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RESEARCH ARTICLE - ELECTRICAL ENGINEERING

Planning Framework for Optimal Resource Utilization Strategy in Microgrid

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Abstract

The incorporation of distributed energy resources and technical innovations has restructured the electrical power system network from conventional grid to microgrid. Consequently, significant impacts on both distribution and utilization of power have been observed triggered by diverse operating condition and enhanced power demand. In planning of microgrid, energy management is a critical issue which is related to efficient utilization of available resources at minimum operating cost. Distributed and intermittent nature of generations in microgrid demands efficient and optimal allocation of existing resources. An allocation technique is necessary to attain optimal utilization of assets and to accomplish decision making for optimal power flow route through shortest path. This paper proposes a multi-objective optimization-based resource allocation technique to efficiently control available generation at any load condition to achieve minimum operating cost while maintaining all system constraints. In proposed framework, line flows are maximized to its load-carrying capability and by controlling power flow through shortest possible path. Proposed methodology suggests proper controller position to sustain desired power flow through the shortest path between each generator and load pair. An interconnected microgrid network topology is considered to demonstrate the proposed methodology.

Keywords Microgrid · Resource allocation · Shortest path · Power flow constraints · Multi-objective optimization · Genetic algorithm (GA)

1 Introduction

Microgrid is an energy-efficient and cost-effective system for sustainable development in power market, but its functioning involves several challenges. Efficient and optimal allocation of existing resources becomes a challenge for real-time energy management as generations are distributed and intermittent in a microgrid. Generations by renewable energy resources (RERs) are sporadic which leads to power outage depending on environmental conditions (e.g., solar power output will be very trivial in cloudy condition or at night and wind does not blow consistently throughout the day). Hence, conventional power generations are included in microgrids to avoid power disturbance due to natural deviations in RERs [1]. Resource allocation is a part of energy management strategy that considers availability of all generations at any particular load level and allocates these generations most suitably to supply the loads subject to any predetermined objective.

There are several areas regarding economic aspects of microgrid operation and planning which are discussed below.

1.1 Literature Review

Resource allocation accords with allocating suitable power source to a load depending on availability at minimum operating costs and any other predefined condition which may be related to environmental concerns also [2, 3]. Due to economical, environmental and technical issues in allocating suitable energy source, resource allocation continues to become a critical issue in microgrids.

In the literature, there exist numerous methods for economically allocating and utilizing available energy resources in context of microgrids usually designated as energy management system (EMS) [4–14] and [16–33],

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while an exhaustive review of different EMSs has been presented in [15]. The brief overviews of existing methods are examined in Table 1.

Optimal power flow problem is solved by mixed-integer nonlinear programming approach in [38] which proves to be computationally efficient. Particle swarm optimization (PSO) is the most commonly used heuristic method because its implementation needs only consideration of few parameters, but it may not converge always with optimal feasible solution for EMS in microgrid [39].

An optimization-based resource allocation is proposed in [37] where genetic algorithm (GA) is used to select a suitable route from source to a certain load and optimizes a cost function based on distance but is applicable only for smart grids with transshipment network. And most significantly, it assumes power will flow through the optimized path irrespective of the physical constraints of the network. An optimal resource allocation algorithm is proposed in [40] which maximizes energy flow through shortest path and decides shortest path between each generator and load using GA by assuming that flow through shortest path between generator and load pair will lead to system loss minimization.

There are some limitations with the above-mentioned energy management methods:

- Execution of control scheme-based energy management techniques is an intricate task as large numbers of control devices are requisite which needs efficient computational techniques.
- A scheduling scheme develops into tedious procedure in heterogeneous environment as a consequence of changed operating conditions.
- Load-classifying methods depend on the type of installation and person carrying out the load scheduling exercise.
- Methods of EMS based on programming approach have computational complexity, especially in heuristic methods.

So, this paper presents a planning framework intended for optimal resource utilization by multi-objective optimization approach. The developed framework can be useful while planning an EMS for microgrid. The proposed method of this article maximizes line flow and minimizes system loss and decides path for line flow between each generator and load pair using GA. GA is used here to solve the proposed multi-objective optimization problem due to the following advantages. GA and any other population-based algorithms have the advantage of implicit parallelism due to which it converges toward high-quality solutions. It can be easily implemented for solving multi-objective optimization problems with least probability of getting local optimal solution like some other methods. GA is suitable for combinatorial problems, while particle swarm optimization (PSO) is not fairly suitable to combinatorial problems. In PSO, particles are updated with internal velocity which is a one-way information sharing mechanism, while GA is based on genetic operators such as ‘crossover’ and ‘mutation,’ which is easily distributed. Tuning learning factors and weight factors

Table 1 Different existing methods for utilizing available resources in microgrid

Paper	Technique	Merits	Demerits
[4, 5]	Fairness index-based resource allocation	Superior than conventional method	Suitable for multi-agent system-based microgrid
[6, 7]	Priority-based process	Depends on quantity of load demand by customers	Lead to energy starvation situation for customers having lower priority
[8–11]	Control schemes and decision-making mechanism	Hierarchical and redesigned from transmission level	Intricate execution with large number of control devices
[12]	Demand side management	Continuation of energy balance by reducing power consumption instead of excess power generation	Involve active participation of consumers
[13, 14]	Scheduling approach	Fully deterministic in centralized scenario	Tedious procedure in heterogeneous environmental structure of microgrid
[16–33]	Programming approach (deterministic [16], stochastic [17, 18], meta-heuristic [19–31] and hybrid [32, 33])	Flexibility for consideration of operating constraints	Computational complexity, especially in heuristic methods
[34–36]	Programming approach based on hybrid cost functions	Includes uncertainty of generation–load	Market-based approach of energy management
[37]	Fuzzy and genetic algorithm-based approach	Maximizes line capacity rather than planning expansion of line	Applicable for transshipment network
Proposed method	Genetic algorithm	Maximizes line capacity and minimizes system loss; applicable for all types of electrical network	Computational efficiency may decrease in case of larger systems

for multi-objective PSO is much complex [17]. For solving unit commitment and economic load dispatch optimization problems, multi-objective GA has been demonstrated appropriate [17]. Hence, GA is used here to solve the optimization problem.

The difference between existing resource allocation methods of the literature and this paper is listed in Table 2.

1.2 Contributions of This Paper

This paper proposes a resource allocation method pertaining to control of power flow path through the microgrid to force power through shortest path, so as to achieve minimum active power loss. The proposed method maximizes the power flow through existing lines in context of efficient utilization of existing resources. It suggests the number of power flow controllers required to make the ensuing power flow to be relevant to the physical properties of the system, an aspect that most of the present resource allocation works ignore.

The method of resource allocation presented in this article includes the physical constraints along with power flow constraints. Due to this, it has been observed that direction of power flow by optimal resource allocation is not matching with that of based on power flow analysis in some of the line. It indicates that to implement the optimal resource allocation by the proposed method, controller installation is required at few locations. The suitable places for controller placement are being indicated by number of mismatches in paths, and the advantage of the proposed technique is that it results into such optimal paths in which placement of single controller can be sufficient for optimal resource allocation in overall network. This has been achieved by solving a multi-objective optimization problem by weighted-sum approach. By varying the weights, different Pareto-optimal solutions can be found. By using appropriate weights, every point of convex Pareto front can be achieved by the weighted sum, so it is frequently used for practical applications. Varying weights is an approach to articulate predilection for Pareto optimality. The major contributions of the proposed method are:

- Multi-objective optimization-based planning framework is proposed for efficient utilization of available resources.
- For optimal utilization, it proposes maximization of line capacity and minimization of systems loss.
- Weighted-sum approach has been opted which is frequently used for practical applications.

1.3 Paper Organization

The next sections depict the proposed resource allocation methodologies in detail. Section 2 outlines and describes the mathematical problem formulation of the proposed methodology adopted for resource allocation. Section 3 demonstrates the application of the proposed method to different test systems with its benefits and limitations. Section 4 presents application of the proposed method in radial system in brief, and Sect. 5 discusses the shortcomings of the proposed method with scope of further research. Finally, Sect. 6 concludes the work.

2 Optimization Problem Formulation for Resource Allocation

There are two major operational challenges in microgrid: control strategy and power management. This paper mainly deals with allocating available resources to individual loads which comes under power management. The primary focus is to fulfill the load requirements at minimum operating cost while maximizing the use of power lines.

2.1 Capacity of Power Lines

Based on heat transfer concepts, Neher–McGrath (NM) equation is proposed for the calculation of load capability of conductors which is given by [41]:-

$$I = \sqrt{\frac{T_{\mathrm{C}} - \left(T_{\mathrm{A}} + \Delta T_{\mathrm{d}}\right)}{R_{\mathrm{dc}}\left(1 + Y_{\mathrm{c}}\right) * R_{\mathrm{CA}}}} \Rightarrow I = \sqrt{\frac{T_{\mathrm{C}} - \left(T_{\mathrm{A}} + \Delta T_{\mathrm{d}}\right)}{k * L^2}} \quad (1)$$

where I = ampacity (kA), defined as capacity of the conductor to carry power continuously (in ampere) without exceeding its temperature rating.

R_{dc} = conductor DC resistance (μΩ/ft);ΔT_{d} = conductor temperature rise due to dielectric loss (°C);Y_{c} = loss increment due to conductor skin and proximity effects;R_{CA} = thermal resistance between conductor and ambient usually called thermal-ohm-feet (°C-ft/W);T_{C} = conductor temperature (°C);T_{A} = ambient temperature (°C);k = constant depending on Y_{c}, resistivity and cross-sectional area of conductor;L = length of conductor;

From Eq. (1), it can be concluded that load-carrying capability of conductors depends on the length of the conductor. To maximize the ampacity of conductor connected between source node $'i'$ and load node $'j'$, length of conductor between buses 'i' and 'j' should be minimized.

2.2 Loss in Conductor

If two conductors of the same material and uniform cross-sectional area are connected between source node $'i'$ and load node $'j'$, then losses will be less in conductor with smaller length. Let L_{ij} denotes length of conductor between buses 'i' and 'j' then

Table 2 Difference of the proposed method and existing literature

Ref.	Algorithm	Weights	Network type	Uncertainty handling approach	Objective functions	Constraints				
						Cost	Power flow	Network loss objective	Voltage limits	Power factor limits
[9]	Grid-adaptive control strategy	n/a	n/a	Forecasted	Optimal DC link regulation, battery life improvement and priority-based load shedding	n/a	n/a	n/a	n/a	n/a
[24]	Scheduling approach	Variable	n/a	Scenario generation method	Minimization of fuel consumption and battery degradation cost	√	√	×	√	×
[37]	Fuzzy	n/a	Transshipment	Forecasted	Minimization of cost and maximization of capacity	√	×	×	×	×
[40]	GA	Fixed	All	Forecasted	Maximization of line capacity to its load-carrying capability and minimization of impedance between generator and load pair	√	√	√	×	×
Present Paper	GA	Variable	All	Forecasted	Maximization of line capacity between shortest path between generator and load pair and minimization of system power loss	√	√	√	√	√

$$\text{As, } R_{ij} \propto L_{ij} \text{ and } P_{\text{loss\_}ij} \propto L_{ij} \tag{2}$$

To minimize the active power loss, bus voltages must be maintained within the specified limits which ensure the system stability also.

2.3 Problem Formulation

The optimal resource allocation based on power flow is a multi-period problem as generator and load are time variant. Available amount of power to be allocated cannot be estimated for a long period in microgrids. Firstly, the amount of available generation throughout a day is calculated from predicted weather data and grid power availability which is known day ahead. According to the availability of generation the flexible loads are dispatched for each hour. Once the hourly generator and load patterns are available to us, the next step is to decide on the generator and load pairs that will supply and consume power. This comes under resource allocation and is the area of discussion in the present paper. The optimal resource allocation is presented in this paper for resources and loads present at a particular time slot. The proposed optimal resource allocation strategy aims for

- Maximizing the use of capacity of the lines while satisfying constraints of the system: Maximization of capacity of lines within its limits defers the installation of new lines to the system. It may help in planning of new DERs into the system also. Further incorporation of DERs can be planned into the lines where actual line flow fall its maximum limit by a marginal value.
- Minimizing the loss associated in dispatching power from generation to demand: Minimization of real power loss leads to reduced cost associated with loss in some way.

The objective is to maximize line flow (Max $\sum P_{ij}$) within its limit which is indirectly related to minimization of distance (Min $\sum L_{ij}$) according to Eq. (1) and to minimize loss $\left(\text{Min} \sum P_{\text{loss\_}ij}\right)$ also leads to minimization of distance (Min $\sum L_{ij}$) as mentioned in Eq. (2). For the present formulation P_{ij} represents the power flow through different branches of the microgrid.

Let $\left(L_{ij}\right)$ denotes length between buses 'i' and 'j,' and P_{ij} is set of decision variables in assigning source at bus 'i' to demand at bus 'j.' Hence, for the proposed resource allocation objective function is given as,

$$f = w_1F_1 + w_2F_2 = \min\left[w_1 * \left(\sum_{\substack{i,j=1 \\ i \neq j}}^{n} \left({L_{ij}}/{P_{ij}} \right) \right) + w_2 * \left(\sum_{\substack{j=1 \\ i \neq j}}^{n} \left({V_j^2}/{R_{ij}} \right) \right) \right] \tag{3}$$

where n is the number of nodes; $w_1 + w_2 = 1$ and w_1 and w_2 are weights of objective function whose value depends on choice of operator. The voltage limits considered here are: $V_{\text{min}} = 0.95$ pu and $V_{\text{max}} = 1.05$ pu.

Subject to

(a) Power balance at each node:

$$\sum_{(i,j)\in G} P_{ik} - \sum_{(i,j)\in G} P_{kj} = P_k \; \forall \, k \in V \tag{4}$$

(b) Power flow constraints:

(i) Active power balance:

$$P_{gi} - P_{li} - P_k = 0 \tag{5}$$

$$P_k = V_k \sum_{i=1}^{n} Y_{ki} V_i \cos\left(\delta_k - \delta_i - \theta_{ki}\right) \tag{6}$$

(ii) Reactive power balance:

$$Q_{gi} + Q_{ci} - Q_{li} - Q_k = 0 \tag{7}$$

$$Q_k = V_k \sum_{i=1}^{n} Y_{ki} V_i \sin\left(\delta_k - \delta_i - \theta_{ki}\right) \tag{8}$$

(c) Active power generation limits:

$$P_{gi}^{\text{min}} \le P_{gi} \le P_{gi}^{\text{max}} \tag{9}$$

(d) PV bus voltage limits:

$$V_{gi}^{\text{min}} \le V_{gi} \le V_{gi}^{\text{max}} \tag{10}$$

(e) Reactive power generation limit:

$$Q_{gi}^{\text{min}} \le Q_{gi} \le Q_{gi}^{\text{max}} \tag{11}$$

(f) PQ bus voltage limits:

$$V_i^{\text{min}} \le V_i \le V_i^{\text{max}} \tag{12}$$

(g) Power factor limits:

$$0.75 \le \text{pf} \le 0.95 \tag{13}$$

(h) Line capacity limits:

$$P_{ij}^{\min} \le \left|P_{ij}\right| \le P_{ij}^{\max} \forall (i,j) \in G \tag{14}$$

Line capacity constraints mentioned in Eq. (14) will assign the amount of line flow near to maximum limit by optimal use of load capability of line.

Design Variables: For the proposed planning framework, line flow and bus voltages are design variables which are represented in mathematical formulation by P_{ij} and V_j. L_{ij} is another design variable for sending power through path decided by optimization which will minimize system loss. Design variable L_{ij} will be used for installation of controllers in the system required. In existing methods [37] and [40], maximization of line capacity is proposed but without consideration of all physical constraints and operational constraints of the system. So, the method proposed in this paper considers all physical and operational constraints of system simultaneously for planning of optimal resource utilization with objectives of maximization of line capacity and minimization of system loss.

Stopping criterion: For the proposed method of multi-objective optimization, maximum number of iterations and relative change in value of objective function in 50 consecutive iterations are considered as stopping criterion. Also, if the number of infeasible solutions becomes equal to maximum stall generation (which is considered as 50 in this case), then terminate/exit the optimization process.

In this case, the number of maximum iterations is dependent on the number of design variables. If system is large, then there will be large number of design variables which will require large number of iterations for obtaining optimal solution.

Maximum iteration, $k =$ (population size)*(number of design variables)

Relative change in objective function $\le 1.0\mathrm{e}-04$

where relative change in objective

$$function = \frac{\left|(functionvalue)_{atk+1^{th}iteration}\right| - \left|(functionvalue)_{atk^{th}iteration}\right|}{\left|(functionvalue)_{atk+1^{th}iteration}\right|} \; for\, k = n\; to\; k = n + 50$$

Population size = 200

2.4 The Algorithm

The proposed resource allocation method can be described by the following steps:

Step 1: Determine available generation for intermittent sources and note down demand at different buses.

Step 2: Perform power flow analysis by a suitable technique.

Step 3: Determine the shortest path between each generator and load pair obeying power flow directions using Johnson's algorithm. These shortest power flow paths correspond to minimum active power loss for resource allocation to the individual loads.

Step 4: Amount of power flow at different branches is optimized to minimize system active power loss by using GA.

Step 5: The directions of power flow through different lines for the optimized result are compared with shortest path decided at step 3. The number of mismatches in power flow directions at the branches will decide the number of controllers required to be connected in the system to force the power to flow through the system according to the optimized flow path.

Step 6: If direction of power flow by GA is different than that of the shortest path between each source and load pair, then controller is required. A controller should be placed accordingly to redirect the power to flow through the optimized path.

Step 7: Number of controllers to be installed in the system is less than the number of mismatches in power flow direction which can be decided by careful observation of the power flow paths of Step 3 and Step 4.

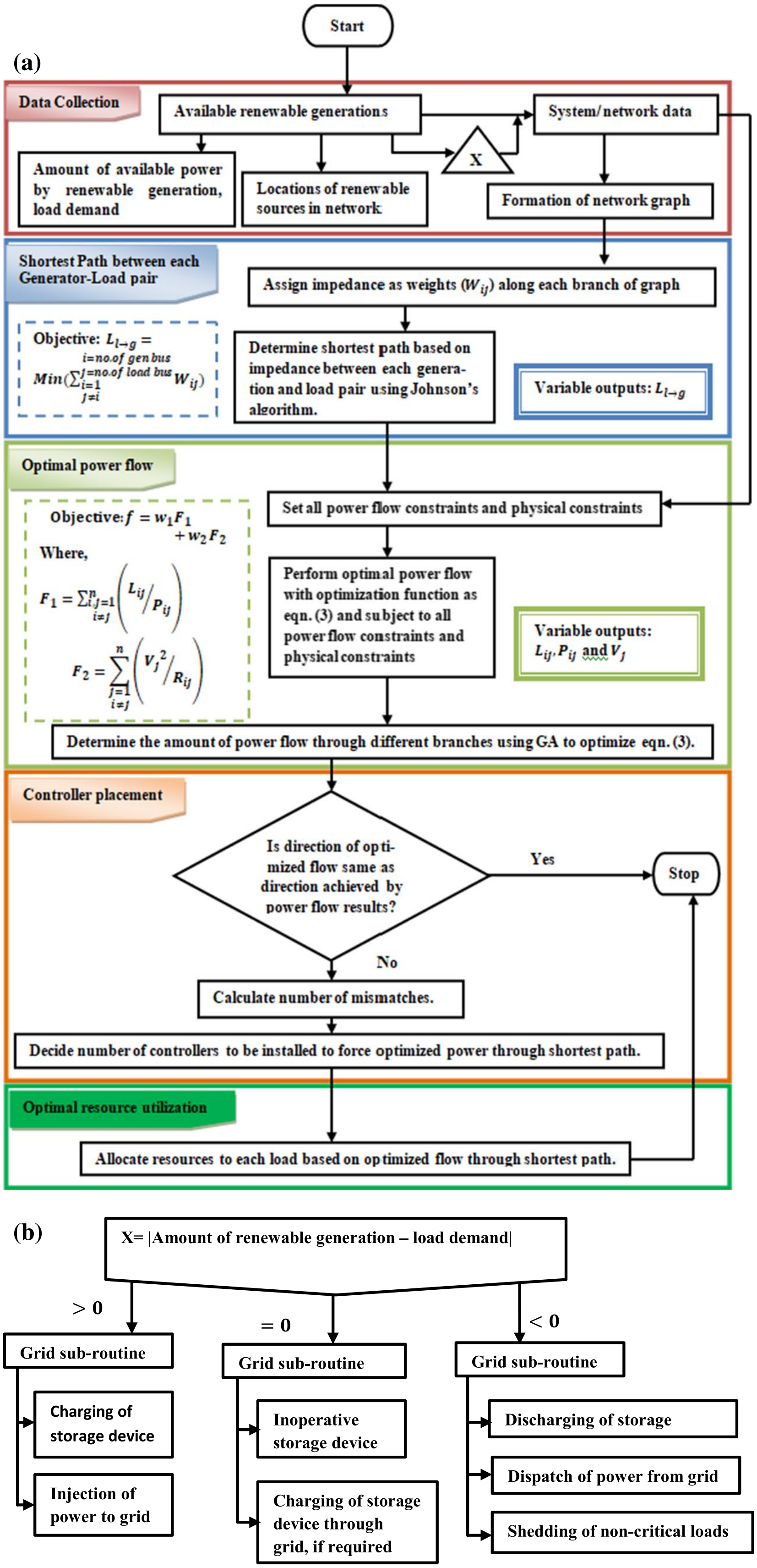
Step 8: Cost of controllers is compared with the cost associated with reduction of loss achieved by controller placement.

Step 9: Finally, the resource is allocated to individual load according to the power directions after controller placement.

The flowchart of the proposed algorithm is also shown as Fig. 1

Based on renewable generator and load demand, there can be three different functioning modes of microgrid which is shown in Fig. 1b. When the energy harvested from renewable resources is much higher than load demand, then excess energy supplied by renewable resources will be fed to the grid through the path decided by the controllers. Excess energy generated by renewable resources will be dispatched to grid through shortest possible path decided by controllers. If controller placed in shortest path between generator and load is not available to facilitate transfer of excess energy to grid, then storage device (battery with ultra-capacitor) will operate in charging mode. In case of standalone mode

Fig. 1 **a** Flowchart of the proposed algorithm. **b** Different modes of microgrid based on renewable generator and load demand



of microgrid also, maintenance of excess energy will be ensured by storage devices.

3 Results and Discussion

3.1 14-Bus System

In this paper, a modified IEEE 14-bus system is used as the microgrid like used in other works as well [42]. In this test system, node 2 is assumed to be connected with a wind farm of 40-MW rated capacity and node 3 has a concentrated solar plant of 60-MW rated capacity. A new branch is added between buses 1 and 3 in this modified system. This simple modification is added in the system structure to depict the complexity in the results. The microgrid is integrated with a conventional power plant (connected to grid) at bus 1 as a backup in case if solar and wind generation is not sufficient to meet load demands. Single-line diagram of the modified test system is shown in Fig. 2 with direction of power flow through the lines.

The test system data for the system are listed in Tables 3 and 4.

The proposed methodology is applied for modified IEEE 14-bus test system. The different convergence conditions of the proposed optimization technique in modified 14-bus system are summarized in Table 5, and Table 6 lists the results of line flow by power flow as well as the results of line flow and bus voltages using the proposed algorithm. Figure 3 compares the line flow achieved by the proposed method and power flow.

We know power flow through different lines of any system depends only on physical conditions of the network, i.e., the voltages at nodes and impedances of lines. Hence, power flow always does not follow shortest path between source and load. Shortest path between each pair of source and load is determined on the basis of impedance present in the path. Paths between source and load pairs are also determined by using direction of power flow from power flow analysis. In Table 7, shortest paths based on impedance value and power flow direction are listed. From the load flow analysis, it has been observed that power flow does not follow the shortest path based on impedance between each generator and load pair. So, for each generator and load pair shortest path based on impedance is compared with that of path of power flow from load flow analysis for deciding the number and position of controller. It is clear from Table 7 that path followed in power flow analysis and shortest path based on impedance is not the same in case of generator 3 to loads 5, 6, 11, 12 and 13. Table 8 presents the resource allocation for different generations to individual loads.

Figure 4 compares optimal value of active power loss for different weights (w_1 and w_2) in modified 14-bus system considered as microgrid.

From Fig. 4, it can be concluded that active power loss is minimum for weights $w_1 = 0.5$ and $w_2 = 0.5$ in 14-bus microgrid. Minimum system loss is 0.0138 MW for

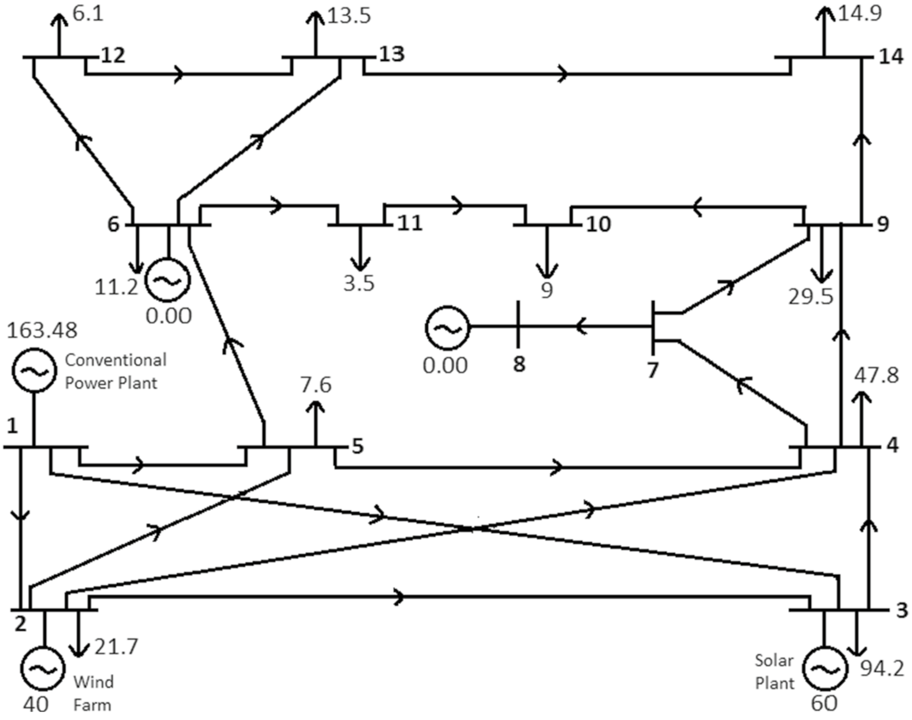


Fig. 2 Modified IEEE 14-bus test system

Table 3 Branch Data of Modified IEEE 14-Bus System

From bus	To bus	Reactance (in Ω)	Resistance (in Ω)	Impedance (in Ω)	Length (in p.u.)
1	2	0.01938	0.05917	0.0623	1.4094
1	5	0.05403	0.22304	0.2295	5.1950
1	3	0.00000	0.04211	0.0421	0.9527*
2	3	0.04699	0.19797	0.2035	4.6060
2	4	0.05811	0.17632	0.1856	4.2025
2	5	0.05695	0.17388	0.1830	4.1419
3	4	0.06701	0.17103	0.1837	4.1582
4	5	0.01335	0.04211	0.0442	1.0000
4	7	0.00000	0.20912	0.2091	4.7338
4	9	0.00000	0.55618	0.5562	12.5902
5	6	0.00000	0.25202	0.2520	5.7050
6	11	0.09498	0.19890	0.2204	4.9895
6	12	0.12291	0.25581	0.2838	6.4245
6	13	0.06615	0.13027	0.1461	3.3073
7	8	0.00000	0.17165	0.1762	3.9875
7	9	0.00000	0.11001	0.1100	2.4903
9	10	0.03181	0.08450	0.0903	2.0439
9	14	0.12711	0.27038	0.2988	6.7632
10	11	0.08205	0.19207	0.2089	4.7280
12	13	0.22092	0.19988	0.2979	6.7441
13	14	0.17093	0.34802	0.3877	8.7771

*Newly added line

Table 4 Bus Data of Modified IEEE 14-Bus System

Bus	Voltage		Generation		Load	
	Mag (p.u.)	Ang (p.u.)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1.060	0.000*	163.48	140.25	–	–
2	1.045	−1.654	40.00	23.69	21.70	12.70
3	1.010	−1.461	60.00	−136.31	94.20	19.00
4	1.017	−5.202	–	–	47.80	−3.90
5	1.020	−4.634	–	–	7.60	1.60
6	1.070	−9.773	0.00	12.84	11.20	7.50
7	1.062	−8.416	–	–	–	–
8	1.090	−8.416	0.00	17.47	–	–
9	1.057	−10.079	–	–	29.50	16.60
10	1.052	−10.310	–	–	9.00	5.80
11	1.057	−10.171	–	–	3.50	1.80
12	1.055	−10.599	–	–	6.10	1.60
13	1.051	−10.651	–	–	13.50	5.80
14	1.036	−11.327	–	–	14.90	5.00

Table 5 Convergence results in modified 14-bus system

Maximum number of iteration	7000
No. of iteration in which optimal result achieved	102
No. of evaluation of fitness function = number of solutions from a complete search on all combinations of the problem variables	20,600
Computational time	78.126 s

$(w_1 = 0.5, w_2 = 0.5)$ in 14-bus microgrid which is very less in comparison with other values of weights.

Controller Selection: From the results listed in Table 7, we see that the results of optimization violate power flow results in lines 4–5 and 10–11. That means, to force the power from generator to flow to load, we need to connect a controller between buses 2–3 and 10–11. Otherwise, physical properties of the system will not allow the flow of

Table 6 Line Flow and Bus Voltages of Modified IEEE 14-Bus System

From bus (i)	To bus (j)	Line flow (based on power flow analysis) $E_{ij} : i \to j$	Line flow (based on optimization) $E_{ij} : i \to j$			Bus	Voltage ($inp.u.$)		
			$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0.6$ $w_2 = 0.4$		$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0.6$ $w_2 = 0.4$
1	2	56.9900	59.8030	59.7716	59.2021	1	1.045	1.05	1.05
1	5	41.7700	44.3854	43.5259	44.5489	2	0.9693	0.9861	0.9949
1	3	64.8200	63.3367	63.1275	62.7204	3	1.0313	0.9710	0.9752
2	3	2.4500	4.8374	4.9054	4.5695	4	1.0213	0.9766	0.9626
2	4	38.8600	35.9309	36.9645	39.3567	5	1.0034	0.9700	1.0422
2	5	33.4000	38.7355	39.9572	39.4631	6	0.9881	0.9733	1.0034
3	4	32.9300	33.4381	34.6427	29.0832	7	1.0305	0.9727	0.9654
4	5	− 24.2700	24.5189	24.7784	19.9158	8	0.9974	0.9599	1.0092
4	7	29.6100	29.7483	29.4894	29.6454	9	1.0351	0.9628	0.9742
4	9	0.0000	18.6281	13.9093	19.6816	10	1.0210	0.9630	0.9746
5	6	16.9600	43.7656	44.5024	43.3991	11	1.0052	0.9597	0.9738
6	11	41.6400	8.6069	9.9604	9.8041	12	1.0033	0.9591	1.0018
6	12	5.8600	9.9056	4.9379	9.2728	13	1.0332	0.9565	0.9838
6	13	7.6000	19.6826	19.6103	18.4763	14	1.0147	0.9617	0.9748
7	8	16.9800	0.0000	0.0000	0.0000				
7	9	29.6100	28.2972	26.3618	28.4314				
9	10	6.7100	8.8511	6.6662	9.7838				
9	14	10.3600	2.8583	4.1993	3.3747				
10	11	− 2.3100	3.4342	4.3258	2.2432				
12	13	1.4300	4.7683	1.2468	1.5721				
13	14	4.7100	4.9464	2.4235	4.9789				

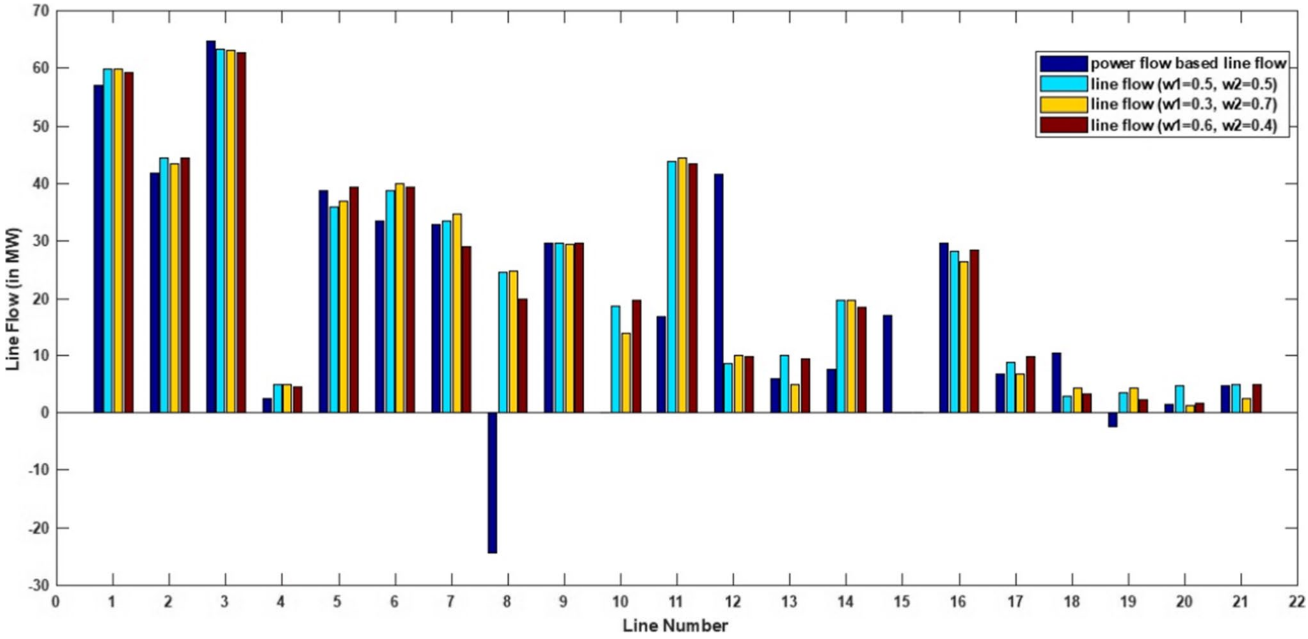


Fig. 3 Comparison of line flow in 14-bus microgrid

Table 7 Shortest Path Based on Impedance and Power Flow Analysis (14-bus system)

Gen	Load	Shortest path	Path based on power flow
1	2	1–2	1–2
1	3	1–3	1–3
1	4	1–3–4	1–3–4
1	5	1–5	1–5
1	6	1–5–6	1–5–6
1	9	1–3–4–7–9	1–3–4–7–9
1	10	1–3–4–7–9–10	1–3–4–7–9–10
1	11	1–5–6–11	1–5–6–11
1	12	1–5–6–12	1–5–6–12
1	13	1–5–6–13	1–5–6–13
1	14	1–3–4–7–9–14	1–3–4–7–9–14
2	2	2–2	2–2
2	3	2–3	2–3
2	4	2–4	2–4
2	5	2–5	2–5
2	6	2–5–6	2–5–6
2	9	2–4–7–9	2–4–7–9
2	10	2–4–7–9–10	2–4–7–9–10
2	11	2–5–6–11	2–5–6–11
2	12	2–5–6–12	2–5–6–12
2	13	2–5–6–13	2–5–6–13
2	14	2–4–7–9–14	2–4–7–9–14
3	2	3–2	NA
3	3	3–3	3–3
3	4	3–4	3–4
3	5	3–4–5	NA
3	6	3–4–5–6	NA
3	9	3–4–7–9	3–4–7–9
3	10	3–4–7–9–10	3–4–7–9–10
3	11	3–4–5–6–11	NA
3	12	3–4–5–6–12	NA
3	13	3–4–5–6–13	NA
3	14	3–4–7–9–14	3–4–7–9–14

Table 8 Resource Allocation for Modified IEEE 14-Bus System

	Gen 1	Gen 2	Gen 3
Load 2	0.0	21.7	0.0
Load 3	34.2	0.0	60
Load 4	29.5	18.3	0.0
Load 5	7.6	0.0	0.0
Load 6	11.2	0.0	0.0
Load 9	29.5	0.0	0.0
Load 10	9.0	0.0	0.0
Load 11	3.5	0.0	0.0
Load 12	6.1	0.0	0.0
Load 13	13.5	0.0	0.0
Load 14	14.9	0.0	0.0

power in the optimized path. By placing controller, flow of power can be forced to follow the shortest path. It is clear from Table 8 that direction of power flow is different in two branches. Hence, two controllers are required to maintain the similar flow obtained by optimization. Additional cost of controllers and cost associated with losses are compared to find out the optimal number of controllers required to maintain desired power flow direction. But, if a controller is placed in lines 4–5 only, then between every pair of generator and load, direction of power flow will be through the shortest path. This will lead to an improved cost. Table 8 describes the amount of generation supplied to different loads that is final resource allocation through shortest path.

Controller Cost Estimation: If optimized amount of line flow is dispatched from generation to demand through shortest path, then losses will be minimized. Controllers are required at appropriate position for dispatching power through shortest path as the physical properties of the line parameters will force the power flow through a different path.

Let us assume cost of installing a controller be C_{cont}, cost of loss initially without controller be C^{i}_{loss} and cost of loss after connecting controller be C^{n}_{loss}.

$$\text{Total cost}_{\text{old}} = \sum_{t=1}^{T} C^{i}_{\text{loss}}$$

$$\text{Total cost}_{\text{new}} = \sum_{t=1}^{T} C^{n}_{\text{loss}} + N * C_{\text{cont}} * \frac{1}{LE}$$

where $T = 24$(number of hours in a day); N is the number of controller to be installed; LE is the life expectancy of the controller in days.

By comparing total cost_{new} and total cost_{old}, controller placement will be decided. If the difference between $\sum C^{i}_{\text{loss}}$ and $\sum C^{n}_{\text{loss}}$ is significant, then installation of controller is opted depending on cost of controller. The cost calculation has to consider the life of the controller installed and has to compare the total amount of loss reduction cost achieved by installation of this controller over the life time.

3.2 30-Bus System

Modified IEEE 30-bus system is considered an interconnected microgrid. In this test system, nodes 23 and 13 are assumed to be connected with a wind farm of 20-MW and 40-MW rated capacity, respectively. Nodes 2, 22 and 27 have a concentrated solar plant of 65-MW, 30-MW and 30-MW rated capacity, respectively. The proposed technique is applied to modified 30-bus system, and different convergence results are given in Table 9. Table 10 lists the results of line flow by power flow as well as the results of

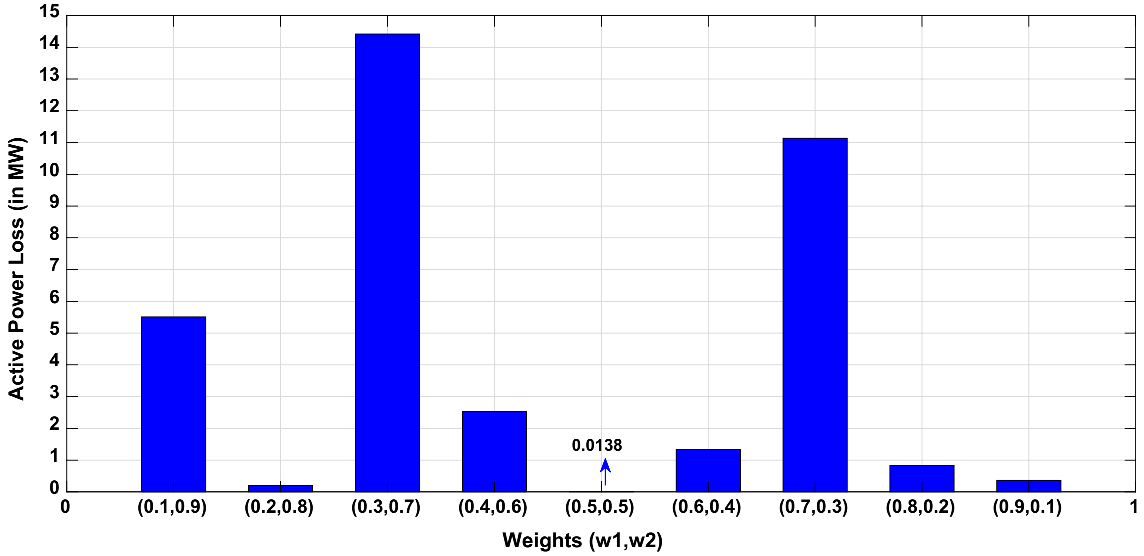


Fig. 4 Comparison of active power loss in 14-bus microgrid for different weights (w_1, w_2)

Table 9 Convergence results in modified 30-bus system

Maximum number of iteration	14,200
No. of iteration in which optimal result achieved	244
No. of evaluation of fitness function = number of solutions from a complete search on all combinations of the problem variables	49,000
Computational time	79.421 s

line flow and bus voltages using the proposed algorithm for 30-bus microgrid. Figure 5 shows the comparison of line flow achieved by GA and power flow. Some of power flow directions for the most optimized condition of microgrid considered in Fig. 5 are presented in Table 11. The results of resource allocation in 30-bus microgrid system are presented in Table 12. Figure 6 compares optimal value of active power loss for different weights (w_1 and w_2) in modified 30-bus system considered as microgrid.

From Fig. 4, it can be concluded that active power loss is minimum for weights $w_1 = 0.5$ and $w_2 = 0.5$ in 14-bus microgrid. Minimum system loss is 7.8570e − 06 MW for ($w_1 = 0.5, w_2 = 0.5$) in 30-bus microgrid which is very less in comparison with other values of weights.

If new loads/DG sources are added/removed to the existing microgrid network, then power flow pattern changes which consequently changes the bus voltages and total system loss. But, factors involved in the objective function (shortest path between each generator and load pair and load-carrying capability of lines) will not be influenced by change in generation–load in the system. The shortest path between each generator and load pair is decided by impedance of the lines, and load-carrying capability of lines is also predefined according to their design parameters. These two factors involved with objective function of optimal resource allocation will be affected when microgrid network will be re-configured by adding/removing lines. Hence, the proposed method for optimal resource allocation can be easily applied to microgrid with updated generation–load at a particular instant as only the constraints will change [Eqs. (4) to (12)] due to generation–load modification.

3.3 Benefits and Limitations of the Proposed Technique

The proposed planning framework is a multi-objective optimization technique solved by weighted-sum approach which is very useful in practical applications. It maximizes line flow and minimizes system loss by satisfying all network constraints (physical constraints and operational constraints) simultaneously. It suggests installation of controllers in network so that power from generation to load demand can follow shortest path leading to loss minimization. The proposed optimization technique is implemented in MATLAB R2017a on a computer with Intel Core i3-2310 M CPU, 4-GB RAM, 64-bit operating system. Stopping criterion for GA is selected as: maximum number of iterations, relative change in value of objective function and number of infeasible solutions. The randomly generated solution is likely to be proved another infeasible solution; therefore, infeasible solutions are replaced by existing solutions in the proposed method. This proves the necessity and superiority of heuristic approach in solving these multi-objective problems.

Table 10 Line Flow and Bus Voltages of Modified IEEE 30-Bus System

From bus (i)	To bus (j)	Line flow (based on power flow analysis) $E_{ij} : i \to j$	Line flow (based on optimization) $E_{ij} : i \to j$			Bus	Voltage ($inp.u.$)		
			$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0.6$ $w_2 = 0.4$		$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0.6$ $w_2 = 0.4$
1	2	52.73	49.9666	49.9949	49.9956	1	0.9871	0.9572	0.9600
1	3	35.19	39.9217	39.6922	39.9628	2	0.9909	0.9876	0.9531
2	4	27.95	29.9837	29.0662	29.9971	3	0.9922	0.9565	0.9599
3	4	32.16	34.9408	34.3733	34.9410	4	1.0263	1.0184	0.9563
2	5	26.50	29.9877	29.9997	29.9917	5	1.0437	0.9562	0.9530
2	6	36.93	39.9908	39.9987	39.6655	6	0.9803	0.9601	0.9577
4	6	46.66	49.4473	48.7892	49.8616	7	1.0013	0.9584	0.9815
5	7	16.13	19.9992	19.7009	19.9958	8	1.0415	0.9652	0.9652
6	7	6.85	9.9808	9.9594	6.5614	9	1.0058	0.9582	0.9546
6	8	28.02	−29.2378	−29.7646	−29.7557	10	0.9916	0.9555	0.9561
6	9	19.46	−19.7124	−19.9607	−19.9847	11	1.0095	0.9567	0.9532
6	10	7.24	9.5140	9.4574	9.9577	12	0.9667	0.9562	0.9548
9	11	10.00	14.9893	14.9044	14.9095	13	0.9931	0.9594	0.9600
9	10	−0.54	4.8199	4.9528	−0.0000	14	0.9925	0.9547	0.9580
4	12	5.25	−9.9047	−9.9056	−9.9661	15	0.9931	0.9581	0.9634
12	13	−37.00	39.9486	39.9007	39.8003	16	0.9845	0.9951	0.9647
12	14	6.17	9.9922	9.9389	9.9843	17	1.0058	0.9677	0.9641
12	15	12.76	14.9303	14.7436	14.9603	18	1.0118	0.9617	0.9773
12	16	12.12	14.9964	14.9997	14.9848	19	0.9834	0.9634	0.9636
14	15	−0.07	4.9367	4.9299	4.6995	20	1.0078	0.9645	0.9562
16	17	8.48	9.9419	9.9987	9.9867	21	1.0146	0.9591	0.9557
15	18	10.52	14.8470	14.9787	14.8146	22	0.9896	0.9601	0.9541
18	19	7.19	9.8992	9.8475	8.2962	23	0.9786	0.9572	0.9515
19	20	−2.34	4.9694	4.9056	4.9961	24	0.9910	0.9568	0.9588
10	20	4.59	4.9924	4.9962	4.9531	25	0.9816	0.9668	0.9525
10	17	0.61	1.7965	1.9790	1.9972	26	1.0139	0.9623	0.9536
10	21	−1.16	−1.9141	−1.9868	−1.9450	27	1.0109	0.9607	0.9543
10	22	−3.14	4.9977	4.9993	5.0000	28	0.9701	0.9587	0.9574
21	22	−18.73	19.9992	19.9950	19.9999	29	0.9954	0.9608	0.9751
15	23	−6.15	−9.8678	−9.9575	−9.9849	30	0.9813	0.9606	0.9647
22	24	−0.47	−0.0000	1.9946	−0.0000				
23	24	9.76	9.9837	9.9467	9.7594				
24	25	0.39	−0.0000	−0.0000	−0.7959				
25	26	3.55	4.7614	4.9648	4.9988				
25	27	−13.16	−19.9331	−19.9539	−19.8199				
28	27	−0.26	−0.0000	−1.9508	−1.9314				
27	29	6.17	9.9692	−0.0000	9.9951				
27	30	7.12	9.9216	9.8255	9.9899				
29	30	3.68	4.9987	4.9518	5.0000				
8	28	−2.13	3.3323	4.9373	4.9970				
6	28	11.92	19.9886	19.9836	19.9234				

The proposed planning framework is solved by GA which converges with feasible solutions in less than 80 s for two different test systems. For 14-bus microgrid system, computational time is 78.126 s, while for 30-bus microgrid system it is 79.421 s. For larger systems, computational time will be higher. So, it cannot be used for real-time application where result is needed within a minute, but it can be useful for any other application like

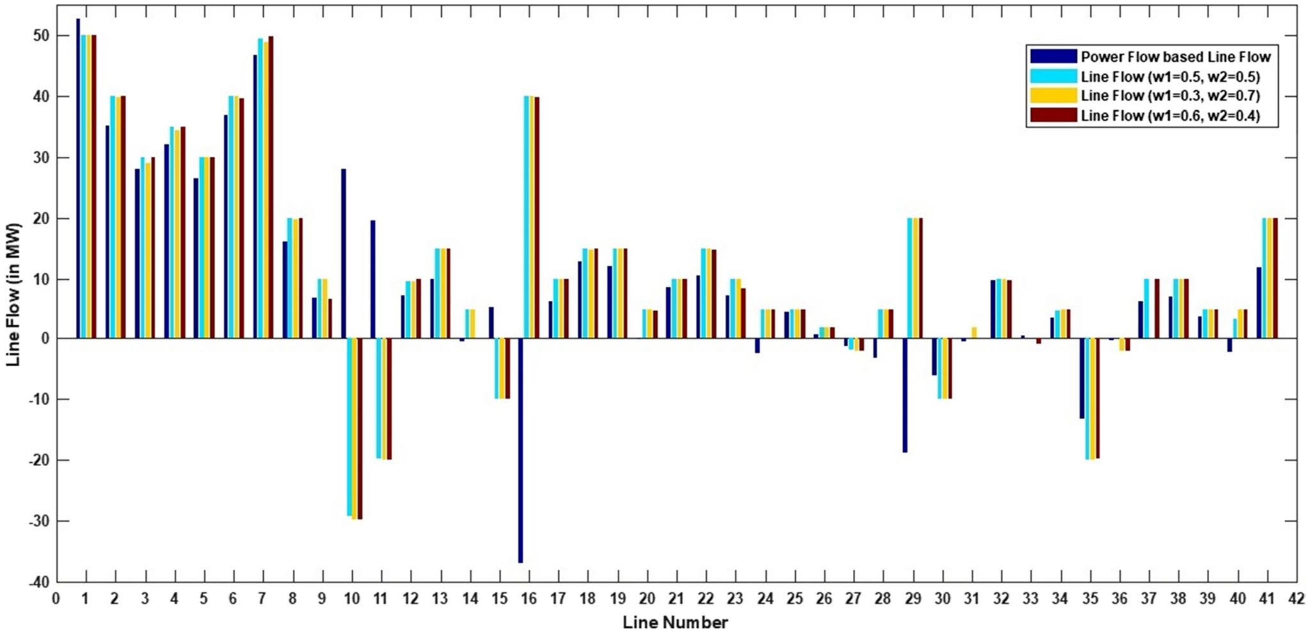


Fig. 5 Comparison of line flow in 30-bus microgrid

short-term (15 min ahead), midterm or long-term planning operation of a microgrid.

3.4 Comparison of the Proposed Method by Different Optimization Techniques

The objective for the proposed planning framework is optimized by GA and FMINCON for 14-bus microgrid system and 30-bus microgrid system. 'SQP' algorithm is used in FMINCON, and stopping criteria are selected as: maximum iterations: 15,000, maximum function evaluations: 10,000, finite difference step size = 1e−2, function tolerance = 1e−4, constraint tolerance = 1e−3, step tolerance = 1e−2. The computational time of FMINCON is very less in comparison with GA, but FMINCON converges with local optimal solutions. The computational time by FMINCON is 2.0766 s in comparison with 78.126 s by GA in case of 14-bus system. For 30-bus system, computational time is 12.469 s with FMINCON while 79.421 s with GA.

The results are compared for line flow and bus voltage by GA and FMINCON in Table 13 and Table 14. Comparisons for different values of weights are shown in Table 13 for 14-bus microgrid system, and the same for 30-bus microgrid system is given in Table 14.

From the results of comparison presented in Tables 13 and 14, it can be observed that results optimal value attained by GA is comparable with that by power flow analysis. From Table 13, it can be examined that voltage at bus 1 (0.9437*pu*) is below the minimum specified limit (0.95*pu*) when $w_1 = 0.5$ and $w_2 = 0.5$ by FMINCON (in 14-bus microgrid system). So, this is not suitable for optimal planning framework. In case of 30-bus microgrid system (Table 14), line flow achieved by FMINCON is not similar to that by power flow analysis, while line flow achieved by GA is showing the similar pattern with power flow results with change in direction at few locations. It is presented in Table 14 that bus voltages have attained minimum specified limits that means system is always operating at its lower limit which is also inappropriate operating condition. Also, comparing Tables 6 and 10 with Tables 13 and 14 we see that the power flow direction corresponding to optimal solution by FMINCON for different lines widely varies from the power flow direction achieved from the power flow result which is shown in the third column of Table 6 and Table 10. Hence, a large number of controllers will be required to maintain this optimized power flow values achieved by FMINCON, which is not a feasible solution. This analysis explains the advantages of GA for optimizing the proposed objectives in planning framework. The optimization of the proposed objectives by GA is computationally exhaustive, but it may be helpful for planning of microgrid where accuracy has higher priority than computational time.

4 Application for Radial System

The proposed method when applied to any radial system results in less number of steps and faster result as the only available path between load and generator pair is the shortest path in most of the cases.

Table 11 Shortest Path Based on Impedance and Power Flow Analysis (30-bus system)

Gen	Load	Shortest Path	Path based on power flow
1	2	1–2	1–2
1	3	1–3	1–3
1	4	1–3–4	1–3–4
1	7	1–2–6–7	1–2–6–7
1	8	1–2–6–8	1–2–6–8
1	10	1–2–6–9–10	1–2–6–9–10
1	12	1–3–4–12	NA
1	14	1–3–4–12–14	NA
1	15	1–3–4–12–15	NA
1	16	1–3–4–12–16	NA
1	17	1–2–6–9–10–17	1–2–6–9–10–17
1	18	1–3–4–12–15–18	NA
1	19	1–2–6–9–10–20–19	1–2–6–9–10–20–19
1	20	1–2–6–9–10–20	1–2–6–9–10–20
1	21	1–2–6–9–10–21	NA
1	23	1–3–4–12–15–23	NA
1	24	1–2–6–9–10–21–22–24	NA
1	26	1–2–6–28–27–25–26	NA
1	29	1–2–6–28–27–29	NA
1	30	1–2–6–28–27–30	NA
13	2	13–12–4–2	NA
13	3	13–12–4–3	NA
13	4	13–12–4	13–12–4
13	7	13–12–4–6–7	13–12–4–6–7
13	8	13–12–4–6–8	13–12–4–6–8
13	10	13–12–16–17–10	13–12–4–6–9–10
13	12	13–12	13–12
13	14	13–12–14	13–12–14
13	15	13–12–15	13–12–15
13	16	13–12–16	13–12–16
13	17	13–12–16–17	13–12–16–17
13	18	13–12–15–18	13–12–15–18
13	19	13–12–15–18–19	13–12–15–18–19
13	20	13–12–15–18–19–20	13–12–4–6–9–10–20
13	21	13–12–16–17–10–21	NA
13	23	13–12–15–23	NA
13	24	13–12–15–23–24	NA
13	26	13–12–4–6–28–27–25–26	NA
13	29	13–12–4–6–28–27–29	NA
13	30	13–12–4–6–28–27–30	NA

Consider a radial topology-based microgrid network as shown in Fig. 7 in which concentrated solar power plant of 90-MW rated capacity is connected at bus 5 and wind farm of 60-MW rated capacity is integrated at bus 9. The microgrid is connected to conventional grid at bus 1.

The direction of power flow is also shown in Fig. 7. There is only one path between each generator and load pair which is the shortest path. If power flow does not follow the shortest path, then placement of controller may be decided to minimize the distance which will lead to reduction of loss. If power flows through the shortest path between each generator and load pair, then suitable resource will be allocated to each load by optimizing the line capacity.

5 Future Scope

The proposed method for optimal resource allocation in interconnected microgrid employs GA to minimize the power loss in the system by identifying the shortest path while maximizing the use of lines near their load-carrying capability. The multi-objective function used for optimal resource allocation is dependent on (a) shortest path between each generator and load pair, (b) load-carrying capability of existing lines and (c) voltages at buses present in the network. The proposed method also suggests the placement of controllers by comparing the cost of controllers and cost associated with reduction in loss.

- If re-configuration of microgrid network is considered due to connection or removal of generation or load, that is, the change in topology of the microgrid is considered over time, and then resource allocation becomes time dependent. The term representing shortest distance between generator and load pair in the objective function [Eq. (3)] and constraints [Eq. (4) to Eq. (12)] will become a function of time which may be considered as future work. In this case, the number of constraints will increase/decrease depending upon number of lines added/removed.
- The proposed optimal resource allocation method implements GA to solve the optimization problem whose computational efficiency may decrease for larger system. Therefore, in future, other optimization techniques may be applied to improve computational efficiency or computational time.
- In this paper, number and location of controller is suggested, so the design and placement of appropriate controller can be future work.

6 Conclusion

This paper presents an optimization-based methodology to allocate suitable source to all individual loads present in interconnected microgrid network. GA is used to minimize the power loss in the system by identifying the shortest path while maximizing the use of lines near

Table 12 Resource Allocation for Modified IEEE 30-Bus System

	Gen 1	Gen 2	Gen 13	Gen 22	Gen 23	Gen 27
Load 2	0.0	21.7	0.0	0.0	0.0	0.0
Load 3	2.4	0.0	0.0	0.0	0.0	0.0
Load 4	0.0	7.6	0.0	0.0	0.0	0.0
Load 5	0.0	10	0.0	0.0	0.0	0.0
Load 6	0.0	9.0	0.0	0.0	0.0	0.0
Load 7	10.2	12.6	0.0	0.0	0.0	0.0
Load 8	30	0.0	0.0	0.0	0.0	0.0
Load 9	10	0.0	0.0	0.0	0.0	0.0
Load 10	3.9	0.0	0.0	1.9	0.0	0.0
Load 11	0.0	0.0	10	0.0	0.0	0.0
Load 12	0.0	0.0	11.2	0.0	0.0	0.0
Load 14	0.0	0.0	6.2	0.0	0.0	0.0
Load 15	0.0	0.0	0.0	0.0	8.2	0.0
Load 16	0.0	0.0	3.5	0.0	0.0	0.0
Load 17	2.9	0.0	6.1	0.0	0.0	0.0
Load 18	0.0	0.0	0.0	0.0	3.2	0.0
Load 19	4.9	0.0	0.0	0.0	4.6	0.0
Load 20	0.0	0.0	0.0	2.2	0.0	0.0
Load 21	0.0	0.0	0.0	17.5	0.0	0.0
Load 23	0.0	0.0	0.0	0.0	3.2	0.0
Load 24	0.0	0.0	0.0	0.0	0.0	8.7
Load 25	0.0	0.0	0.0	0.0	0.0	10
Load 26	3.5	0.0	0.0	0.0	0.0	0.0
Load 28	10	0.0	0.0	0.0	0.0	0.0
Load 29	0.0	0.0	0.0	0.0	0.0	2.4
Load 30	4.8	0.0	0.0	0.0	0.0	5.8

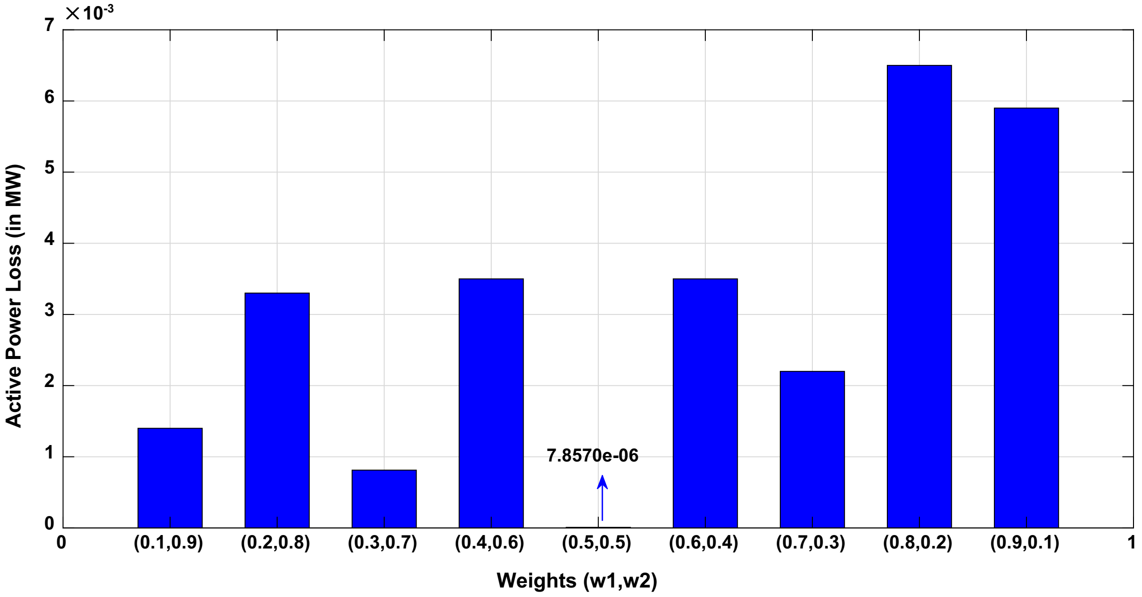


Fig. 6 Comparison of active power loss in 30-bus microgrid for different weights (w_1, w_2)

Table 13 Comparison of GA and FMINCON in 14-bus microgrid system

From bus (i)	To bus (j)	Line flow (based on optimization) $E_{ij} : i \rightarrow j$						Bus	Voltage ($inp.u.$)					
		$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$			$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$	
		GA	FMINCON	GA	FMINCON	GA	FMINCON		GA	FMINCON	GA	FMINCON	GA	FMINCON
1	2	59.8030	−5.1294	59.7716	−5.2847	59.2021	−21.6938	1	1.045	0.9437	1.05	1.0500	1.05	0.9500
1	5	44.3854	−0.2750	43.5259	−0.1254	44.5489	−13.8009	2	0.9693	0.9759	0.9861	1.0500	0.9949	0.9500
1	3	63.3367	−31.0537	63.1275	−31.1506	62.7204	−41.2998	3	1.0313	0.9948	0.9710	1.0500	0.9752	0.9500
2	3	4.8374	4.5292	4.9054	5.0000	4.5695	4.1125	4	1.0213	0.9500	0.9766	0.9500	0.9626	0.9500
2	4	35.9309	−22.1052	36.9645	−22.1450	39.3567	−27.5079	5	1.0034	0.9500	0.9700	0.9817	1.0422	0.9500
2	5	38.7355	4.6734	39.9572	5.7150	39.4631	−8.7962	6	0.9881	0.9500	0.9733	0.9516	1.0034	0.9500
3	4	33.4381	−17.0976	34.6427	−17.1294	29.0832	−22.5057	7	1.0305	0.9500	0.9727	0.9500	0.9654	0.9500
4	5	24.5189	20.8254	24.7784	20.1457	19.9158	6.6119	8	0.9974	0.9500	0.9599	0.9500	1.0092	0.9500
4	7	29.7483	9.5117	29.4894	11.1856	29.6454	−2.4373	9	1.0351	0.9500	0.9628	0.9500	0.9742	0.9500
4	9	18.6281	−6.4437	13.9093	−6.3174	19.6816	−10.5752	10	1.0210	0.9500	0.9630	0.9500	0.9746	0.9500
5	6	43.7656	−0.0053	44.5024	−0.0057	43.3991	−13.9506	11	1.0052	0.9500	0.9597	0.9500	0.9738	0.9500
6	11	8.6069	−2.9450	9.9604	−2.2924	9.8041	−5.0005	12	1.0033	0.9500	0.9591	0.9500	1.0018	0.9500
6	12	9.9056	−4.7647	4.9379	−4.4052	9.2728	−6.4163	13	1.0332	0.9500	0.9565	0.9500	0.9838	0.9500
6	13	19.6826	−12.9061	19.6103	−12.3536	18.4763	−15.4969	14	1.0147	0.9500	0.9617	0.9500	0.9748	0.9500
7	8	0.0000	2.7284	0.0000	5.0000	0.0000	−0.0047							
7	9	28.2972	−16.5185	26.3618	−16.4980	28.4314	−20.5927							
9	10	8.8511	−8.6359	6.6662	−8.4870	9.7838	−9.0808							
9	14	2.8583	−14.6308	4.1993	−14.5132	3.3747	−16.2791							
10	11	3.4342	3.6998	4.3258	5.0000	2.2432	3.2613							
12	13	4.7683	2.1086	1.2468	0.9738	1.5721	1.0631							
13	14	4.9464	0.9917	2.4235	1.0500	4.9789	0.5130							

Table 14 Comparison of GA and FMINCON in 30-bus microgrid system

From bus (i)	To bus (j)	Line flow (based on optimization) $E_{ij} : i \to j$						Bus	Voltage ($inp.u.$)					
		$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$			$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$	
		GA	FMINCON	GA	FMINCON	GA	FMINCON		GA	FMINCON	GA	FMINCON	GA	FMINCON
1	2	49.9666	44.7664	49.9949	39.2904	49.9956	49.3334	1	1.045	0.95	0.9572	0.95	0.9600	0.95
1	3	39.9217	14.8447	39.6922	−2.3194	39.9628	6.6007	2	0.9693	0.95	0.9876	0.95	0.9531	0.95
2	4	29.9837	18.5947	29.0662	−1.2393	29.9971	8.7913	3	1.0313	0.95	0.9565	0.95	0.9599	0.95
3	4	34.9408	7.1937	34.3733	−6.2272	34.9410	−0.3684	4	1.0213	0.95	1.0184	0.95	0.9563	0.95
2	5	29.9877	−4.1964	29.9997	−9.9485	29.9917	−5.8602	5	1.0034	0.95	0.9562	0.95	0.9530	0.95
2	6	39.9908	32.6994	39.9987	0.5758	39.6655	30.0470	6	0.9881	0.95	0.9601	0.95	0.9577	0.95
4	6	49.4473	2.1117	48.7892	−9.3964	49.8616	−1.2636	7	1.0305	0.95	0.9584	0.95	0.9815	0.95
5	7	19.9992	−15.3410	19.7009	−16.3943	19.9958	−15.6596	8	0.9974	0.95	0.9652	0.95	0.9652	0.95
6	7	9.9808	−4.9826	9.9594	−6.3871	6.5614	−5.5771	9	1.0351	0.95	0.9582	0.95	0.9546	0.95
6	8	−29.2378	−29.9888	−29.7646	−29.9994	−29.7557	−29.9967	10	1.0210	0.95	0.9555	0.95	0.9561	0.95
6	9	−19.7124	−19.8710	−19.9607	−19.9929	−19.9847	−19.9617	11	1.0052	0.95	0.9567	0.95	0.9532	0.95
6	10	9.5140	−0.0006	9.4574	−5.3795	9.9577	−3.6582	12	1.0033	0.95	0.9562	0.95	0.9548	0.95
9	11	14.9893	−8.2134	14.9044	−9.9871	14.9095	−8.9017	13	1.0332	0.95	0.9594	0.95	0.9600	0.95
9	10	4.8199	4.9780	4.9528	−0.3978	−0.0000	5.0000	14	1.0147	0.95	0.9547	0.95	0.9580	0.95
4	12	−9.9047	−9.3551	−9.9056	−9.9646	−9.9661	−9.8089	15	0.9931	0.95	0.9581	0.95	0.9634	0.95
12	13	39.9486	−36.1751	39.9007	−36.9923	39.8003	−36.3878	16	0.9845	0.95	0.9951	0.95	0.9647	0.95
12	14	9.9922	−3.5943	9.9389	−6.1900	9.9843	−5.1280	17	1.0058	0.95	0.9677	0.95	0.9641	0.95
12	15	14.9303	−11.7945	14.7436	−12.5699	14.9603	−12.1396	18	1.0118	0.95	0.9617	0.95	0.9773	0.95
12	16	14.9964	5.4261	14.9997	−3.4700	14.9848	−0.2514	19	0.9834	0.95	0.9634	0.95	0.9636	0.95
14	15	4.9367	2.1500	4.9299	−2.4160	4.6995	−0.0012	20	1.0078	0.95	0.9645	0.95	0.9562	0.95
16	17	9.9419	−7.7975	9.9987	−8.6272	9.9867	−8.4035	21	1.0146	0.95	0.9591	0.95	0.9557	0.95
15	18	14.8470	7.3988	14.9787	−3.1691	14.8146	0.7291	22	0.9896	0.95	0.9601	0.95	0.9541	0.95
18	19	9.8992	−9.0288	9.8475	−9.4987	8.2962	−9.3357	23	0.9786	0.95	0.9572	0.95	0.9515	0.95
19	20	4.9694	2.9244	4.9056	−1.1300	4.9961	1.3336	24	0.9910	0.95	0.9568	0.95	0.9588	0.95
10	20	4.9924	4.7148	4.9962	−1.0472	4.9531	5.0000	25	0.9816	0.95	0.9668	0.95	0.9525	0.95
10	17	1.7965	2.0000	1.9790	−0.3647	1.9972	2.0000	26	1.0139	0.95	0.9623	0.95	0.9536	0.95
10	21	−1.9141	0.5776	−1.9868	−1.7407	−1.9450	−0.2911	27	1.0109	0.95	0.9607	0.95	0.9543	0.95
10	22	4.9977	5.0000	4.9993	5.0000	5.0000	5.0000	28	0.9701	0.95	0.9587	0.95	0.9574	0.95
21	22	19.9992	18.3443	19.9950	16.5965	19.9999	19.7882	29	0.9954	0.95	0.9608	0.95	0.9751	0.95
15	23	−9.8678	−9.4462	−9.9575	−9.9696	−9.9849	−9.8358	30	0.9813	0.95	0.9606	0.95	0.9647	0.95

Table 14 (continued)

From bus (i)	To bus (j)	Line flow (based on optimization) $E_{ij} : i \to j$						Bus	Voltage ($inp.u.$)					
		$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$			$w_1 = 0.5$ $w_2 = 0.5$		$w_1 = 0.3$ $w_2 = 0.7$		$w_1 = 0.6$ $w_2 = 0.4$	
		GA	FMINCON	GA	FMINCON	GA	FMINCON		GA	FMINCON	GA	FMINCON	GA	FMINCON
22	24	−0.0000	−0.0000	1.9946	2.0000	−0.0000	2.0000							
23	24	9.9837	−7.8397	9.9467	−8.6927	9.7594	−8.7024							
24	25	−0.0000	2.0000	−0.0000	−0.0000	−0.7959	2.0000							
25	26	4.7614	1.2644	4.9648	−0.7047	4.9988	−1.7441							
25	27	−19.9331	−19.8543	−19.9539	−19.9919	−19.8199	−19.9567							
28	27	−0.0000	−0.0000	−1.9508	2.0000	−1.9314	2.0000							
27	29	9.9692	5.4916	−0.0000	−2.3785	9.9951	1.9345							
27	30	9.9216	−5.1193	9.8255	−7.8865	9.9899	−7.1482							
29	30	4.9987	2.2018	4.9518	−2.7003	5.0000	0.2251							
8	28	3.3323	4.9792	4.9373	2.5602	4.9970	4.9706							
6	28	19.9886	−10.5244	19.9836	−12.5363	19.9234	−11.0972							

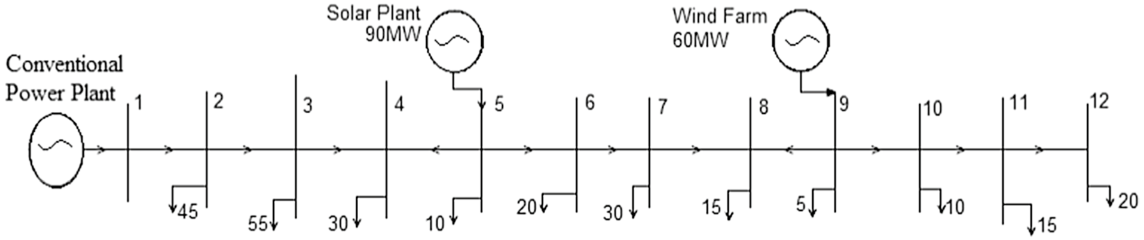


Fig. 7 12-Bus radial system

their load-carrying capability; this is achieved by using an objective function that depends on distance. A source is allocated to every load present in the network which corresponds to shortest path. To make the achieved optimum result applicable to the system in reality, the system physical properties need to be analyzed to check whether power can be forced through the system according to the optimal path. To accomplish this, the optimum path and power flow directions are compared to decide on number of controllers and their locations. Number of controllers that finally will be installed is decided by comparing the cost of controllers and the cost associated with reduction in loss. Hence, the local microgrid operator will have the flexibility to choose between cost reductions in terms of power loss reduction by introducing controllers which again increases cost. The method is applicable for any type of microgrid configuration whether it is interconnected or radial topology. The proposed method will become computationally exhaustive for real-time applications, but it can be useful in planning of microgrid energy management system.

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