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MULTIOBJECTIVE LOCATING AND SIZING OF MULTIPLE DISTRIBUTED ENERGY RESOURCES VIA SHUFFLED FROG LEAPING ALGORITHM

J. Olamaei [1]   M.M. Khademi [1,2]

1. Department of Electrical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
j_olamaei@azad.ac.ir, khademi366@gmail.com
2. Hormozgan Electric Power Distribution Company, Hormozgan, Iran

Abstract- Several benefits can be gained from implementation of Distributed Energy Resources (DERs) in distributed systems. This paper proposes the application of Shuffled Frog Leaping Algorithm to optimally determination the location and size of multiple DERs considering a multi-objective benchmark. Several objectives including loss minimization, reduction in power purchased from the network and upgrade investment deferral are considered as advantages of DER implementation in this study. Moreover, the impact of these resources on voltage profile of the network is investigated. The cost of installation of DERs is also considered to compare the benefits versus the costs of DER application. The proposed method is carried out on the IEEE 30-bus radial standard distribution test system. The obtained results are presented in detail to show the benefits of installation of DER units in the distribution network. Results also demonstrate the effectiveness of the proposed approach in finding the best location and optimal size of multiple DR units.

Keywords: Distributed Generation, Distributed Energy Resources, Shuffled Frog Leaping Algorithm (SFLA), Loss Reduction, Voltage Profile Improvement.

I. INTRODUCTION

Distributed Energy Resources (DERs) including Distributed Generation (DG) and energy storage devices has been given a great deal of attention in the last decade, especially under the new power systems known as smart grids. DG is defined as generation plants that are connected to distribution system has been the subject of many research studies for many years. DER units have many impacts on operation as well as planning of distribution systems.

Installation without thorough and meticulous consideration may cause some troubles in distribution systems. Size, location and method of utilization are three important factors that determine the positive or negative impacts of these units on the network [1, 2]. Therefore, evaluating the effect of DERs on distribution system and determining their optimum size and location are essential.

Finding the optimal location and size of DER units is an arduous job because of the combinatorial and complicated nature of this problem. Many benefits can be gained by DER implementation, namely, emission reduction [3], flexibility of investment for future planning of distribution system [4] and investment deferral [5, 6] to meet the load growth, loss reduction [7], and reliability improvement.

Moreover, voltage profile improvement is also a key factor in siting and sizing of DERs [8]. However, the most important benchmarks in the distribution network has been and will be energy loss that is widely used to evaluate the performance of the distribution network. Being a very difficult and complicated optimization problem, DER locating attracted many researchers and different approached have been applied to solved this combinatorial problem. Reference [9] proposed the use of analytical approaches both for radial and meshed topologies of distribution systems. However, in the above study, the optimal size of DG is not taken into account and so the optimal size of units is not determined.

The main drawback of classic mathematical approaches is that they could not be easily modified to accommodate the model of some features of power systems. As a result, the application of heuristic approaches have been proposed in the last decades. Many heuristic approaches have been applied, namely, Genetic Algorithm (GA) and Hereford Ranch optimization algorithm [10], Tabu search [11] and Fuzzy-GA approach in [12], to integrate DER units in the distribution system with the objective of loss minimization.

Moreover, other heuristic optimization methods like Particle Swarm Optimization (PSO) [13] for multiple DG placement in order to minimize the system loss, a combination of Tabu Search and Simulated Annealing and GA [14-15] to investigate the impact of DER units on loss reduction and determination of optimal size of these units, have been applied for solving this problem. However, considering only one objective for DER implementation might render solutions that are sub-optimum and might ever worsen the network characteristic from other aspects, i.e. voltage profile and reliability.

Although, quantifying all benefits of DER is not easy and different studied in this regard. Reference [16] presented a set of indices to quantify some of the technical benefits of DER application. In [17] a cost/worth analysis is proposed for DER locating considering reliability indices and loss reduction. A Strength Pareto Evolutionary Algorithm is used in [18] to optimally determine the location and sizing of DG. Reference [19] proposed a Strength Pareto as a multi-objective algorithm that optimizes DG size and place while DG cost and system total power loss as optimization objectives.

Imperialist Competitive Algorithm (ICA) is used to solve the complicated optimization problem of placing and sizing of multiple DER units in [20]. In [21] the optimum size and location of DGs are determined for maximizing voltage profile in distribution systems. Eusuff et al. [22] developed the Shuffled Frog Leaping Algorithm (SFLA). So far, SFLA has been used to solve different optimization problems; [23-25] demonstrate potential of SFLA in solving complicated problems in realm of power system.

In this paper, SFLA is employed as an optimization tool to solve the problem of locating and sizing of multiple DER units. The objectives considered in this study are loss reduction, distribution network upgrade cost minimization, reliability improvement, and reduction of power purchased from electricity market to form a multi-objective optimization problem. The proposed approach is carried out on conventional 30-bus distribution system to demonstrate the effectiveness of DER implementation as well as the proposed scheme.

The rest of the paper is organized as follows. An overview of SFLA is given in Section II. Proposed methodology to solve the multi-objective problem of locating multiple DER units is presented in section III. The simulation results on a radial distribution test system are presented in detail in section IV. The conclusion remarks are drawn in section V.

II. SHUFFLED FROG LEAPING ALGORITHM

Heuristic methods are improvised from the natural phenomenon in order to help solving complicated optimization problems. Generally, these algorithms go from one generation to another with the aim of optimizing the given objective. The SFLA is a new heuristic optimization approach conceptualized from the Memetic evolution of a group of frogs, which are in seek for the location with the maximum amount of available food. This method involves a population consisted of possible solutions defined by a set of virtual frogs that is partitioned into subsets, called memeplexes.

To achieve the optimum solution, SFLA combines the components of the local best solution extracted from each memeplexes and the data of the global optimal solution such that within each memeplex, each frog holds the ideas about the food that could be changed by those of other frogs. Therefore, the ideas of frogs evolve via a process of Memetic evolution. Moreover, at the same time SFLA performs an independent local search in each memeplex and improve each virtual frog using the local and global optimum solutions.

Ensuring the global exploration, in SFLA, the virtual frogs are shuffled and recategorized into new memeplexes after a defined number of memeplex evolution steps. In case reaching a better solution is not satisfied, random virtual frogs are generated and take the place of worst frogs in the population. The local search, improvements and the shuffling processes are repeated until the defined convergence criterion are met [22].

The procedure of SFLA in finding the optimal solution can be explained based on the following steps:

1- Generate an initial population of N frogs randomly $Pop = [X_1, X_2, \ldots, X_N]$. For an optimization problem with S variables, the ith frog is as $X_i = [x_{i1}, x_{i2}, \ldots, x_{iS}]$.

2- Evaluate the solution using the fitness function. The objective (fitness) function of ith frog can be calculated as follows:

$$Fitness = f(X_i) \tag{1}$$

where, $f(X_i)$ is the objective function which is aimed to be minimized.

3- Rank the solutions in an ascending order in terms of fitness function value. In this step the memeplexes are formed. All frogs (solutions) are divided to m memeplexes such that each memeplex contains n frogs.

4- For qth memeplex, the best and worst solutions are identified as X_{bq} and X_{wq}, respectively. The frog, which holds the best value of fitness function in all memeplexes, is identified as X_g. In the memeplex evolution process, X_w leaps toward the X_b and X_g using the pre-defined frog leaping rule. Therefore, the new position of worst frog in memeplex is updated as presented in the following [22]:

$$X_{wq}^{new} = g\left(X_{wq}^{old} + c[X_{bq} - X_{wq}^{old}]\right) \tag{2}$$

where, c is a random number between 0 and 1 and $g(.)$ is a function limiting the optimization variables not to go higher than their maximum, after updating process.

In case this new leaping solution is a better one, it takes the place of worst frog and once again, the algorithm searches for the new X_{wq}. If not, procedure presented in Equation (2) is repeated but this time considering the global best frog as shown in Equation (3) [22].

$$X_{wq}^{new} = g\left(X_{wq}^{old} + c[X_g - X_{wq}^{old}]\right) \tag{3}$$

$$g(a_j) = \begin{cases} a_j^{\max} & a_j^{\max} < a_j \\ a & a_j^{\min} < a_j < a_j^{\max} \\ a_j^{\min} & a_j < a_j^{\min} \end{cases} \tag{4}$$

If improvement in the worst solution becomes impossible, the worst frog is omitted from that memeplex and a new randomly generated frog takes its place. For each memeplex, the calculations continue for a pre-defined number of evolution steps.

5- Shuffling process, the entire population is mixed together in a process called the shuffling process.

6- Repeating, steps 1 to 5 are repeated until convergence criterion is met.

III. PROPOSED METHODOLOGY

In smart grids, the objective is minimizing the operation and planning costs of the power system, while ensuring the quality and reliability of the power delivered to the customers. Having a relatively high investment cost, DER should be located in the network with meticulous elaboration and consideration of different aspects of the network in order to reduce the risk as much as possible. In this study, optimal DER siting and sizing is studied considering several objectives. Regarding to mentioned subjects and in order to consider these objectives simultaneously, benefits costs ratio approach is employed.

A. Problem Formulation

In most power systems, the load of the system change over time. Therefore, it is necessary to consider load growth in DER application. Taking into account the load growth rate of α, the load of the *t*th year can be determined as follows:

$$Pd_t = Pd_B \times (1+\alpha)^{t-1} \tag{5}$$

where, Pd_t and Pd_B are load at the *t*th year and the first (base) year, respectively.

As mentioned earlier, here a cost/worth approach is employed to evaluate the implementation of DER units in the distribution network. Different objectives are considered in this study that are explained in the following. Moreover, all costs of DER units including, Investment Cost (IC), Operation Costs (OC) and Maintenance Costs (MC) are taken into account. The proposed objective function for this study is shown in Equation (6).

$$Max\, BCR = \frac{Benefit_{DER}}{Cost_{DER}} \tag{6}$$

where, *BCR* refers to Benefit to Cost Ratio, $Benefit_{DER}$ and $Cost_{DER}$ indicate to the benefits and costs of implementation of DER units in the distribution network, respectively. The benefits and costs of DER units is calculated using Equations (7) and (8), respectively [20].

$$Benefit_{DER} = \sum_{k=1}^{N_{DER}} \sum_{t=1}^{T} PPS_{kt}^{DER} + LRR_{kt}^{DER} + UID_{kt}^{DER} + RE_{kt}^{DER} \tag{7}$$

$$Cost_{DER} = \sum_{k=1}^{N_{DER}} IC_k^{DER} + \sum_{t=1}^{T} (OC_{kt}^{DER} + MC_{kt}^{DER}) \tag{8}$$

where, N_{DER} and *T* refer to the number of DER units and number of years in the study horizon, respectively.

As discussed earlier not all benefits of DER can be modeled as economic values such as emission reduction and voltage profile improvement. However, other benefits that can be evaluated financially are considered in this study as presented in the following.

A.1. Loss Reduction Revenue (LRR)

One of the most important problem in power systems is loss and it has drawn substantial attention from the utilities. With the implementation of DER unit's loss can be decreased, the total revenue gained from reduction of real power losses in a distribution system can be calculated as follows [20]:

$$LRR = \sum_{t=1}^{T} (P_{Loss,t} - P_{Loss,t}^{DER}) \times EP_t \tag{9}$$

where, $P_{Loss,t}$ is the active power loss before installation of DER units in the network at the *t*th year and $P_{Loss,t}^{DER}$ is the active power loss after DER implementation at the *t*th year.

A.2. Power Purchased Saving (PPS)

Power Purchased Saving refers to reduction in purchased electric power from electricity market to meet the demand of customers due to power generation of DER units [20].

$$PPS = \sum_{t=1}^{T} \sum_{k=1}^{N_{DER}} P_{kt}^{DER} \times EP_t \tag{10}$$

where, P_{kt}^{DER} denotes the output power of the *k*th DER unit at the *t*th year and EP_t refers to the price of the energy at the *t*th year. Considering interest rate (*ir*), the energy price for the *t*th year can be determined using Equation (10) based on [20].

$$EP_t = EP_1 \times (1+ir)^{t-1} \tag{11}$$

A.3. Upgrade Investment Deferral (UID)

Increase in power demand of the network necessitate upgrade of the network and/or construction of new infrastructures, e.g. distribution feeders. However, with installation of DER units in the network this need can be compensated. As discussed in [26], the value of this benefit highly depends on the cost-structure, the type of feeder, network configuration and planning strategies, the areas that DER units will be placed as well as the load growth rate. In this study an annual value of 120 $/kVA for this benefit is taken into consideration.

A.4. Reliability Enhancement (RE)

Reliability of the distribution system can be enhanced by the installation of DER units if they are correctly coordinated with the rest of the distribution system. Moreover, DER units are able to supply all or part of the load in the case of the main source is unavailable. Reliability enhancement of the network after implementation of DER units is calculated as presented in the following [20]:

$$RE = \sum_{t=1}^{T} CIC_t - CIC_t^{DER} \tag{12}$$

where, CIC_t is the annual Customer Interruption Cost, in the base case where there is not DER units at the *t*th year and CIC_t^{DER} is the annual customer interruption cost in the presence of DER units at the *t*th year. The value of loss of load is considered 1000 $/MVA based upon [27].

B. Optimization Procedure

Depicted in Figure 1, is the proposed optimization procedure based on the SFLA. After initializing the optimization problem and algorithm parameters, Power Flow (PF) is performed. Considering the results of this PF, that shows the base case condition of the distribution network, loss and reliability of the base case are calculated. In this study, all buses of the system are considered as a candidate location for placement of DER units.

It should be noted that the DER units are considered to be non-dispatchable, so the power production of DER unit is considered to be fixed in a value from zero to P_{DER}^{Max} . As shown in Figure 1, for each frog a Power Flow (PF) is performed. Based on the results of this PF loss reduction, reliability improvement and other benefits of DER units is calculated. Using this information the fitness function for each solution (frog) is computed. Afterwards, using the algorithm parameters and functions a new population is generated. This procedure is repeated until the termination criterion is satisfied which is considered to be number of iteration in this study.

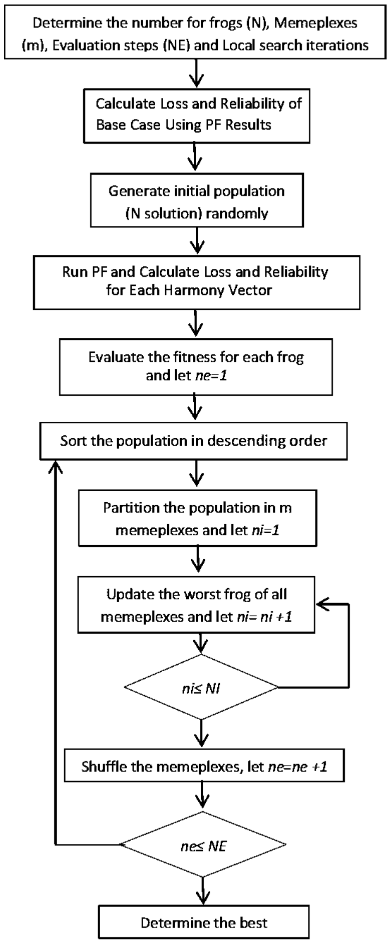

Figure 1. Flowchart of the proposed procedure

IV. SIMULATION RESULTS

The proposed methodology is carried out on the IEEE 30-bus distribution system, depicted in Figure 2, including one main feeder, 6 auxiliary substations and 22 load buses. The data of this test system are borrowed from [28]. The loads of the buses at base case and the first year are given in Table 1. The base voltage of this test system is 23 kV, *S* base is 100 MVA and the total load is 15 MW. The following assumptions has been made in this study:
- Study horizon (*T*) is considered to be 5 years.
- The *ir* is assumed to be 10%.
- The average utilization rate of DERs units is 40%.

Two different cases are analyzed. In the first case, loss reduction and reduction in the power purchased from the electricity market are considered as the benefits of DER implementation. While in second one, a multi-objective optimization is performed for DER placement that simultaneously considers all aforementioned benefits of DER units.

Table 1. IEEE 30-bus distribution system data [28]

From Bus *i*	To Bus *j*	r_{ij} (p.u.)	x_{ij} (p.u.)	Base active load at *j* (MW)	Base reactive load at *j* (MW)
Main Feeder	1	0.0963	0.3219	0	0
1	2	0.0414	0.0022	0.5220	0.1740
2	3	0.0659	0.0651	0	0
3	4	0.2221	0.1931	0.9360	0.3120
4	5	0.1045	0.0909	0	0
5	6	0.3143	0.1770	0	0
6	7	0.2553	0.1438	0	0
7	8	0.2553	0.1438	0	0
8	9	0.2506	0.1412	0.1890	0.0630
9	10	0.2506	0.1412	0	0
10	11	0.7506	0.4229	0.3360	0.1120
11	12	0.3506	0.1975	0.6570	0.2190
12	13	0.1429	0.0805	0.7830	0.2610
13	14	0.2909	0.1639	0.7290	0.2430
8	15	0.0898	0.0781	0.4770	0.1590
15	16	0.1377	0.0775	0.5490	0.1830
16	17	0.2467	0.1390	0.4770	0.1590
6	18	0.0915	0.0795	0.4320	0.1440
18	19	0.3005	0.2612	0.6720	0.2240
19	20	0.2909	0.1639	0.4950	0.1650
6	21	0.1143	0.0994	0.2070	0.0690
3	22	0.1066	0.1054	0.5220	0.1740
22	23	0.0649	0.0641	1.9170	0.0630
23	24	0.1083	0.0941	0	0
24	25	0.2760	0.2399	1.1160	0.3720
25	26	0.2009	0.1746	0.5490	0.1830
26	27	0.2857	0.1609	0.7920	0.2640
1	28	0.0881	0.0047	0.8820	0.2940
28	29	0.3091	0.1741	0.8820	0.2940
29	30	0.2106	0.1187	0.8820	0.2940

A. Case 1

It is shown in this case study that omitting some objectives from DERs placement optimization problem can cause the BCR to be non-optimal. Loss minimization is considered one of the objectives as well as the reduction of power purchasing cost reduction. Table 1 shows the results of this case. As can be seen in this table the value of BCR is lower comparing to the first case due to elimination of some objectives and sub-optimal solution.

The value of BCR, which is presented in this table, cannot be compared to the value of BCR for the solution of first case. Because, though the reliability improvement and reduction in expansion cost are not considered in cost function in the second case but installation of the selected unit in bus 14 has a great effect on the reliability improvement as well as network expansion cost reduction.

Therefore, it is better to compare the BCR, which considers all 4 costs for the solution of the first and second cases. Table 1 shows this comparison. As the results demonstrate even when not all benefits of DER units are taken into account, DER implementation is financially reasonable.

B. Case 2 - Multi-Objective DER Placement

Conducting an economic analysis employing SFLA, the optimum size and location of DER units is determined. For this case, the optimum solution is shown in Table 3. Depicted in Figure 3, is the value of the BCR regarding each iteration of the SFLA. There is an ascending trend for the value of BCR as was expected.

Table 2. The optimum solution for the first case

Bus No	*DER* size	LRR ($)	PPR ($)	Benefit ($)	Cost ($)	BCR
14	500	51758	210240	261998	205920	1.2894

C. Comparison and Discussion

In this sub-section, the results obtained are compared with those reported in the literature. Table 4 shows the comparison of the SFLA with [20]. As depicted in this table the proposed method renders the best solution among the different methods that have been applied to solve this complicated optimization problem. As can be seen from the obtained results of both cases, buses 12 and 14 are the best locations for DER installation.

Referring to Table 2 and Figure 2 it can be seen that the value of load at these buses reduce the losses of the system effectively. Moreover, these buses are far from the substation, and there will be low voltage at these buses that will result in further loss. Therefore, these buses are good candidates for DER units' placement. Therefore, the proposed methodology is capable of finding the optimum solution.

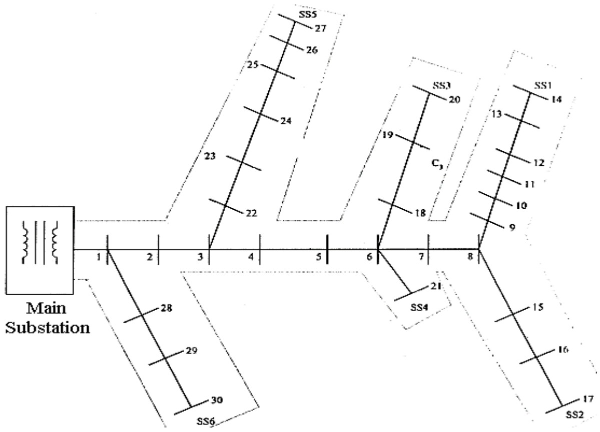

Figure 2. IEEE 30-bus distribution system [28]

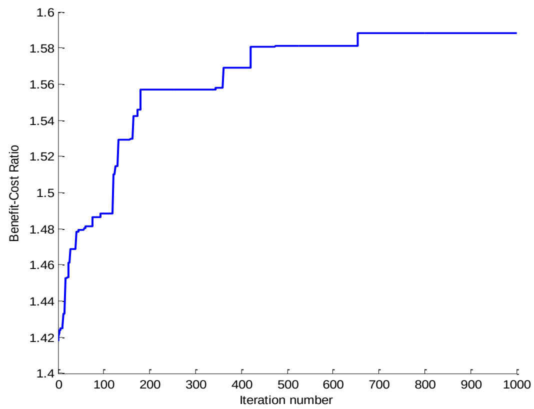

Figure 3. BCR improvement during iterations

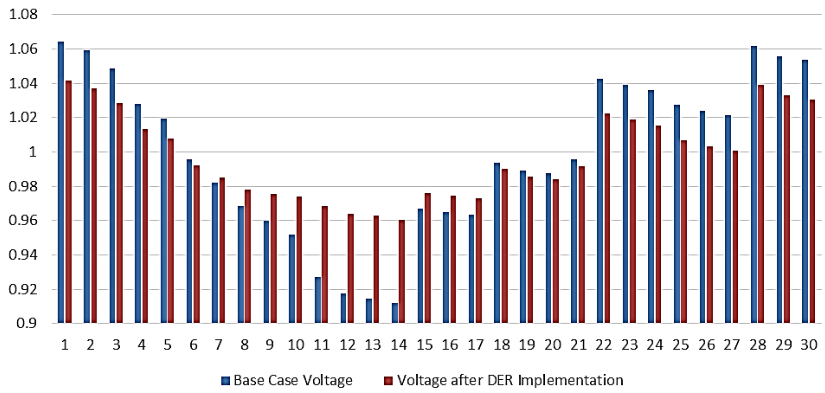

Figure 4. Comparison of the voltage profile before and after DER employment

Table 3. The optimum solution for the second case

Bus No	*DER* size	BCR	Loss Cost Reduction ($)	Purchasing Cost Reduction ($)	Interruption Cost Reduction ($)
12	100.04	1.5859	25287	97823	1632.7
14	133.27				

The comparison of voltage profile before and after implementation of DER units for the multi-objective case is presented in Figure 4. As it can be seen from this figure for the base case, the voltage variation in the system is considerable while by employment of DER units the voltage profile is smooth. The voltage of buses 11-14 is relatively low in the base case.

Table 4. Comparison of the best solution obtained by different methods

Method	*DER* Location	Size (kW)	*BCR*	Loss Cost Reduction ($)
ICA	14	222.05119	1.2891	117889.2288
PSO	11	223.3239	1.2369	372210.3527
	14	377.0356		
	18	130.2792		
HSA	12	144.2115	1.2781	188197.1178
	14	213.3091		
SFLA	12	100.04	1.5859	25287
	14	133.27		

That is one of the reasons that the proposed algorithm selected buses 12 and 14 as the optimal locations for DER implementation. After DER installation, however, the voltage of these buses has improved considerably. Moreover, after DER implementation there is no need for the substation to have a high voltage to support all buses, therefore the voltage of buses near to the substation is lower than the base case.

V. CONCLUSIONS

An efficient approach for siting and sizing of multiple DER units in distribution system was proposed. The multi-objective formulation simultaneously considers reduction in power losses, power purchased from market, reliability enhancement as well as upgrade investment deferral. SFLA as a novel heuristic approach was employed to optimally determine the best location and size of DER units. The obtained results demonstrate that DER application can effectively reduce the loss and improve reliability and defer the upgrade of the distribution system.

So employing DER units is financially reasonable as the obtained results showed about 1.6 BCR. Comparing the results with those obtained by the other methods demonstrated the effectiveness of the proposed method in finding the optimum solution. The results also shown that the proposed methodology is capable of finding the optimum solution.

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BIOGRAPHIES

Javad Olamaei was born in Qom, Iran in 1966. He received his B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering from University of Tabriz (Tabriz, Iran), Amirkabir University of Technology (Tehran, Iran) and Islamic Azad University, Science and Research Branch, (Tehran, Iran), in 1988, 1992 and 2008, respectively. He is currently a Faulty Member of Department of Electrical Engineering, Faculty of Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran.

Mohammad Mehdi Khademi was born in Yazd, Iran in 1987. He received the B.Sc. degree from South Tehran Branch, Islamic Azad University, Tehran, Iran in 2009. He is currently a M.Sc. student in the same university in Power Electrical Engineering. His research interests include distributed generation, renewable energy and smart grid.