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OPTIMAL DESIGN OF ELECTRICAL ENERGY STORAGE SYSTEMS IN THE PRESENCE OF INTELLIGENT DISTRIBUTION NETWORK TO IMPROVE TECHNICAL, ECONOMIC, AND PERFORMANCE CRITERIONS

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Abstract- In smart networks and micro-networks, mostly resources and applications are discussed in combination in studies. Regarding the nature of new distribution networks and intelligent control programs, these networks can highly integrate consumer-side resources and energy storage devices. In the current paper, without the need to strengthen the network, the location and management of energy storage resources are introduced and used as a new method in the existing distribution network. Likewise, the effect of the load management program on placement is considered. In addition to the presence of batteries in the distribution system, the combined study of load management program and optimal placement of energy storage devices in smart distribution networks with load response programs, private sector energy storage systems, private sector independent load management, and energy exchange with the upstream network is considered using the intelligent method of genetic algorithm. In addition to energy storage devices, load response programs are also used to manage peak load.

Keywords: Battery, Load Management Program, Demand Response, Losses, Optimal Placement, Intelligent Distribution Network.

1. INTRODUCTION

In today's distribution networks, particularly with the rising trend of privatization and competitiveness of the electricity market, the prime objective of distribution companies is to decrease costs related to the operation, maintenance, network construction and at the same time raise the technical indicators of the network [1-3]. One of the most effective methods to respond to the growth of the load and to meet the technical standards of operation is the use of distributed generation and energy storage devices [4-6].

Renewable resources, due to their stochastic nature in the distribution system, have problems. As it is difficult to forecast the power output and this issue causes a sharp fluctuation in output power [7]. This will cause numerous difficulties for the power systems operation. Due to this fact, it is necessary to use energy storage systems in different parts of the power system to balance production and consumption [8-10]. Storages are one of the emerging equipment in distribution networks whose optimal location depends on the consumption curve, the presence or absence of traditional and renewable distributed generation sources, as well as design goals. The dominance of energy storage systems is a solution to solve system stability problems [11-15].

In [16], a multi-objective optimization algorithm is offered to solve the energy storage design problem. In [17], one of the main challenges of integrating energy storage resources in the existing power system network is to determine the capacity and optimal location of these resources in distribution systems. In [18], by adding energy storage resources to the network, its effect on the efficiency of the distribution network has been studied. In [19], the optimal design of batteries in the distribution network is discussed to solve the problems of uncontrollable resources in the distribution system.

The importance of battery placement in consort with the load management program has attracted various factors such as privatization of electricity markets, efforts to increase system profitability, and reduce environmental concerns, to energy storage sources. These power sources can be a reliable and flexible option for the distribution network operator to manage the growing electrical network. However, connecting a large number of these resources to the distribution network creates several technical challenges in the operation of the network [20]. Consequently, to avoid the costs of system amplification, the distribution system operator needs a reliable technique for the optimal operation of the system. Using energy storage devices can solve some of these problems. In this paper, without the need to strengthen the network, the placement and management of energy storage resources are introduced and used as a new method in existing distribution networks. The effect of the load management program on placement is also considered. In addition to the presence of batteries in the distribution system, the combined study of load management program and optimal placement of energy storage devices in intelligent distribution systems with load response programs, energy storage dependents of private sectors, and load management independent of private sectors and energy exchange with the upstream network have been considered. In addition to energy storage devices, load response programs are also used to manage peak load.

In the following and the second section, mathematical modeling and formulation are examined. Similarly, in the third section, the genetic algorithm and its structure that is used are stated. In the fourth section, the simulation results are described in detail, and in the fifth section, the conclusion is stated.

2. MATHEMATICAL MODELING AND FORMULATION

The load variation curve is modeled by multiplying three parameters. $S_{i,base}^{D}$ is the base load in the first year of the evaluation interval and is divided into the level of demand (N_{dlf}) each year? The demand level factor (DLF_h) is defined to determine the predicted value of the load-to-peak load ratio, which varies between 0 and 1. The length of each load surface is h denoted by τ_h. Consequently, the demand at the ith bus and the hth demand level is calculated as follows:

$$P_{i,t,h}^{D} = P_{i,base}^{D} \times DLF_h \tag{1}$$

$$Q_{i,t,h}^{D} = Q_{i,base}^{D} \times DLF_h \tag{2}$$

$$S_{i,t,h}^{D} = P_{i,t,h}^{D} + j\,Q_{i,t,h}^{D} \tag{3}$$

where, in Equations (1) to (3) $S_{i,t,h}^{D}$, $P_{i,t,h}^{D}$ and $Q_{i,t,h}^{D}$ are the apparent, active, and reactive powers at the ith bus and the demand level hth and year tth, respectively.

The price of energy purchased from the main network is not the same at different demand levels. Generally, it is expected that the price of energy purchased from the main network at the hth demand level is determined using Equation (4).

$$\lambda_h = \rho \times PLF_h \tag{4}$$

In Equation (4), ρ the base price and PLF_h the price level coefficient h, which are assumed to be known values. The number of battery units that are candidates for installation in the network is shown in Equation (5).

$$\sum_{i=1}^{N_b} U_i = N_{ES} \qquad U_i \in \{0,1\} \tag{5}$$

If the binary variable U_i is equal to one, the nth battery unit will be installed on the ith bus. The power distribution equations are shown in the ith bus and the hth dimension level and tth year in Equations (6) and (7).

$$\begin{aligned} & P_{i,t,h}^{ss} \pm P_{i,t,h}^{ES} \times U_i - P_{i,t,h}^{D} = \\ & = V_{i,t,h} \sum_{j} V_{j,t,h} \left(G_{ij} \cos\delta_{i,t,h} + B_{ij} \sin\delta_{j,t,h} \right) \end{aligned} \tag{6}$$

$$\begin{aligned} & Q_{i,t,h}^{ss} \pm Q_{i,t,h}^{ES} \times U_i - Q_{i,t,h}^{D} = \\ & = V_{i,t,h} \sum_{j} V_{j,t,h} \left(G_{ij} \cos\delta_{i,t,h} - B_{ij} \sin\delta_{j,t,h} \right) \end{aligned} \tag{7}$$

where, in (6) and (7), $P_{i,t,h}^{ss}$ and $Q_{i,t,h}^{ss}$ are the active and reactive powers produced (or absorbed) in the ith bus and at the dimension level hth and year tth, respectively. $V_{i,t,h}$ and $\delta_{i,t,h}$ show the magnitude and angle of the voltage at the ith bus and the dimension level hth and year tth, respectively. The voltage of each bus at each dimension level h and year t must be kept within the safe operating range as shown by the mains voltage in (8).

$$V_i^{\min} \le V_{i,t,h} \le V_i^{\max} \tag{8}$$

where, in (8), $V_i^{\max}$ and $V_i^{\min}$ are the maximum and minimum allowable voltage ranges for safe operation, respectively.

The active and reactive power ranges of the post will be commensurate with its capacity. Equations (9) and (10) represent the limits of active and reactive power in the distribution network, respectively.

$$P_{ss}^{\min} \le P_{t,h}^{ss} \le P_{ss}^{\max} \tag{9}$$

$$Q_{ss}^{\min} \le Q_{t,h}^{ss} \le Q_{ss}^{\max} \tag{10}$$

where, $P_{ss}^{\max}$ and $Q_{ss}^{\max}$ represent the maximum active power and the maximum reactive power of the substation capacity, respectively.

For the battery, the restrictions related to the maximum charge, the minimum and maximum charge level, the charging speed, and the effect of the depreciation cost and its internal losses will be in the form of (11) to (14).

$$\begin{cases} 0 \le P_{k,h}^{c} \le b_{k,h}^{c} P_{k,h}^{c,\max} \\ 0 \le P_{k,h}^{disc} \le b_{k,h}^{disc} P_{k,h}^{disc,\max} \end{cases} \tag{11}$$

$$E_k^{\min} \le E_{k,h} \le E_k^{\max} \tag{12}$$

$$\begin{cases} b_{k,h}^{c} + b_{k,h}^{disc} = 1 \\ b_{k,h}^{c}, b_{k,h}^{disc} \in \{1,0\} \end{cases} \tag{13}$$

$$E_{k,h+1} = E_{k,h} + \left(\eta_k^{C} \times P_{k,h}^{c} - \frac{P_{k,h}^{disc}}{\eta_k^{disc}} \right) \tag{14}$$

In recent equations, $P_{k,h}^{c}$ and $P_{k,h}^{disc}$ respectively show the charge and discharge capacity of the battery k at h. Also $b_{k,h}^{c}$ and $b_{k,h}^{disc}$ show the status of battery charge and discharge in binary order, respectively. $P_{k,h}^{c,\max}$ and $P_{k,h}^{disc,\max}$ also express the maximum amount allowed for charging and discharging the battery, respectively. In this paper, a cost function is offered to determine the size and location of the battery to show the effect of active network management. In this model, it is supposed that the distribution network operator is responsible for providing energy demand to customers, storing and selling energy, operating the battery depot, and managing and controlling the distribution system.

Performing these tasks in an intelligent environment reduces costs and provides the right conditions for the operation of the distribution network.

2.1. Battery Location Investment Cost

Battery charging location investment cost is a function of installation capacity and its unit cost is λ_{inv}^{ES} that is calculated through Equation (15).

$$ES_{IC} = \sum_{t=1}^{T} \left(\sum_{n=1}^{N_{ES}} S_{\max}^{ES} \times \lambda_{inv}^{ES} \right) \tag{15}$$

2.2. Operating and Maintenance Costs

Operating costs of the battery charging location are assumed to be equal to the cost of fuel and its cost of depreciation. Maintenance costs also include the cost of upgrading and repairing parts, which is supposed to be the same for all battery charging stations. The present value of this sub-function, or ES_{OC}, is determined by considering the interest rate and inflation rate over the time horizon using Equation (16).

$$ES_{OC} = \left\{ \sum_{t=1}^{T} \sum_{h=1}^{N_h} \sum_{n=1}^{N_{ES}} \begin{pmatrix} P_{i,t,h}^{ES} \times OC_{ES} \times \tau_{dl} \\ + \mathrm{Cos}\, t_{main,n} \end{pmatrix} \right\} \tag{16}$$

2.3. Cost of Electricity Purchased from the Network

The cost of purchasing power from the upstream network (GC) is calculated by considering its cost using Equation (17).

$$GC = \sum_{t=1}^{T} \sum_{h=1}^{N_h} P_{t,h}^{SS} \times \lambda_h \times \tau_h \tag{17}$$

2.4. Active Power Loss Cost

This sub-function is determined for the time horizon and is calculated by considering its price using (18).

$$LC = \sum_{t=1}^{T} \sum_{h=1}^{N_h} P_{t,h}^{loss} \times \lambda_h \times \tau_h \tag{18}$$

Therefore, the cost function is defined using (19), which will be minimized to determine the optimal size and location of the battery charging station.

$$Objective = \left\{ ES_{IC} + ES_{OC} + GC + LC \right\} \tag{19}$$

The voltage stability index is calculated using (20).

$$\mathrm{SI} = \left\{ |V_S|^4 - 4 \begin{pmatrix} (\mathrm{P}_L.\mathrm{R} + \mathrm{Q}_L.\mathrm{X}).\mathrm{V}_S^{\,2} \\ +(\mathrm{P}_L.\mathrm{X} - \mathrm{Q}_L.\mathrm{R})^2 \end{pmatrix} \right\} \tag{20}$$

The voltage profile index is defined using (21).

$$F_2 = \sum_{i=2}^{nbus} (V_{n_i} - V_{ref})^2 \tag{21}$$

where, V_{ref} is the reference voltage, which in most cases is considered a per-unit. The bus (1) is a feeder bus and its voltage are a per-unit.

3. GENETIC ALGORITHM STRUCTURE

The genetic algorithm is inspired by Darwin's genetics and evolutionary theory and is based on the survival of the fittest. A common application of genetic algorithms is to use them as an intelligent method to solve optimization problems. Generally, genetic algorithms are composed of chromosomes, population, and fitness functions. To better understand how to implement the algorithm in the problem under study, we will briefly explain each part of the algorithm [21, 22].

In genetic algorithms, each chromosome represents a point in the search space and a possible solution to the problem. The chromosomes themselves (solution) are made up of a fixed number of genes (variables). Binary coding is commonly used to represent chromosomes. A set of chromosomes make up a population. With the effect of genetic agents on each population, a new population with same number of chromosomes is formed.

To solve any problem using genetic algorithms, a fitness function must first be developed for that problem. For each chromosome, this function returns a non-negative number that indicates the individual competence or ability of that chromosome. In genetic algorithms, genetic operators are used during the reproductive phase. By affecting these populations on a population, the next generation of that population is produced. Selection, synthesis, and mutation operators are most used in genetic algorithms [23, 24].

3.1. Selection Operator

This operator selects several chromosomes from among the chromosomes in a population to reproduce. The fittest chromosomes are more likely to be selected for reproduction.

3.2. Combination Operator

The combination operator acts on a pair of chromosomes of the productive generation and produces a new pair of chromosomes. There are several combination operators, such as single-point combinations and two-point combinations.

3.3. Mutation Operator

Upon completion of the fusion operation, the mutation operator affects the chromosomes. This operator randomly selects a gene from a chromosome and then changes the content of that gene. If the gene is binary, it inverts it, and if it belongs to a set, it replaces that gene with another value or element. Figure 1 shows how the fifth and tenth genes of a chromosome mutate. After the mutation is accomplished, the generated chromosomes are known as a new generation and sent to the next round of algorithm execution. The steps of implementing the genetic algorithm are shown in Figure 2.

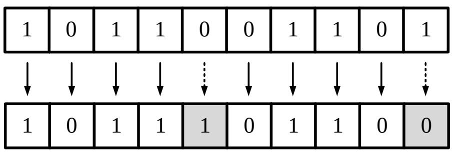

Figure 1. Genetic mutation of a genetic algorithm

4. SIMULATION RESULTS

This section describes the results of battery placement and its effect on losses, cost, and voltage drop. The placement has been done for storage with or without a load management program. The base price of energy purchased from the network is assumed to be 115 [$ per MWh]. The rest of the parameters used to locate the battery are listed in Table 1.

The simulations were performed on a 33-bus distribution network. The structure of this network is shown in Figure 3.

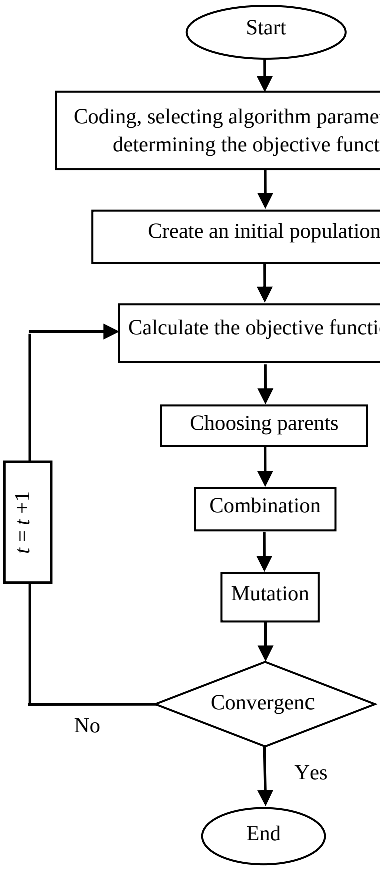

Figure 2. Stages of implementation of genetic algorithm

Table 1. Technical and economic information of the planning problem

Parameter	Value	Parameter	Value
$V_i^{\min}$	0.95 [p.u.]	$V_i^{\max}$	1.05 [p.u.]
λ_{inv}^{ES}	10000[$/MW]	OC_{ES}	100 [$/MWh]
$\lambda_{inv\&o}^{AM}$	0.9 [$/MWh]	ρ	115 [$/MWh]

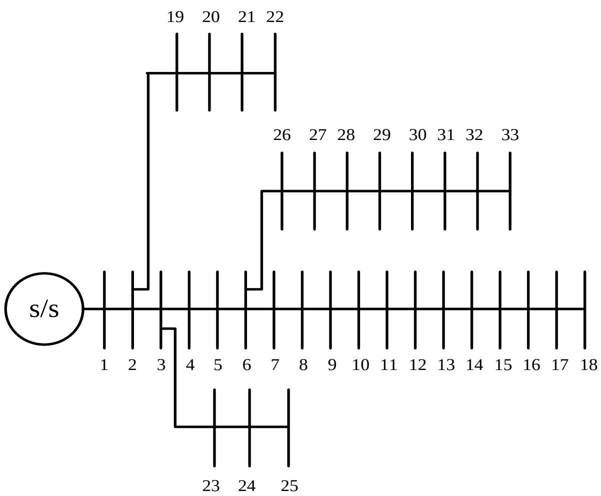

Figure 3. Single line diagram of 33 bus system distribution network

The hypothetical voltage level of the above distribution is 12.66 kV and the hypothetical capacity of the feeder is 8 MVA. The peak load is assumed at 6012 kW and 3012 kVar. The distribution network will be operated along with the battery compartment. The simulation results for the 33-bus distribution network with and without considering the load response program are shown in Table 2.

According to Table 2, the profit from the purchase of energy from the upstream network and the profit from the reduction of losses have increased significantly with the implementation of the proposed program. Consequently, with the implementation of the proposed program, the distribution company will face an increase in profits. The simulation results for locating the two charging and discharging stations are presented in Table 3. Based on Table 3, the selected bases for the location of the batteries are similar if the load management program is implemented or not, but the implementation of the load management program reduces the need for batteries to some extent. This is due to the similar behavior and impact of both in the network. In other words, both of these cases flatten the network load curve by reducing the energy consumption amount during peak hours and increasing energy consumption during non-peak hours, leading to a reduction in daily losses.

The use of batteries is in complete control of the network, but the implementation of load management programs is more complex and requires network cooperation and part of the network loads. Of course, the amount of load transfer in this article is limited. The results for more batteries in the network are presented in Table 4. Noticeably, as the location of the stations increases, the total capacity of the batteries in the network and the benefits of using them increase. In addition to the fact that the proposed method has a positive effect on the cost of operating the network and peak load, it also has significant effects on improving the voltage profile and reducing losses. On the other hand, the suggested method can also solve the problems caused by load growth in the long run. Based on Tables 3 and 4, proper battery allocation in the network can play a significant role in reducing losses. Likewise, by increasing the total capacity of the batteries and its better distribution in the network, increasing the number of batteries improves the technical parameters more effectively. Figure 4 shows the voltage profile in the network for normal network mode as well as the location of two or three battery locations. Proper battery placement can correct electrical voltage profile.

To compare the results of the simulations, the criteria used in distribution networks have been used. Technical indicators include losses and voltage drops. The loss rate is based on the average of the different load levels in the simulation for the placement of the two batteries and is based on the required calculation presented in Table 5.

Table 2. Simulation results with and without load response program

Load information	Without demand response program	With demand response program
Profit from purchasing energy from the overhead network [$]	2.9742×10^{7}	2.9911×10^{7}
Profit from loss reduction [$]	-	7.9246×10^{5}
Total profit [$]	2.9742×10^{7}	3.0703×10^{7}

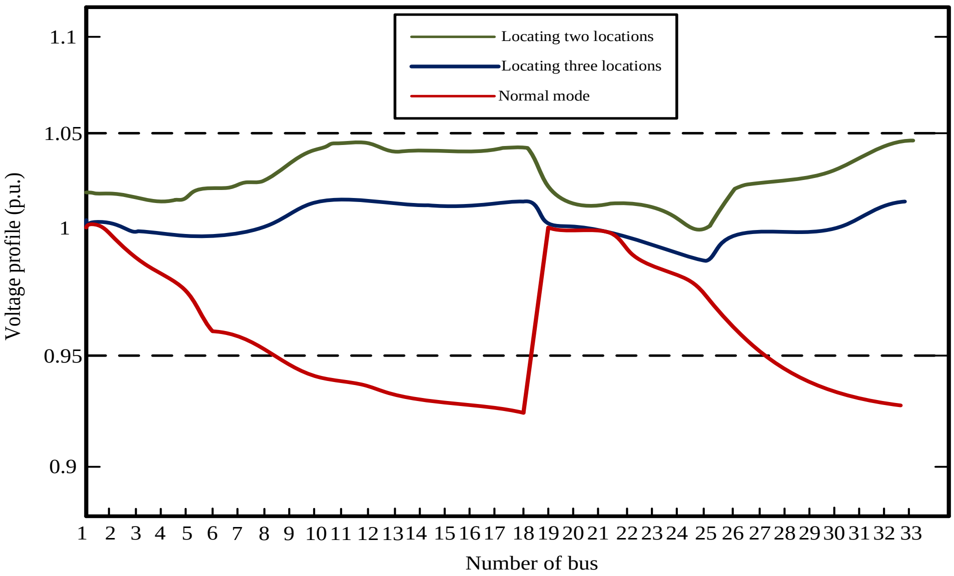

Figure 4. Voltage profiles for different modes

Table 3. Simulation results for locating two battery-charging stations

Load information	Without demand response program		With demand response program	
Bus number	31	17	31	17
Battery location capacity	740	890	650	780
Maximum load supply profit [$]	2.0357×10^6		1.7831×10^6	
Charge program benefit [$]	0.8086×10^5		0.7083×10^5	
Profit from purchasing energy from the overhead grid [$]	3.8281×10^7		3.7343×10^7	
Loss reduction profit [$]	7.5998×10^5		1.4047×10^6	
Investment cost [$]	1.1087×10^7		0.9711×10^7	
Total profit [$]	3.0070×10^7		3.0890×10^7	

Table 4. Simulation results for placement with and without load response program

Load information	Without demand response program			With demand response program		
Bus number	31	17	9	31	17	9
Battery location capacity	550	790	390	460	580	250
Maximum load supply profit [$]	2.7785×10^6			2.1116×10^6		
Charge program benefit [$]	1.1038×10^5			0.8388×10^5		
Profit from purchasing energy from the overhead network [$]	4.1348×10^7			3.8693×10^7		
Profit from loss reduction [$]	9.8129×10^5			1.4950×10^6		
Investment cost [$]	1.5133×10^7			1.1500×10^7		
Total profit [$]	3.0085×10^7			3.0883×10^7		

Table 5. Average voltage losses and deviations with two batteries

Indicator	With load management	Without load management
Losses	44.32	65.11
Voltage deviation	0.17	9.23

Table 6. The sum of the bus voltage deviations in the second scenario

Indicator	With load management	Without load management
Losses	33.71	46.32
Voltage deviation	0.14	0.19

According to the results in Table 6, the lowest losses for all load levels are when battery usage and load management are performed. Another indicator used to compare the results is the voltage deviation of the buses. The result is calculated as the average load for the simulations performed.

According to the results of Table 5, it is clear that this index improves with a further reduction of the peak load. The results for the location of the three battery compartments are presented in Table 6. It is observed that more storage resources by increasing the penetration of batteries in the network and its better distribution at the level of network buses effectively reduce further losses and voltage deviations.

On the other hand, load management always has a significant impact. Likewise, as the dominance of batteries in the network increases, the execution of load programs will have less function than the mode of less penetration of batteries, because the performance is similar to the use of batteries and load management programs in the network. In addition, due to the control of the network on the batteries, its implementation will be easier and with fewer problems for the network operator.

5. CONCLUSIONS

Regarding the nature of new distribution networks and intelligent control programs, these networks can highly integrate consumer-side resources and energy storage devices. In the future systems, resources and programs are mainly presented in combination in studies. The objectives of combining different technologies and applications mainly include reducing peak load, reducing energy costs, improving technical parameters including voltage and loss profiles, the possibility of operating the network as an island, and increasing network reliability. In this paper, the location of storage resources was investigated based on their impact on the reduction of network peak and losses, using load management programs. The proposed method for locating and storing and using energy in energy storage devices was able to improve the technical and economic goals properly. According to the selected objective function in the location problem, goals such as reducing losses, reducing energy costs and network peak were achieved. To reduce losses and energy costs and network peak, placement and sizing were performed using the intelligent method of genetic algorithm. Likewise, this article examines the power of storage devices and their location that can be optimally determined and installed, along with the restrictions on the amount of storage and how to charge and discharge and their efficiency, and in this regard, costs have been reduced economically.

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