperm}) and the number of broods (N_{Brood}) are defined.

Step 2: Generate an initial population: In this step, an initial population based on state variable is generated, randomly. That is formulated as:

$$\begin{aligned} &\text{Drone} = [X_1 \quad X_2 \quad .... \quad X_{N_{Drone}}]' \\ &X = [Tie_1, Tie_2, ..., Tie_{N_{tie}}] \quad i = 1,2,3,....,N_{Drone} \end{aligned} \tag{11}$$

Step 3: Calculate the objective function value: For each individual (X_i) the membership values of all the different objectives are evaluated. For example, when the k^{th} tie switch of a distribution system is closed, a loop is formed with number of branches in the loop. Now, opening each branch in this loop is an option. After opening the i^{th} branch in this loop (radial structure is retained), the load-flow run was carried out to compute the membership functions. The degree of overall satisfaction for this option is the minimum of all the above membership values. Now, a fuzzy decision for overall satisfaction may be defined as the choice that satisfies all of the objectives. In the present work, classical fuzzy set intersection is used and the fuzzy decision for overall satisfaction is then given by

$$ob_k^i = \min_k \{\mu_{f1}, \mu_{f2}, \mu_{f3}, \mu_{f4}\}; \; k = 1,2,...,N_b^k \tag{12}$$

where N_b^k is the total number of branches including the tie branch in the loop when the k^{th} tie switch is closed.

The optimal solution is the maximum of all such overall degrees of satisfaction. Now, a fuzzy decision for an optimal solution may be defined as the choice that maximizes all such overall degrees of satisfaction. In the proposed algorithm, the classical fuzzy set union is used and the fuzzy decision for an optimal solution is then given by

$$obj\_fun^i = \max_k \{ob_k^i\}; \; k = 1,2,...,N_b^k \tag{13}$$

Step 4: Sort the initial population based on the objective function values

Step 5: Select the queen: The individual (X_{best}) that has the maximum objective function should be considered as the queen.

Step 6: Generate the queen speed: The queen speed is randomly generated as:

$$S_{queen} = rand(.) \times (S_{max} - S_{min}) + S_{min} \tag{14}$$

where *rand(.)* is a random function generator.

Step 7: Generate the queen's spermatheca matrix (Mating flight): At the start of the mating flight, the queen flies with her maximum speed. A drone is randomly selected from the population of drones. The mating probability is calculated based on the objective function values of the queen and the selected drone. A number between 0 and 1 is randomly generated and compared with the calculated probability. If it is less than the calculated probability, the drone's sperm is sorted in the queen's spermatheca and the queen speed is decreased. Otherwise, the queen speed is decreased and another drone from the population of drones is selected until the speed of the queen reaches to her minimum speed or the queen's spermatheca is full.

$$\begin{aligned} &Sperma = [Sp_1 \quad Sp_2 \quad .... \quad Sp_{N_{Sperm}}]^T \\ &Sp_i = [s_j]_{1\times n} = [Tie_1, Tie_2, \ldots, Tie_{N_{tie}}] \qquad (15) \\ &\quad i = 1,2,3,\ldots,N_{Sperm} \end{aligned}$$

where Sp_i is the i^{th} individual in the queen's spermatheca.

Step 8: Breeding process: In this step, a population of broods is generated based on mating between the queen and the drones stored in the queen's spermatheca. The i^{th} individual is generated as:

At first the i^{th} individual of the queen's spermatheca is randomly selected and then an integer number (m) between 1 and n is randomly generated. The j^{th} brood is generated by using the following process:

$$\begin{aligned} &X_{best} = \left[x^1_{best} \quad x^2_{best} \quad \ldots \quad x^n_{best}\right] \\ &Sp_i = \left[s^1_i \quad s^2_i \quad \ldots \quad s^n_i\right] \qquad (16) \\ &Brood_j = X_{best} + \beta \times (X_{best} - Sp_i), \quad j=1,2,3,\ldots N_{Brood} \end{aligned}$$

where β is a random number between 0 and 1. $Brood_j$ is the j^{th} brood.

Step 9: Feeding selected broods and queen with the royal jelly by workers: The population of broods is improved by applying different heuristic functions and mutation operators as follows:

At first the i^{th} brood is randomly selected. Two integer numbers ($B1$ and $B2$) between 1 and n are randomly generated. It is assumed $B1 < B2$. The brood is changed and improved as below:

$$\begin{aligned} &Brood_i(j) = Brood_i(j) \quad \text{if} \quad j < B1 \\ &Brood_i(j) = rand(.) \times (x^j_{max} - x^j_{min}) + x^j_{min}, \\ &\text{if} \quad B1 \le j \le B2 \qquad (17) \\ &Brood_i(j) = Brood_i(j) \quad \text{if} \quad j > B2 \\ &i = 1,2,3,\ldots,N_{Worker} \end{aligned}$$

where x^j_{max} and x^j_{min} are the maximum and minimum values of the j^{th} state variables, respectively.

Step 10: Calculate the objective function value for the new generated solutions: The objective function for the new population is calculated as mentioned in step 3.

Step 11: Check the termination criteria: If the termination criteria satisfied finish the algorithm, else discard all previous trial solutions and go to step 2 until convergence criteria met.

SIMULATION AND RESULTS

In this section, the proposed algorithm is employed to solve the distribution feeder reconfiguration for two distribution test feeders. The parameters required for implementation of the proposed algorithm are the speed of queen at the start of a mating flight (S_{max}), the speed of queen at the end of a mating flight (S_{min}), the speed reduction schema (α), the number of workers (N_{Worker}), the number of drones (N_{Dreone}), the size of the queen's spermatheca (N_{Sperm}), the number of broods (N_{Brood},) c_1, c_2, ω_{min} and ω_{max}. In this paper, the best values for the aforementioned parameters are S_{max} =1, S_{min} =02, α=0.93, N_{Worker} =10, N_{Dreone}=16, N_{Sperm} =15 and N_{Brood} =15 determined by 100 runs of the algorithm. The number of the initial population is 16.

Case 1-Baran & Wu Test System [17]: The Baran & Wu distribution test system is a hypothetical 12.66 kV system with a two-feeder substation, 32 buses and 5 looping branches (Fig. 2). The number of ties and sectionalizing switches are 5 and 32, respectively. The system data is given in [17] and the single line diagram of this system is shown in Fig. 3. The total load conditions are 5058.25 kW and 2547.32 kVar. The normally open switches, s33, s34, s35, s36 and s37, are represented by doted lines. The normally closed switches, s1 to s32, are represented by solid lines. Before reconfiguration, the initial losses and minimum per unit voltage are 202.67 kW and 0.913, respectively.

Table 1 shows a comparison between the proposed algorithm and some other algorithms. It is seen that the proposed algorithm lead to the global optimum configuration.

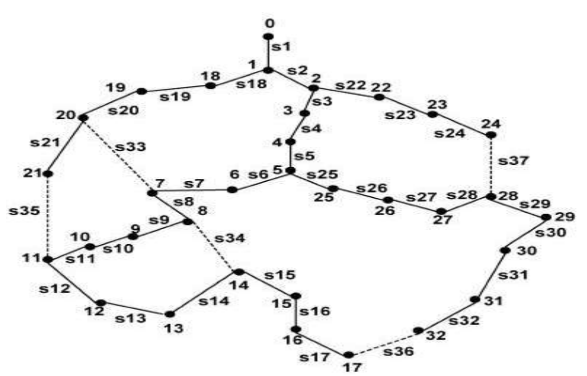

Fig. 2: A single line diagram of Baran & Wu distribution test system

Table 1: Results for different methods

Method	Power losses (kW)	Minimum voltage (p.u)	Saving (%)	CPU time (Sec)	Open switches
Optimum	139.53	0.938	31.14	647.03	s7, s9, s14, s32, s37
The proposed algorithm	139.53	0.938	31.14	6	s7, s9, s14, s32, s37
Goswami[7]	139.53	0.938	31.14	0.87	s7, s9, s14, s32, s37
MeDemott [18]	139.53	0.938	31.14	1.99	s7, s9, s14, s32, s37
Shirmohammadi [2]	140.26	0.9378	30.78	0.14	s7, s10, s14, s32, s37
Vanderson Gomes and *et al.* [17]	139.53	0.938	31.14	1.66	s7, s9, s14, s32, s37

Table 2: Results for different methods

Method	Power losses (kW)	Minimum voltage (p.u)	Saving (%)	CPU time (Sec)	Open switches
Optimum	139.53	0.938	31.14	647.03	s7, s9, s14, s32, s37
The proposed algorithm	139.53	0.938	31.14	8	s7, s9, s14, s32, s37
Goswami[7]	143.69	0.9397	29.08	0.65	s7, s9, s14, s32, s37
MeDemott [18]	139.53	0.938	31.14	1.99	s7, s9, s14, s32, s37
Shirmohammadi [2]	140.26	0.9378	30.78	0.14	s7, s10, s14, s32, s37
Vanderson Gomes and *et al.* [17]	139.53	0.938	31.14	1.66	s7, s9, s14, s32, s37

Table 3: Results for different methods

Method	Power losses (kW)	Minimum voltage (p.u)	Saving (%)	CPU time (Sec)	Open sectionalizing switches	Closed tie switches
The proposed algorithm	205.32	0.9268	9.76	8	s26-27, s14-15, s37-38, s49-50, s44-45, 65-6	tie 1, tie 3, tie 4, tie 7, tie 8, tie 9
D. Das[16]	205.32	0.9268	9.76	3	s26-27, s14-15, s37-38, s49-50, s44-45, s65-6	tie 1, tie 3, tie 4, tie 7, tie 8, tie 9

To demonstrate that the proposed algorithm does not depend on the initial switching configuration, the initial configuration has been changed, closing the normally open switches s33 and s37 and opening the normally closed s3 and s6. The initial losses and minimum voltage in per unit are 208.15 kW and 0.9212, respectively.

The simulation results are shown in Table 2, where it can be seen that the proposed algorithm gives the global optimum configuration, which means that the proposed approach does not depend on the initial switching configuration.

Case 2-A 70-Bus 11 kV Radial Distribution System [16]: A single line diagram of the 11kV radial distribution system having two substations, four feeders, 70 nodes and 78 branches (including tie branches) is shown in Fig. 3. The system data is given in [16].

Before reconfiguration, the initial losses and the minimum voltage in per unit are 227.53 kW and 0.9052, respectively. The simulation results are presented in Table 3. As shown in the Table, only 6 out of 11 tie switches has changed. Also, the currents of the feeders after reconfiguration are more balanced than after reconfiguration.

Table 4 shows the feeders' currents before and after reconfiguration. It is seen that the current of each feeder is more balanced after reconfiguration.

Table 4: Feeder current before and after reconfiguration

Method	Before reconfiguration (A)	After Reconfiguration (A)	Capacity of feeder (A)
IF1	99.9	117.01	270
IF2	109.01	131.57	270
IF3	162.3	133.93	270
IF4	148.86	135.13	270

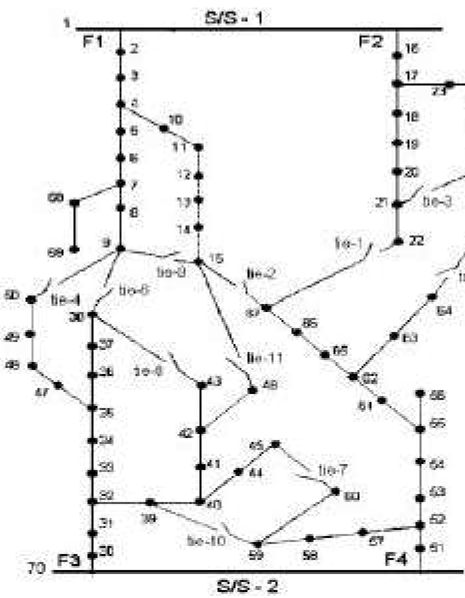

Fig. 3: A single line diagram of 11kV distribution test system

CONCLUSION

In this paper, an efficient hybrid algorithm based on combining the HBMO algorithm and fuzzy set has been proposed to solve the multi objective distribution feeder reconfiguration. In the proposed algorithm, the objectives are modeled as fuzzy set and the HBMO algorithm is used to optimize the problem. The simulation results for several tests have shown that global or close to global optimum solutions for the system losses, the voltage deviation and load balancing were attained. Also, the proposed method has minimized the number of switching operations. The introduced method takes the advantage of being independent on the initial status of network switches.

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