Multi-Objective Jaya Algorithm for Optimal Scheduling of DGs in Distribution System Sectionalized into Multi-Microgrids

C. Srinivasarathnam, Chandrasekhar Yammani and Sydulu Maheswarapu

Department of Electrical Engineering, National Institute of Technology, Warangal, India

ABSTRACT

In this paper, the power dispatch problem of distributed generators (DGs) for optimal operation of the islanded distribution system has been addressed. In order to mitigate the number of customers being affected by a fault at any remote location of the system, the islanded distribution system is sectionalized into several self-supplied microgrids such that reliable power can be supplied to maximum loads. These microgrids can be operated individually or joining with other microgrids such that rescheduling of DGs can be performed for attaining desired objective. The objectives considered in this paper are minimization of operating cost of DGs, system losses, voltage deviation individually. Furthermore, a multi-objective problem is formulated considering minimization of operating cost & losses, operating cost & voltage deviation and losses & voltage deviation simultaneously. While scheduling the distribution system, dispatchable DGs are used. A novel, algorithm-specific parameter-free meta-heuristic algorithm named Jaya algorithm is used in this paper for solving the stated optimization problem. The feasibility of the proposed technique is verified with the modified 33 bus distribution network and obtained results have been validated by comparison with prior-art algorithm available in the literature.

Abbreviation:

- $P_{ij}$: Active power generation of unit $j$ in microgrid $i$
- $Q_{ij}$: Reactive power generation of unit $j$ in microgrid $i$
- $P_{i, \text{loss}}$: Active power loss in the microgrid $i$
- $Q_{i, \text{loss}}$: Reactive power loss in the microgrid $i$
- $P_{i, \text{demand}}$: Active power demand in the microgrid $i$
- $Q_{i, \text{demand}}$: Reactive power demand in the microgrid $i$
- $P_{ij}^{\text{min}}$: Minimum active power generation limit of unit $j$ in microgrid $i$
- $P_{ij}^{\text{max}}$: Maximum active power generation limit of unit $j$ in microgrid $i$
- $Q_{ij}^{\text{min}}$: Minimum reactive power operating limit of unit $j$ in microgrid $i$
- $Q_{ij}^{\text{max}}$: Maximum reactive power operating limit of unit $j$ in microgrid $i$
- $V_{i,k}^{\text{min}}$: Minimum voltage limit of bus $k$ in microgrid $i$ in P.U
- $V_{i,k}^{\text{max}}$: Maximum voltage limit of bus $k$ in microgrid $i$ in P.U
- $V_{i,k}$: Actual voltage magnitude at bus $k$ in microgrid $i$ in P.U
- $V_{i,k}^{\text{ref}}$: Specified voltage magnitude at bus $k$ in microgrid $i$ in P.U
- $F_1$: Objective function-1 with cost minimization as objective
- $F_2$: Objective function-2 with loss minimization as objective
- $F_3$: Objective function-3 with voltage deviation minimization as objective
- $x$: Admissible decision vector
- $\text{Total cost}_{\text{actual}}$: Actual cost of generation in the microgrid(s)
- $\text{Total cost}_{\text{max}}$: Maximum cost of generation in the microgrid(s)
- $V_{\text{deviation}_{\text{actual}}}$: Actual value of voltage deviation in P.U in the microgrid(s)
- $V_{\text{deviation}_{\text{max}}}$: Maximum value of voltage deviation in P.U in the microgrid(s)
- $P_{\text{loss}_{\text{actual}}}$: Actual...
1. Introduction

The main aim of the power system network is to make a balance of supply and demand in the power system network [1,2]. As the power system network is very large, at each node, real-time energy requirement should sense and it shall be balanced with the amount of produced energy. The balancing of generated power and demand is the main challenge in the power system [3]. The power demand varies from time to time which depends on the end-users usage of electric appliances. Furthermore, due to highly unpredictable factors, such as weather conditions, energy pricing and an increasing penetration of electric transportation, energy usage is highly affected [4]. The above challenges in power system network have been mostly sorted by the concept of microgrid [5].

A microgrid is a low/medium voltage distribution network, comprising Distributed Generators such as wind power, solar power, Diesel generators, CHP etc., storage devices such as battery and controllable loads, which can be operated in either the grid-connected mode or islanded mode [6-7]. The introduction of microgrid concept has provided environmental compliance, conservation of energy, improvement in grid reliability, enhancement of operational efficiency and customer service [1]. Also, a microgrid is able to respond quickly to the power grid and satisfy various demands of consumers [5].

The distribution system is prone to faults and failures without early warnings due to animal or tree contacts, lightning strikes, falling of trees on electrical lines, etc. Due to fault in a certain region of a distribution network, some other regions also get either overloaded or isolated due to load redistribution [8,9]. This redistribution of load continuous on other regions often leads to a cascading phenomenon which propagates throughout the system, which in turn can cause a catastrophic failure leads to power disruptions, and has huge social and economic impacts on society [10].

The microgrid in grid-connected mode, connected to the main grid either totally or partially and takes or delivers power from or to the main grid. Islanding from the main power distribution network is the remarkable feature of the microgrid. Whenever a fault is associated with the distribution system, islanding is performed to disconnect rapidly the microgrid from faulty system to protect the microgrid components from upstream disturbances and provide uninterrupted power supply to consumers [11]. Furthermore, islanding is done to protect voltage sensitive loads from significant voltage drops whenever immediate restoration of voltage problem in the main grid is not imminent. To date, throughout the world, there are ample research projects on the design-control-operation aspects of microgrids, such as the USA CERTS microgrid [12], the European Microgrid project [13] and in Japan, the new energy integration test project which is carried out by NEDO [6].

The main aim of the smart grid manager or Microgrid Central Controller (MGCC) is to minimize the operation cost, reduce the power loss, maintain better voltage profile in microgrid in which optimal power output of DGs are determined while satisfying both equality and inequality constraints of the system. Many research works have been done in the field of operation cost minimization of Microgrid [14]. In paper [15], the author has proposed ELD for MMG using PSO. Multi-objective optimal power flow among MMG considering cost minimization, voltage deviation minimization and energy loss minimization using interline power flow controller has been attempted in [16]. In [17], Imperialist Competitive Algorithm (ICA) has been used by the author for optimal power dispatch among MMG considering sold and purchase of power from either from main grid or from other microgrids. NSGA-II has been considered by the author in [18] for multi-objective optimization of minimizing operating cost, emission cost and power losses. In [19], sequential-quadratic programming (SQP) solver has been used by the author for multi-objective optimization of cost, voltage deviation and feeder congestion in MMG.

According to IEEE standard 1547.4, the operation and reliability of a distribution system can be improved by splitting the network into multiple microgrids [20-21]. However, research work is in progress for sectioning the distribution system into self-adequate microgrids when there is fault existing in the system which is self-healing mode [21].

The topology of the distribution network, location of DGs and loads could play a crucial role in supplying the microgrid loads with diverse reliability requirements. Locating DG nearer to load will decrease the power outage duration and the frequency of power
outages as well as the level of energy not supplied at a microgrid [22]. In a grid-connected mode, outages of the main grid could lead to the microgrid islanding.

The planning of any system is an off-line study which needs to consider both technical aspects and economic analysis for aiming quality power supply to customers in a reliable manner. In order to avoid the stated difficulties arise due to a fault in the distribution system, to avail the potential benefits of microgrid system as mentioned above and considering the topology of the network, size & location of DGs in the network & load demand at each bus, it is proposed in this paper that the islanded distribution system is sectionalized into several microgrids without violating operational constraints such that each microgrid has DGs which can feed power to its load i.e. self-adequate Microgrids [23] so as to provide reliable power supply to as many customers as possible. Furthermore, these on-outage microgrids share power among themselves. The existing micro-sources are optimally scheduled in individual microgrids or among on-outage microgrids for obtaining the following single-objectives (i) minimization of cost (ii) minimization of loss and (iii) minimization of voltage deviation and multi-objectives (i) cost & loss (ii) cost and voltage deviation and (iii) loss and voltage deviation. This has been attempted for the first time in the literature for optimally scheduling the micro-sources for sectionalized microgrids. The multi-objective problem has been solved using weighted sum multi-objective method. The effectiveness of the proposed model is analyzed on a modified 33 bus distribution. A novel meta-heuristic algorithm named Jaya algorithm is used for optimal scheduling of micro-sources and the results obtained are compared with GA.

The contributions of the paper are as follows

1. Sectionalized the distribution system into self-adequate microgrids based on fault(s) location, DGs position and topology of the distribution system.
2. Optimally schedule the DGs in each microgrid for single-objective optimization i.e., cost minimization or loss minimization or voltage deviation minimization individually or multi-objective optimization considering two objectives at a time using weights sum approach and also obtain the pareto-front with different weight factors of objective functions.
3. A novel optimization algorithm – Jaya algorithm has been considered for optimization.
4. In this paper, modified 33 bus distribution system has been considered as a test case for illustrating the strategy considered and the obtained results are compared with Genetic Algorithm.

2. Sectionalizing of Distribution System

The strategy considered is that to operate the system during normal operating conditions and also during faulty conditions to supply power to as many consumers as possible.

During normal operating conditions, the control variables i.e., micro-sources in the entire distribution system are optimally scheduled for obtaining the desired objective functions such as minimization of operating cost, minimization of system losses, minimization of voltage deviation considering single objective at a time and also to obtain multi-objectives operating cost & system losses, operating cost and voltage deviation and system losses and voltage deviation minimization at a time.

Whenever a fault occurs in the system, the traditional distribution system enters into self-healing mode and reconfiguration of the system to be made for interconnection of on-outage areas and isolating the faulty region from the rest of the system. In general, as the distribution networks are radial in nature while reconfiguring these network, this quality of the distributions network has been preserved. A tie switch and a sectionalizing switch is composed by each loop in the network such that each time that one is open, the other one is closed to maintain the radial nature of the network [24].

Sectionalization of the distribution system will be made based on the self-adequate of supply and demand which in turn is necessary for the stability of micro-grids. It is assumed that microgrid central controller (MGCC) will take the decision of sectionalizing the system into self-adequate microgrids. In this paper,
transient stability and dynamic stability aspects of the system are ignored considering that stability will be maintained while sectionalizing the network [25–27].

A simple distribution system with three microgrids is shown in Figure 1. It is assumed that three microgrids shown in Figure 1 are self-adequate. From the figure, it can be analyzed that whenever a fault occurs in any one of the microgrid say microgrid-1, then microgrid-1 will be disconnected from the rest of the microgrids (microgrid-2 and microgrid-3) by opening the static switches of tie-lines and microgrid-2 and microgrid-3 will be operated. Similarly, whenever multi-area fault occurs then faulted areas will be disconnected from the rest of the microgrid. During the fault condition also, the various objectives considered in the normal state have been evaluated in on-outage area. On clearing the fault, the system goes back to normal state. The flowchart for network sectionalization is shown in Figure 2.

3. Problem Formation

The optimization problem is defined as finding the best solution from the set of feasible solutions. The optimization problem can be either minimization or maximization based on the objective. The objective functions for the optimal scheduling problem are formulated as follows.

3.1. Single Objective Optimization

In this single objective optimization approach, only one of the objective function described below is considered for minimization.

3.1.1. Minimization of Generation Cost

One of the objectives in optimal power scheduling problem is the minimization of total active power generation cost in the system. The generation cost of all units is assumed to be the function of active power generation of that unit and it is represented by the second order quadratic equation. The objective function for minimization can be expressed as the sum of the quadratic cost model at each generating unit and is expressed as follows: $F_1(x)$ [28].

$$F_1(x_{ij}) = \sum_{i=1}^{m} \sum_{j=1}^{N_{gen}} \left[ a_{ij}x_{ij}^2 + b_{ij}x_{ij} + c_{ij} \right] \frac{\$/hr}{P_{i,j}}$$

$$x_{ij} = [P_{i,1} P_{i,2} P_{i,3} \ldots \ldots P_{i,j-1} P_{i,j}], i = 1 to m \text{ where } m \text{ is the no. of microgrids and } j = 1 to N_{gen}$$

While minimizing $F_1(x_{ij})$, the following constraints are need to be maintained.

3.1.1.1. Power Balance Constraints

The total power generation in the microgrids considered for operation must be equal to the total demand and power losses inside the microgrids considered for operation. Since the network is a radial system, with multiple buses and loads in each feeder, there is need to consider power losses in the system.

$$\sum_{i=1}^{m} \sum_{j=1}^{N_{gen}} P_{i,j} = \sum_{i=1}^{m} P_{i,demand} + \sum_{i=1}^{m} P_{i,loss}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{N_{gen}} Q_{i,j} = \sum_{i=1}^{m} Q_{i,demand} + \sum_{i=1}^{m} Q_{i,loss}$$

3.1.1.2. Generation Capacity Constraints

For stable operation, real power output of each generator $P_i$ is restricted by lower and upper limits as follows:

$$P_{ij}^{min} \leq P_{ij} \leq P_{ij}^{max}$$

$$Q_{ij}^{min} \leq Q_{ij} \leq Q_{ij}^{max} \text{ i = 1 to m and j = 1 to } N_{gen}$$

Where $P_{ij}^{min}$ and $P_{ij}^{max}$ are the Minimum and Maximum active power operating limits of unit ‘i’ in microgrid ‘j’ and $Q_{ij}^{min}$ and $Q_{ij}^{max}$ are the Minimum and Maximum reactive power operating limits of unit ‘i’ in microgrid ‘j’.
3.1.1.3. Bus Voltage Constraints Bus Voltage Constraints

For voltage stability of the system, the bus voltage magnitude of bus ‘k’ in each microgrid ‘i’ must be within lower and upper limits [29].

\[ V_{i,k}^{\text{min}} \leq V_{i,k} \leq V_{i,k}^{\text{max}} \]  

(6)

3.1.2. Minimization of Active Power Loss

In the power system, the total power generation in the system must be equal to the total power demand and power losses. The objective of real power loss minimization in the system is described as follows[30]:

\[ F_2(x) = \text{Minimize} \ (P_{\text{loss}}) \]

where \( P_{\text{loss}} = \sum_{i=1}^{m} \sum_{j=1}^{N_{pg}} P_{ij} - \sum_{i=1}^{m} P_{i,demand} \)

(7)

3.1.3. Minimization of Voltage Deviation

In a power system, it is necessary to maintain the voltage deviation limits within ± 5% of the rated value to maintain the stability. The voltage deviation minimization is defined as the square of the difference between the node voltage \( V_i \) at busbar \( i \) and its nominal value. In this paper, optimal scheduling of micro-sources has been performed considering voltage deviation minimization [31] as an objective which is defined as

\[ F_3(x_i,k) = \text{Minimize} \left[ \sum_{i=1}^{m} \left( \frac{1}{n} \sum_{k=1}^{n} (V_{i,k} - V_{i,k}^{\text{nom}})^2 \right) \right] \]

(8)

3.2. Multi-Objective Approach

The multi-objective function is defined as optimizing two or more conflicting objective functions at a time. Due to this conflicting nature, no unique solution is possible for this multi-objective problem. However, we aim to find a tradeoff solution to this problem [32]. In this paper, the multi-objects are minimizing the generation cost \( F_1(x) \), minimization of active power losses \( F_2(x) \) and minimization of voltage deviation \( F_3(x) \) in the system defined in equations (1), (7) and (8), subjected to the Power balance constraints, Generation capacity constraints, Bus voltage constraints which are defined above, over the set of admissible decision vector of active power generation of DGs \( P_i \). The multi-objective function minimization is defined as follows:

\[ F_4(x) = w_1 F_1(x_i) + w_2 F_2(x_{ij}) + w_3 F_3(x_{ik}) \]  

(9)

where \( w_1, w_2, w_3 \) are the weights for the objective functions such that the sum of the weights must be equal to 1. i.e., \( w_1 + w_2 + w_3 = 1 \).

There are many solution algorithms for solving multi-objective (MO) problems such as combined artificial intelligence and linear-programming technique [23], fuzzy mathematics based methods [33, 34], the weighted sum method [35] and the augmented ε-constraint approach [36]. It is clearly demonstrated in [37] that the weighted sum method is straightforward in comparison with other methods, as the other methods are based on multi-steps in which the single objective problems are solved first. Furthermore, it is proclaimed that the weighted sum method has excellent performances pertaining to programming complexity, software use complexity, computational complexity and is also effective in handling the preference information.

To know the optimum value in the weighted sum method, the normalized coefficient \( K \) has been evaluated considering production cost, system loss, and voltage deviation to evaluate the effectiveness of the algorithm:

\[ %K = \left( \frac{\text{Total cost}_{\text{actual}}}{\text{Total cost}_{\text{max}}} * w_1 + \frac{P_{\text{loss,actual}}}{P_{\text{loss,\text{max}}}} * w_2 \right. \]

\[ \left. + \frac{V_{\text{deviation,actual}}}{V_{\text{deviation,\text{max}}}} * w_3 \right) * 100 \]  

(10)

For a given values of \( w_1, w_2 \) and \( w_3 \), the minimum value of \( K \) is the better.

4. Jaya Algorithm Optimization Approach

There are different types of population-based algorithms such as Evolutionary algorithms and swarm intelligence algorithms. These are probabilistic algorithms required the tuning of control parameters, some of which are common parameters of all algorithms such as population size, number of iterations etc. and the rest are algorithm specific parameters such as crossover probability, mutation probability, elitism probability in Genetic algorithm (GS), inertia weight, acceleration rate in Particle Swarm Optimization (PSO) algorithm, harmony memory in Harmon Search(HS) algorithm. These parameters play a vital role in finding the global optimum in the search space and improper tuning of these parameters leads to premature convergence.

Considering the stated facts, a novel heuristic algorithm which is independent of algorithm specific parameters rather needs only common control parameters such as population size and maximum number of iterations ie. Jaya algorithm has been considered in this paper.
Jaya algorithm has been proposed by R. Venkata Rao in 2016, is a simple and powerful global optimization algorithm [38]. The flowchart for the optimal scheduling of micro-sources for the problem considered in this paper has been presented in Figure 3. The optimization technique contains three phases which are as follows.

Figure 3. Flow chart for optimal scheduling of micro-sources using Jaya Algorithm in various scenarios and case studies.
4.1. Evaluation of Best and Worst Solution Phase
In each iteration, best solution candidate and worst solution candidate of the population will be evaluated.

4.2. Update Phase
On obtaining the best and worst solution candidates of the population, each candidate solution will be updated as follows:

\[ X_{j,k,i}^1 = X_{j,k,i} + r_{1,j,i}(X_{j,best,i} - |X_{j,k,i}|) \]
\[ + r_{2,j,i}(X_{j,worst,i} - |X_{j,k,i}|) \]  (11)

4.3. Comparison Phase
If \( X_{j,k,i}^1 \) gives better function value \( X_{j,k,i} \), then replace \( X_{j,k,i} \) with \( X_{j,k,i}^1 \) otherwise retain the previous solution.

The algorithm and the flow chart for the generators scheduling is as follows.

4.4. Algorithm for Optimal Scheduling Using Jaya Algorithm

1. Read input data i.e., bus voltages, fuel cost coefficients of generators, active power generation limits of all generator, cost coefficients of all generators.
2. Read algorithm parameters i.e., population size \( (P\_size) \), maximum number of iterations.
3. Select the microgrid(s) \( (A1, A2, \text{ and } A3) \) which are active.
4. Select the weights \( w_1, w_2 \& w_3 \) for cost function, loss function and voltage deviation function, respectively, based on scenario selected. i.e. scenario-1[cost minimization], scenario-2 [loss minimization] and scenario-3[cost & loss minimization] and based on multi-objective optimization.
5. Initialize population within their limits of generators output power:

\[ \{x_{ij}\} \]

\[ \{x_{p,ij}\} = \{P_{p,i,1}, P_{p,i,2}, P_{p,i,3}, \ldots, P_{p,i,j}\} \]

where \( p = 1 \) to \( P\_size \), \( i = 1 \) to \( m \) microgrids and \( j = 1 \) to \( N\_gen \)

6. Set iteration count = 1.

(7) Run load flow to evaluate the voltage magnitude at each bus and losses in each line of the system.
(8) Calculate the total cost of generation using equation (1), total loss in the system using equation (7), voltage deviation using equation (8) and evaluate the fitness function based on objective function.
(9) Evaluate the best fitness candidate and worst fitness candidate in the population.
(10) Update the candidate using update phase as indicated in equation (11)
(11) Go to comparison phase and based on function fitness value either replace the candidate or retain the candidate.
(12) Increment iteration count and repeat steps (7) to (11) until a convergence criterion is met.
(13) Stop and print the results.

5. Results and Discussions
The flowchart for sectionalizing the distribution system is presented in Figure 2. The test distribution system considered in this work is the standard 33 Bus distribution system as shown in Figure 4(a). The 33 bus distribution system data [39–41] has been presented in Table A1 of Appendix. The distribution system is sectionalized into three self-adequate microgrids and the radiality of the system has been preserved. While making the microgrids, the existing 33Bus system is modified for certain cases as explained below. The area wise, meeting the percentage of the active power load and reactive power load are presented in Table 1.

5.1. Modified 33 Bus Distribution System and Formation of Microgrids
The 33 bus distribution network is sectionalized into three microgrids and named as microgrid-1(A1), microgrid-2(A2) and microgrid-3(A3). The following modifications are made in the 33 bus system, for sectionalizing the system into microgrids. The modified 33 Distribution bus system is shown in Figure 4(b) indicating locations of DGs and tie-lines. The details of the line status are provided in Table 2 for various cases.

(a) When Microgrid-1 alone is active, the lines (no.2 and 34) between Bus no.2 & Bus no.3 and Bus no.2 & Bus no.23 are opened.
(b) When Microgrid-2 alone is active, three lines (no.2, 22 and 25) between Bus no.2 & Bus no.3, Bus no.3 & Bus no.23 and Bus no.6 & Bus no.26 are opened.
(c) When Microgrid-3 alone is active, the line (no.33) is closed between Bus no.25 & Bus no.29 and the lines (no.22, 25 and 34) between Bus no.3 & Bus no.23, Bus no.6 & Bus no.26 and Bus no.2 and Bus no.23 are opened. The details of line (no.33) resistance and reactance are presented in Table 2.

(d) When Microgrid-1 and Microgrid-2 are working together, three lines (no.22, 25 & 34) are opened between Bus no.3 & Bus no.23, Bus no.6 & Bus no.26 and Bus no.2 & Bus no.23.

(e) When Microgrid-2 and Microgrid-3 are working together, the lines (no.2 & 34) between Bus
(f) When Microgrid-1 and Microgrid-3 are working together, two lines (no.33 and 34) are closed between Bus no.25 & Bus no.29 and Bus no.2 & Bus no.23 and the lines (no.2, 22 and 25) between Bus no.2 & Bus no.3, Bus no.3 & Bus no.23 and Bus no.6 & Bus no.26 are opened.

(g) When all the microgrids are working together, the line (no.33 and 34) between the Bus no.2 & Bus no.23 and Bus no.25 & Bus no.29 are opened.

For testing the proposed algorithm, the following assumptions are made:

(1) The DGs considered in this work are dispatchable and their locations are fixed. The DG locations of the 33 Bus system is presented in Table 3.

(2) Isolation and Tie line connections are possible through a static switch.

The Jaya Algorithm parameters considered in this work are Population size- 80; Maximum iterations- 100; Based on the optimization parameters, three scenarios are formed to optimize for single objective optimization. They are, Scenario-1: Cost minimization, Scenario-2: Loss minimization and Scenario-3: Voltage deviation minimization. For multi-objective optimization, the following combinations are considered. (a) Cost and Loss minimization (b) Cost and voltage deviation minimization and (c) Loss and voltage deviation minimization.

Furthermore, the following case studies are studied. Multiple areas fault: Case-I: only A1 is in operation; Case-II: only A2 is in operation; Case-III: only A3 is in operation;

Single area fault: Case-IV: only A1 & A2 are in operation; Case-V: only A2 & A3 are in operation; Case-VI: only A1 & A3 are in operation and

No fault: Case-VII: A1, A2 & A3 are in operation.

5.2. Single Objective Optimization

5.2.1. Scenario-1 (cost minimization)

In this scenario, the objective function considered is only cost minimization. The fuel cost coefficients of each DG for 33 Bus distribution system are presented in Table 4.

Tables 5 and 6 show the scheduled power output of various DGs, total system losses, total cost of generation, system power demand in each case considering cost minimization as objective using Jaya algorithm and Genetic algorithm, respectively. From Tables 5 and 6, it is observed that Jaya algorithm is giving better cost of 19,256.43$/hr, 70,902.88$/hr, 97,919.59$/hr, 89,446.93$/hr, 168,665.57$/hr, 115,067.73$/hr and 187,652.72$/hr as against Genetic algorithm of 19,256.44$/hr, 70,902.99$/hr, 97,919.86$/hr, 89,480.97$/hr, 168,996.73$/hr, 115,367.94$/hr and 188,885.73$/hr from case-I to Case-VII, respectively. From this,
it is clear that as the size of the system increases, the effectiveness of Jaya algorithm is significant in minimization of production cost. The convergence characteristics of Jaya algorithm and GA are plotted in Figure 5 for case-VII and from the figure, it can be observed that Jaya algorithm converges in 30 iterations. The voltage profile at various buses from case-I to case-VII is plotted in Figure 6 using Jaya algorithm. From the plot, it can be assessed that the voltage deviation is within the limits of ± 5% in all the case studies.

5.2.2. Scenario-2 (Loss Minimization)

In this scenario, the objective function considered is only loss minimization. It is assumed that the available

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**Table 5.** Optimal values for various case studies with scenario-1 for 33 bus system with jaya algorithm.

| Case   | Case II | Case III | Case IV | Case V | Case VI | Case VII |
|--------|---------|----------|---------|--------|---------|----------|
| $P_{G1}$ (KW) | 164.190617 | – – | 264.206277 | – | 327.745906 | 321.856022 |
| $P_{G2}$ (KW) | 198.485931 | – – | 198.388250 | – | 199.99972 | 199.218531 |
| $P_{G3}$ (KW) | 98.021964 | – – | 99.218545 | – | 99.99986 | 99.218545 |
| $P_{G4}$ (KW) | – 272.369749 | – – | 613.626227 | – | 749.010884 | 717.167176 |
| $P_{G5}$ (KW) | – 479.267333 | – – | 438.241697 | – | 542.417506 | 486.153778 |
| $P_{G6}$ (KW) | – – | – – | 438.542873 | – | 439.682478 | 439.682478 |
| $P_{G7}$ (KW) | – 463.369898 | – – | 434.554273 | – | 439.316178 | 439.316178 |
| $P_{G8}$ (KW) | – – | – – | 439.682478 | – | 439.682478 | 439.682478 |
| $P_{G9}$ (KW) | – – | – – | 439.682478 | – | 439.682478 | 439.682478 |
| $P_{loss}$ (KW) | 0.698512 | 9.689491 | 34.307441 | 12.417283 | 55.889963 | 35.792021 |
| $Q_{loss}$ (KVAR) | 0.662523 | 7.693408 | 27.669649 | 9.148087 | 42.178957 | 26.691609 |
| Cost($)/hr | 19,256.43 | 70,902.88 | 97,919.59 | 89,446.93 | 168,665.57 | 115,067.73 |
| VDEV (in P.U) | 8.10035E-6 | 2.82300E-4 | 1.96800E-02 | 2.89000E-4 | 7.93624E-4 | 4.31400E-4 |
| $P_{demand}$ (KW) | 460 | 1405 | 1850 | 1865 | 3255 | 2310 |
| $Q_{demand}$ (KVAR) | 220 | 680 | 1400 | 900 | 2080 | 1620 |

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**Table 6.** Optimal values for various case studies with scenario-1 for 33 bus system using genetic algorithm.

| Case   | Case II | Case III | Case IV | Case V | Case VI | Case VII |
|--------|---------|----------|---------|--------|---------|----------|
| $P_{G1}$ (KW) | 164.140188 | – – | 259.725883 | – | 297.381901 | 293.911010 |
| $P_{G2}$ (KW) | 198.095210 | – – | 199.169691 | – | 198.730131 | 149.645889 |
| $P_{G3}$ (KW) | 98.461525 | – – | 99.975566 | – | 99.780206 | 99.169705 |
| $P_{G4}$ (KW) | – 272.554959 | – – | 281.807042 | – | 322.106584 | 300.854594 |
| $P_{G5}$ (KW) | – 664.615291 | – – | 604.248999 | – | 760.146413 | 697.826520 |
| $P_{G6}$ (KW) | – 477.509090 | – – | 432.527412 | – | 539.047543 | 552.234355 |
| $P_{G7}$ (KW) | – – | – – | 464.957200 | – | 372.717620 | 404.395548 |
| $P_{G8}$ (KW) | – – | – – | 640.233067 | – | 628.815540 | 626.373538 |
| $P_{G9}$ (KW) | – – | – – | 779.096350 | – | 688.839952 | 665.201372 |
| $P_{loss}$ (KW) | 0.696923 | 9.67934 | 34.286616 | 12.454594 | 56.727653 | 35.196021 |
| $Q_{loss}$ (KVAR) | 0.661003 | 7.675902 | 27.669649 | 9.143795 | 42.751923 | 26.182652 |
| Cost($)/hr | 19,256.44 | 70,902.99 | 97,919.86 | 89,480.97 | 168,996.73 | 115,367.94 |
| VDEV (in P.U) | 8.0959E-6 | 2.82241E-4 | 1.96830E-2 | 2.91619E-4 | 7.91800E-4 | 4.31400E-4 |
| $P_{demand}$ (KW) | 460 | 1405 | 1850 | 1865 | 3255 | 2310 |
| $Q_{demand}$ (KVAR) | 220 | 680 | 1400 | 900 | 2080 | 1620 |

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**Figure 5.** Convergence characteristics of Jaya algorithm vs. GA for Cost minimization as objective function for 33 Bus system Scenario-1 Case-VII.
DGs are dispatchable with fixed location. The loss for various case studies described above is presented in Tables 7 and 8 for Jaya algorithm and GA, respectively, for 33 Bus distribution system.

Tables 7 and 8 illustrate the scheduled output power of each DG, active and reactive power losses of system, total production cost. From Tables 7 and 8, it is observed that Jaya algorithm is giving minimum losses of 690.474 watts, 9499.427 watts, 33,673.17 watts, 12,122.236 watts, 53,424.97 watts, 34,635.059 watts and 71,707.68 watts as against Genetic algorithm of 690.496 watts, 9520.185 watts, 33,708.979 watts, 12,150.093 watts, 53,469.600 watts, 34,644.690 watts and 71,902.238 watts from case-I to Case-VI, respectively. From the convergence characteristics shown in Figure 7, it can be observed that Jaya algorithm gives minimum power losses as compared to GA. Furthermore, from Figure 8, it is clear from the observation that on sectionalizing the distribution system into various microgrids, the

![Figure 6. Voltages(P.U) profile of 33 Bus system for different case studies with Scenario-1 using Jaya Algorithm.](image-url)

**Table 7.** Optimal values for various case studies with scenario-2 for 33 bus system using jaya algorithm.

| Case | Case-I | Case-II | Case-III | Case-IV | Case-V | Case-VI | Case-VII |
|------|--------|---------|----------|---------|-------|--------|---------|
| $P_{DG}$ (KW) | 160.690516 | – | – | 126.109051 | – | 338.774535 | 130.737498 |
| $P_{DG}$ (KW) | 199.999972 | – | – | 199.316211 | – | 174.407790 | 68.522579 |
| $P_{DG}$ (KW) | 99.999986 | – | – | 98.412685 | – | 99.973566 | 99.023185 |
| $P_{DG}$ (KW) | – | 221.581402 | – | 268.689285 | 640.122537 | – | 849.816730 |
| $P_{DG}$ (KW) | – | 767.570100 | – | 117.613934 | 751.355206 | – | 666.373333 |
| $P_{DG}$ (KW) | – | 425.347926 | – | 426.080526 | 424.718455 | – | 415.238037 |
| $P_{DG}$ (KW) | – | – | – | 499.999930 | – | 498.347228 | 499.384929 |
| $P_{DG}$ (KW) | – | – | 583.673352 | – | 221.001190 | 798.632666 | 758.583532 |
| $P_{DG}$ (KW) | – | – | – | 799.99987 | – | 772.649464 | 430.453572 |
| $P_{Loss}$ (KW) | 0.690474 | 9.499427 | 33.673170 | 12.122236 | 53.424970 | 34.635095 | 71.707680 |
| $Q_{Loss}$ (KVAR) | 0.655399 | 7.298935 | 27.151174 | 8.947885 | 39.603160 | 25.729368 | 49.247457 |
| Cost ($/hr) | 19.257.57 | 71.409.28 | 98.125.16 | 91.347.5 | 177.748.39 | 116.787.91 | 208.999.64 |
| VDEV(in P.U) | 7.9987E-06 | 2.891E-04 | 1.966E-02 | 2.914E-04 | 7.093E-04 | 4.328E-04 | 1.028E-03 |
| $Q_{demand}$ (KW) | 460 | 1405 | 1850 | 1865 | 3255 | 2310 | 3715 |
| $Q_{demand}$ (KVAR) | 220 | 680 | 1400 | 900 | 2080 | 1620 | 2300 |

**Table 8.** Optimal values for various case studies with scenario-2 for 33 bus system using genetic algorithm.

| Case | Case-I | Case-II | Case-III | Case-IV | Case-V | Case-VI | Case-VII |
|------|--------|---------|----------|---------|-------|--------|---------|
| $P_{DG}$ (KW) | 160.690538 | – | – | 187.650941 | – | 334.046682 | 119.674427 |
| $P_{DG}$ (KW) | 199.999972 | – | – | 124.200227 | – | 199.560141 | 154.578733 |
| $P_{DG}$ (KW) | 99.999986 | – | – | 95.311342 | – | 98.779895 | 99.853466 |
| $P_{DG}$ (KW) | – | 221.407699 | – | 271.062233 | 628.885117 | – | 780.463871 |
| $P_{DG}$ (KW) | – | 767.765460 | – | 775.775227 | 595.91076 | – | 393.453728 |
| $P_{DG}$ (KW) | – | 425.347926 | – | 423.150124 | 426.666607 | – | 427.106167 |
| $P_{DG}$ (KW) | – | – | 499.999930 | – | 498.778929 | 482.882716 | 495.726426 |
| $P_{DG}$ (KW) | – | – | 586.834925 | – | 390.700336 | 428.571368 | 559.218481 |
| $P_{DG}$ (KW) | – | – | 796.874125 | – | 763.476356 | 799.805427 | 756.825290 |
| $P_{Loss}$ (KW) | 0.690496 | 9.499427 | 33.673170 | 12.122236 | 53.424970 | 34.635095 | 71.707680 |
| $Q_{Loss}$ (KVAR) | 0.655399 | 7.298935 | 27.151174 | 8.947885 | 39.603160 | 25.729368 | 49.247457 |
| Cost ($/hr) | 19.257.57 | 71.409.28 | 98.125.16 | 91.347.5 | 177.748.39 | 116.787.91 | 208.999.64 |
| VDEV(in P.U) | 8.0137E-06 | 2.8905E-04 | 1.9668E-02 | 2.9020E-04 | 7.6860E-04 | 4.328E-04 | 1.028E-03 |
| $Q_{demand}$ (KW) | 460 | 1405 | 1850 | 1865 | 3255 | 2310 | 3715 |
| $Q_{demand}$ (KVAR) | 220 | 680 | 1400 | 900 | 2080 | 1620 | 2300 |
minimum PU voltage value in sectionalized microgrids is better than the combined operation of microgrids and is maintained within the permissible limits of ± 5% for all the cases. The voltage profile at various buses from case-I to case-VII is plotted in Figure 8 using Jaya algorithm.

5.2.3. Scenario-3 (Voltage Deviation Minimization)
In this scenario, the objective function considered is voltage deviation minimization. The voltage deviation minimization for various case studies described above is presented in Tables 9 and 10 for 33 Bus system using Jaya algorithm and GA.

Table 9. Optimal values for various case studies with scenario-3 for 33 bus system using jaya algorithm.

| Case   | Case-I          | Case-II         | Case-III        | Case-IV         | Case-V          | Case-VI         | Case-VII        |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| PG1(KW)| 160.690516      | –               | –               | 0.327297        | –               | 178.276814      | 12.732559       |
| PG2(KW)| 199.999972      | –               | –               | 40.830275       | –               | 198.388250      | 8.449327        |
| PG3(KW)| 99.999986       | –               | –               | 71.843702       | –               | 99.877886       | 70.305240       |
| PG4(KW)| –               | 492.164913      | –               | 989.010850      | 65.220141       | –               | 709.645810      |
| PG5(KW)| –               | 348.717900      | –               | 186.959681      | 0.781441        | –               | 15.042733       |
| PG6(KW)| –               | 575.677575      | –               | 592.087829      | 350.036581      | –               | 290.549410      |
| PG7(KW)| –               | –               | 499.999930      | –               | 457.997494      | 486.324718      | 117.582401      |
| PG8(KW)| –               | –               | 583.673352      | –               | 2018.314734     | 582.417500      | 2485.958136     |
| PG9(KW)| –               | –               | 799.999887      | –               | 425.885166      | 799.999887      | 96.507923       |
| Ploss(KW)| 0.690474      | 11.560388      | 33.673170      | 16.059633       | 63.235556       | 35.285056       | 91.773540       |
| Qloss(KVAR)| 0.653399      | 9.648214       | 27.151174      | 12.856239       | 47.462250       | 26.261464       | 64.613988       |
| Cost(S/ht)| 19,257.57      | 76,157.67      | 98,125.16      | 129,300.31      | 251,389.09      | 116,995.68      | 347,147.63      |
| Vdev (P.U)| 799870E-06     | 2.76524E-04    | 1.96663E-02    | 2.69284E-04     | 7.06163E-04     | 4.24881E-04     | 9.74101E-04     |
| Pdemand(KW)| 460            | 1405           | 1850           | 1865            | 3255           | 2310           | 3715           |
| Qdemand(KVAR)| 220            | 680            | 1400           | 900             | 2080           | 1620           | 2300           |
Tables 9 and 10 shows the scheduled power output of various DGs, total system losses, total cost of generation, voltage deviation in each case considering voltage deviation minimization as objective using Jaya algorithm and Genetic algorithm, respectively. From Tables 9 and 10, it is observed that Jaya algorithm is giving minimum voltage deviation in P.U of 7.99898E-06, 2.76533E-04, 1.96671E-02, 2.70032E-04, and 9.80675E-04 against Genetic algorithm of 7.99898E-06, 2.76533E-04, 1.96671E-02, 2.70032E-04, and 9.80675E-04.
5.3. Multi-Objective Optimization:

5.3.1. Cost and Loss Minimization Simultaneously

In this scenario, the objective function considered is cost and loss minimization simultaneously. The cost and loss for various case studies described above are presented in Tables 11 and 12 for 33 Bus system using Jaya and GA algorithms. The voltage magnitudes at different buses of 33 Bus system for various case studies are plotted in Figure 13. It is observed that the voltage magnitude at all the buses is maintained within the limits.

### Table 11. Optimal values for various case studies with scenario-3 for 33 bus system using jaya algorithm.

| Case     | Case-I             | Case-II            | Case-III           | Case-IV            | Case-V             | Case-VI            | Case-VII           |
|----------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| $P_G$ (KW) | 160.788215         | --                 | --                 | 219.726866         | --                 | 324.432881         | 314.517604         |
| $P_G$ (KW) | 199.902292         | --                 | --                 | 198.681291         | --                 | 199.706932         | 196.190449         |
| $P_G$ (KW) | 99.999986          | --                 | --                 | 99.120865          | --                 | 99.926726          | 60.854692          |
| $P_G$ (KW) | --                 | 272.874550         | --                 | 223.198992         | 418.879726         | --                 | 441.025579         |
| $P_G$ (KW) | --                 | 692.747155         | --                 | 705.250206         | 693.723956         | --                 | 621.245334         |
| $P_G$ (KW) | --                 | 448.937666         | --                 | 431.208731         | 450.402867         | --                 | 488.205060         |
| $Q_G$ (KVAR) | --                 | 499.511529         | --                 | 499.877830         | 452.136689         | --                 | 441.025579         |
| Cost ($/hr) | 1865               | 2310               | 1850               | 235.8974           | 628.88512          | 70,951.86          | 98,123.35          |
| % K        | 99.438405          | 98.634072          | 99.091584          | 97.418485          | 97.223042          | 99.728556          | 99.920244          |
| $P_{demand}$ (KW) | 460               | 1405               | 1850               | 1865               | 3255               | 2310               | 3715               |
| $Q_{demand}$ (KVAR) | 220               | 680                | 1400               | 900                | 2080               | 1620               | 2300               |

### Table 12. Optimal values for various case studies with scenario-3 for 33 bus system using genetic algorithm.

| Case     | Case-I             | Case-II            | Case-III           | Case-IV            | Case-V             | Case-VI            | Case-VII           |
|----------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| $P_G$ (KW) | 160.81273          | --                 | --                 | 239.89036          | --                 | 313.340921         | 274.96426          |
| $P_G$ (KW) | 199.902292         | --                 | --                 | 199.41389          | --                 | 199.218831         | 196.83001           |
| $P_G$ (KW) | 99.975566          | --                 | --                 | 79.964964          | --                 | 98.925905          | 82.710611          |
| $P_G$ (KW) | --                 | 272.48654          | --                 | 235.8974           | 628.88512          | --                 | 516.23924           |
| $P_G$ (KW) | --                 | 691.96572          | --                 | 695.4822           | 599.95108          | --                 | 651.72152           |
| $P_G$ (KW) | --                 | 450.10983          | --                 | 431.64829          | 426.6661           | --                 | 452.00149           |
| $Q_G$ (KVAR) | --                 | 499.99993          | --                 | 498.77893          | 452.380889         | --                 | 469.84121           |
| Cost ($/hr) | 19,257.50          | 70,951.86          | 98,123.35          | 87,424.45          | 115,623.96         | 190,814.09         | 190,814.09          |
| % K        | 99.442522          | 98.638789          | 99.517116          | 99.335015          | 97.228556          | 99.920244          | 99.920244          |
| $P_{demand}$ (KW) | 460               | 1405               | 1850               | 1865               | 3255               | 2310               | 3715               |
| $Q_{demand}$ (KVAR) | 220               | 680                | 1400               | 900                | 2080               | 1620               | 2300               |
Figure 11. Convergence characteristics of Jaya algorithm vs. GA for Cost vs. Iterations in Cost and Loss minimization as objective function for 33 Bus system Scenario-3 Case-VII.

Figure 12. Convergence characteristics of Jaya algorithm vs. GA for Loss vs. Iterations in Cost and Loss minimization as objective function for 33 Bus system Scenario-3 Case-VII.

Figure 13. Voltages(P.U) profile of 33 Bus system for different case studies with Scenario-3 using Jaya Algorithm.
considered as 0.0 and $W_2$ is considered as 1.0, the importance given to cost minimization is minimum and for loss minimization, it is maximum. In this approach the weight factor for cost reduced from 1.0 to 0.0 and weight factor for loss increased from 0.0 to 1.0.

### 5.4. Cost and Voltage Deviation Minimization Simultaneously

Figure 15 shows the pareto-front for minimization of cost & voltage deviation simultaneously for case-I to case-VII using Jaya algorithm. In this approach, when $W_1$ is considered as 1.0 and $W_3$ is considered as 0.0, the importance given to cost minimization is more and for voltage deviation minimization, it is minimum. Similarly when $W_1$ is considered as 0.0 and $W_3$ is considered as 1.0, the importance given to cost minimization is minimum and for voltage deviation minimization, it is maximum. In this weighted sum method, the weight factor for cost reduced from 1.0 to 0.0 and weight factor for voltage deviation increased from 0.0 to 1.0.

### 5.5. Loss and Voltage Deviation Minimization Simultaneously

Figure 16 shows the pareto-front for minimization of Loss & voltage deviation simultaneously using Jaya algorithm for case-I to Case-VII. In this approach, when $W_2$ is considered as 1.0 and $W_3$ is considered as 0.0, the importance given to loss minimization is more and for voltage deviation minimization, it is minimum. Similarly when $W_2$ is considered as 0.0 and $W_3$ is considered as 1.0, the importance given to loss minimization is minimum and for voltage deviation minimization, it is maximum. In this weighted sum method, the weight factor for loss reduced from 1.0 to 0.0 and weight factor for voltage deviation increased from 0.0 to 1.0.
sum method, the weight factor for loss reduced from 1.0 to 0.0 and weight factor for voltage deviation increased from 0.0 to 1.0.

Based on the above combinations, whenever a fault is associated in the system, a part of the total load can be fed with individual operation of microgrid or group operation of microgrids by isolating the faulty portion, such that the number of consumers being affected by power interruption will be reduced. Based on the situation and importance of objectives, the Microgrid central controller (MGCC) has to take a decision, either the microgrids to be operated in together or independent.

6. Conclusion
In this paper, optimal operation of microgrid by economic scheduling of DGs has been performed by sectionalizing the existing distribution system into several self-sufficient microgrids. However, these microgrids can be operated individually or united with other microgrids so as to attain the desired objective. Either in individual mode of operation of microgrid or combined mode of operation of microgrids, both single objective function and multi-objective functions are considered for minimizing the objective function value. Single objective function considered in this
study are minimizing the total operating cost of DGs, system losses and voltage deviation while optimally dispatching the distributed generators. Furthermore, multi-objective optimization using weighted sum approach for minimization of operating cost of DGs & system losses, system losses & voltage deviation and operating cost of DGs & voltage deviation simultaneously have been performed. Jaya algorithm which is a novel meta-heuristic optimization algorithm has been exercised for optimizing the objective functions on modified 33 bus distribution system. The results obtained are compared with GA which is a well-known algorithm in the literature and the obtained results are validated. The supremacy of the Jaya algorithm is evident from the results obtained in terms of minimum operating cost, minimum system losses and minimum voltage deviation in single objective case studies and multi-objective case studies.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Notes on contributors**

Srinivasarathnam C. obtained his B.Tech degree in electrical and electronics engineering from Jawaharlal Nehru Technological University, Hyderabad, India, in 2007. He received his M.Tech degree in power systems engineering from the National Institute of Technology Warangal (NITW), Warangal, India, in 2013. He has seven years of Industrial experience. Currently, he is working towards Ph.D degree in power systems at National Institute of Technology, Warangal, India.
Chandrasekharam Yammani received B.Tech degree in electrical and electronics engineering from Jawaharlal Nehru Technological University, Hyderabad, India, in 2007. He possessed M.Tech and Ph.D degrees in power systems engineering from the National Institute of Technology Warangal (NITW), Warangal, India, in 2009 and 2015, respectively. He completed post-doctorate fellowship from UWS, Scotland under Erasmus Mundus Program in 2018. He has been working as an assistant professor in Electrical Engineering Department of NIT Warangal since March 2012. His research areas include power system operation and control, planning studies of distribution generation and renewable energy resources in power systems, smart grids, microgrids, optimization techniques, meta-heuristic techniques, Blockchain Technologies, electric vehicles, reliability and resilience studies of power systems.

Sydulu Maheswarapu obtained his B.Tech (electrical engineering, 1978), M.Tech (power systems, 1980), Ph.D (electrical engineering – power systems, 1993) degrees from Regional Engineering College Warangal, Andhra Pradesh, India. His research areas of interest include real-time power system operation and control, ANN, fuzzy logic, and genetic algorithm applications in power systems, distribution system studies, economic operation, reactive power planning and management. Currently, he is professor of electrical engineering at National Institute of Technology, Warangal (formerly RECW).

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Appendix

Table A1. 33 bus system data.

| Line no | From bus | To bus | R (P.U) | X (P.U) | P (KW) | Q (KVAR) |
|---------|----------|--------|---------|---------|--------|----------|
| 1       | 1        | 2      | 0.000574| 0.000293| 100    | 60       |
| 2       | 2        | 3      | 0.00307 | 0.001564| 90     | 40       |
| 3       | 3        | 4      | 0.002279| 0.001161| 120    | 80       |
| 4       | 4        | 5      | 0.002373| 0.001209| 60     | 30       |
| 5       | 5        | 6      | 0.0051  | 0.004402| 60     | 20       |
| 6       | 6        | 7      | 0.001166| 0.003853| 200    | 100      |
| 7       | 7        | 8      | 0.00443 | 0.001464| 200    | 100      |
| 8       | 8        | 9      | 0.006413| 0.004608| 60     | 20       |
| 9       | 9        | 10     | 0.006501| 0.004608| 60     | 20       |
| 10      | 10       | 11     | 0.001224| 0.000405| 45     | 30       |
| 11      | 11       | 12     | 0.002331| 0.000771| 60     | 35       |
| 12      | 12       | 13     | 0.009141| 0.007192| 60     | 35       |
| 13      | 13       | 14     | 0.003372| 0.004439| 120    | 80       |
| 14      | 14       | 15     | 0.00368 | 0.003275| 60     | 10       |
| 15      | 15       | 16     | 0.004647| 0.003394| 60     | 20       |
| 16      | 16       | 17     | 0.008026| 0.010716| 60     | 20       |