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Analysis of Electrical Distribution Network Voltage Configuration with Mixed-Integer Linear Programming Algorithm and Genetic Algorithm Regarding Energy Cost

Leyla Akbulut[1], Süleyman Sungur Tezcan[2], Ahmet Coşgun[3]

[1]Department of Electrical-Energy, Akseki Vocational School, Alanya Alaaddin Keykubat University, Antalya, Turkey
[2]Department of Electrical-Electronic Engineering, Gazi University, Faculty of Engineering, Ankara, Turkey
[3]Department of Electrical-Energy, Vocational School of Technical Sciences, Akdeniz University, Antalya, Turkey

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ABSTRACT

Because natural and social resources are unevenly distributed over the earth's surface, socioeconomic developments differ in time and space. Although the most critical causes of inequality are natural or geographical reasons, the lack of energy supply-demand balance-specific to the region increases inequality. Undoubtedly, eliminating the supply-demand imbalance because of the increase in energy demand by costing energy cheaply will significantly reduce these differences. The existing electricity grid must be expanded or partially or completely replaced to meet the energy demand. This study aims to design a new electricity network or expand an existing network to meet consumers' needs by providing energy distribution with minimum cost and maximum quality. In this study, we analyzed the energy costs generated by re-planning a network that distributes electricity at different voltage levels to meet the increasing energy needs. We established a minimization function by determining the required transformer powers and their numbers considering the physical and electrical conditions to obtain the optimum network design. We analyzed the generated function by using a mixed-integer programming algorithm and a genetic algorithm in MATLAB.
Keywords: Electricity distribution network p, Energy cost, MATLAB GA, MATLAB-Mixed integer linear programming, voltage level configuration

Introduction

Today, energy needs are increasing because of technological and industrial developments. To eliminate the supply-demand imbalance because of the increase in energy demand, the existing electricity grid must be expanded or partially or completely replaced. Adding, extending, or renewing new facilities to the existing electricity distribution network requires careful engineering. Engineering studies vary according to the network operation (operation, maintenance, renovation, and repair) to be performed in the short-, medium-, and long-term. These studies aim to provide quality energy with optimum cost to users within the reliability criteria. The electricity distribution network is examined using different optimization methods from different angles, such as active power, reactive power, technical loss, non-technical loss, voltage drop, and overload [1-3]. Reducing the lost costs caused by switching operations during the operation of the distribution system and renewal costs resulting from the renewal of the distribution system required the solving of a comprehensive optimization problem with the help of a genetic algorithm and optimum design [4-8].

Although economic distribution network design problems are generally evaluated regarding active power, optimization problems are used for reactive power and active power to solve electrical distribution network design problems. Baysal and Altas [4] provided an optimal capacitor in radial power systems to maximize annual net savings by reducing energy losses. They created a solution to the placement and sizing (OCPS) problem. The reliability assessment of the grid was conducted by considering the distributed power systems that were subsequently added to the electricity grid [8-12]. In this paper, we re-planned a medium-voltage electricity distribution network (Figure 1), performing a multistage distribution activity at different voltage levels, and a single-stage distribution activity at high-voltage levels to meet the increasing energy demand (Figure 2).

Corresponding Author:
Leyla Akbulut

E-mail:
leyla.akbulut@alanya.edu.tr

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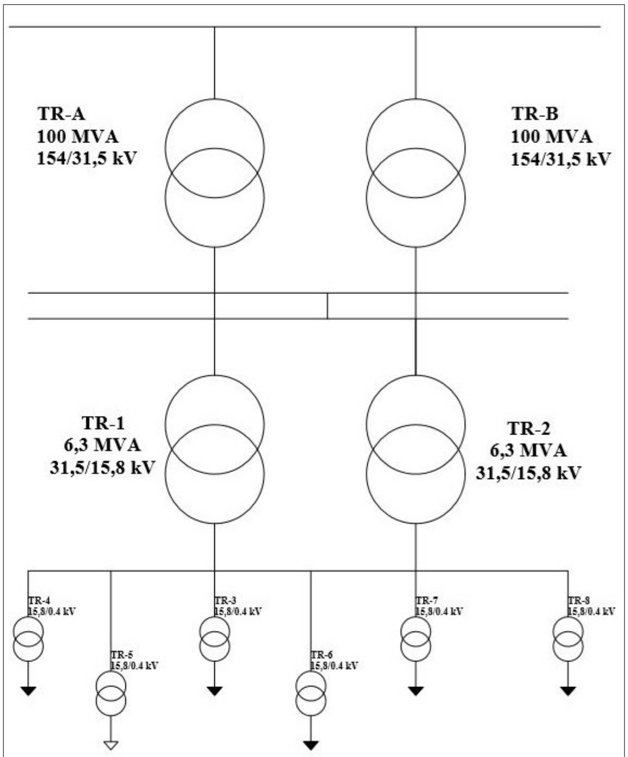

Figure 1. An example of a distribution network that maintains a dual-stage electricity distribution activity

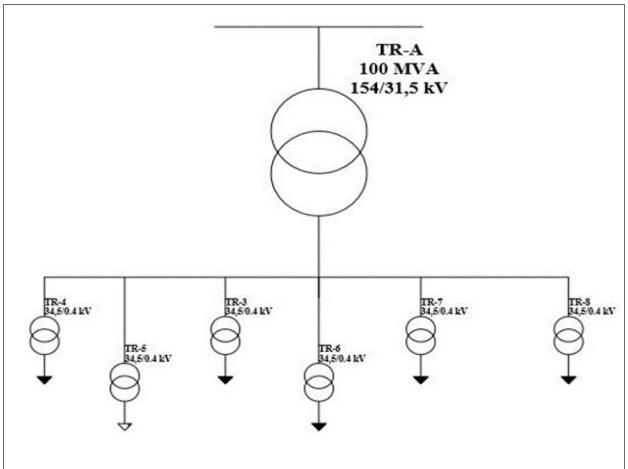

Figure 2. An example of a network operating in a single voltage stage distribution

In Turkey, varying voltage levels, such as 6.3 kV, 15.8 kV, 10 kV, 31.5 kV, 33 kV, and 34.5 kV, are used in medium-voltage power distribution networks. The reason for the difference between the medium-voltage levels is that the municipalities built an electrical distribution network in line with their budgets during the foundation years of the country. The distribution of electrical energy at low voltage levels is advantageous regarding material supply (financially) but is technically disadvantageous because it cannot meet the increasing energy demand (voltage drop). Therefore, from a technical viewpoint, switching from a double-stage distribution to single-stage electricity distribution (voltage configuration) is more advantageous for the network expansion. This paper evaluates whether the voltage configuration is financially advantageous. In this paper, the objective function created to answer this question was analyzed in MATLAB by a mixed-integer programming algorithm (mathematical programming) and genetic algorithm (heuristic method). We evaluated the results by considering the amortization periods and determined the necessity of a voltage configuration.

Theoretical Method

It is possible to collect the costs of the materials used in the electricity distribution network under two main headings, namely fixed costs and variable costs. The fixed costs include the labor and material costs incurred during the assembly or disassembly of the material or equipment, while the variable costs include the loss costs incurred during the operation of the material or equipment in the network.

Cost of a Step-Down Transformer Station

The annual costs of step-down transformer centers are found by collecting the annual facility cost of the step-down transformer center and the annual loss cost of the step-down transformer [13].

$$Sd_t = Sd_f + Sd_l \quad (1)$$

$$Sd_f = (Sd)_a + e_c.(Pi)_a.8760 \quad (2)$$

$$Sd_l = e_c.(Pc)_a.L_f.8760 \quad (3)$$

Sd_t: One-year total cost of the step-down transformer station (TL)

Sd_f: Facility cost of the step-down transformer station (TL)

Sd_l: The lost cost of step-down transformer station (TL)

$(Sd)_a$: The cost of the mounting step-down transformer station with a power of a (TL)

e_c: energy unit cost (TL/kWh)

$(Pi)_a$: step-down transformer iron loss in "a" kWh power (kWh)

$(Pc)_a$: step-down transformer copper loss in "a" kWh power (kWh)

L_f: Loss factor

Cost of the Distribution Transformer Station

$$D_t = D_f + D_l \quad (4)$$

$$D_f = (D_f)_b + e_c\,(Pi)_b.8760 \quad (5)$$

$$D_l = e_c\,(Pc)_b.L_f.8760.\,(S / S_n)^2 \quad (6)$$

D_t: One-year total cost of the distribution transformer station (TL)

D_f: Facility cost of the distribution transformer station (TL)

D_l: The lost cost of the distribution station (TL)

$(Pi)_b$: Step-down transformer iron loss in "b" kWh power (kWh)

$(Pc)_b$: Step-down transformer copper loss in "b" kWh power (kWh)

S: Distribution transformer power (kVA)

S_n: Distribution transformer nominal power (kVA)

Distribution line cost

The cost of the distribution line is determined by adding the fixed cost resulting from the material assembly to the variable cost resulting from the losses that occur on the line [13].

$$L_t = L_f + L_v \quad (7)$$

$$L_f = (L_f)_c.l \quad (8)$$

$$L_v = e_c.(r)_c.P^2 / |V^2|.L_f.l.8760.10^{-3} \quad (9)$$

L_t: Total annual cost of the line (TL)

L_f: Fixed cost of the line (TL)

L_v: Variable cost of the line (TL)

(L_f) c: Cost of assembly of the conductor in section c (TL)

$(r)_c$: Resistance per unit length of the conductor in section c (Ω / km)

l: Length (km)

P: Active power (W)

V: Voltage of the line (V)

Problem Design and Optimization Methods

Figure 1 shows an example of the network operating a dual-stage electricity distribution. Figure 2 provides a redesign of the existing two-stage distribution network in its current form. We compared the network operating a single voltage stage distribution and the situation of redesign without the step-down station financially, creating two objective functions.

In the models we used, we considered the plant and loss (iron and copper losses) costs of the distribution and step-down transformers and the plant and loss costs of the distribution line. When designing a minimum-cost distribution network, we considered restrictions such as meeting the demanded loads, cable current carrying capacity, voltage drop, branching off the line, and feeding all the consumers. The total annual costs of the step-down transformer station and distribution transformer centers were calculated at different operating voltages. We also calculated the costs of the distribution line according to the three conductors most used on the distribution lines.

The results showed that the line costs decrease as the voltage level increases. In case the voltage level is not raised, the cost of the step-down transformer station is considered because we will require the step-down transformer station.

Problem Model for Network Redesign without Voltage Level Configuration

The objective function created when the electricity distribution network is designed, as in Figure 1, is described below. The objective function is achieved by assuming that the value of Equation (7) is constant and assuming the possible values of Equation (1) and (4) by multiplying them by the number variable.

$$MinZ_1 = \sum_{i=1}^{n}\sum_{a\in Na}(Sdf + Sdl)Xa + \sum_{j=1}^{m}\sum_{b\in Nb}(Df + Dl)Yb + \sum_{k=1}^{p}\sum_{c\in Nc}(Lt)c \quad (10)$$

Constraints [12]:

- The network must meet the request

$$\sum_{l=1}^{m}(Plj - Pjl) \geq Pj$$

- The maximum current carrying capacity of the line must not be exceeded

$$\frac{Pk}{|Vk|} \leq \frac{Pk^{max}}{|Vk|} \quad (k=1,2,..,m)$$

- The power requested from the distribution transformer must not be greater than the nominal power of the distribution transformer

$$Pt \leq Pt^{max}$$

Problem model for network redesign in the case of voltage configuration

In the case of redesigning the network (Figure 2) as a single-step voltage distribution system, the value of Equation (7) is accepted as a constant and multiplied by the number of possible values in Equation (4). The objective function is calculated as

$$MinZ_2 = \sum_{j=1}^{m}\sum_{b\in Nb}(Df + Dl)Yb + \sum_{k=1}^{p}\sum_{c\in Nc}(Lt)c \quad (11)$$

The constraint conditions are the same.

Optimization Methods Used in Problem-Solving

Integer-Mixed Linear Programming Model

By using the objective function and restrictions terms, any known problem can be modeled using mathematical pro-

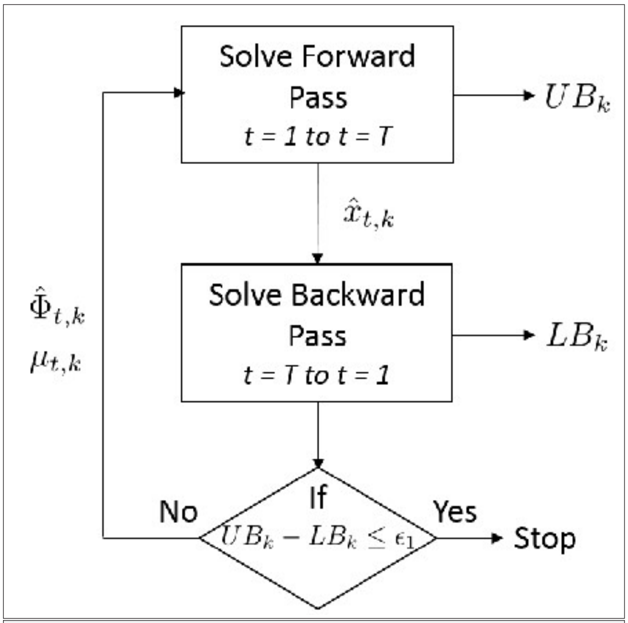

Figure 3. As in the mixed-integer algorithm

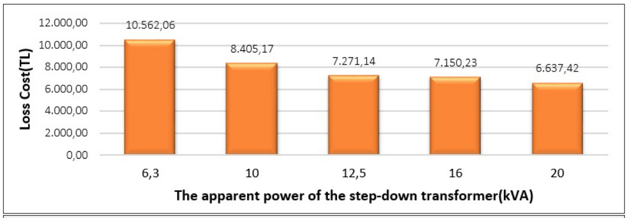

Figure 4. Loss cost of the step-down transformers

gramming methods. The generated models are analyzed using mathematical programming to reach the global optimum with an acceptable error. Integer-mixed linear programming is a mathematical programming method.

A mixed-integer programming problem refers to some of the decision variables with integer values (i.e., −1, 0, 1, 2). It is a problem where it is bounded by integers in the optimal solution. Linear programming problems with mixed integers are generally solved using the linear programming-based branch and boundary algorithm. In (10) and (11), the purpose-functions created in the equations are solved using the branch boundary method in MATLAB. The branch and boundary method determine all possible solution options. However, some solution options that do not lead to the optimal solution are eliminated in advance. Therefore, the number of required evaluations often divides the solution space into small subsets. The subsets created are called branching points. Each branching point is re-evaluated to determine whether further research is needed. In cost minimization problems, to evaluate the objective function values, find the lower limit for the efficient solutions of the subset. Fig. 3 shows the mixed-integer algorithm that creates the performed operation.

Genetic Algorithm

Genetic algorithms, a numerical optimization method, are part of the evolutionary computational technique. Traditional methods are used to solve problems that are challenging or nearly impossible to solve. Genetic algorithms are used in the optimization phase in experimental studies, while in the field of application, in industrial applications and classifications. In the field of engineering, it is most commonly used for optimization. In this paper, the GA tool was used in MATLAB.

Results and Discussion

Table 1, Table 2, and Table 3, respectively, give the technical specifications and costs of the possible step-down transformers, distribution transformers, and conductors to be selected. In Table 1, the one-year costs for step-down transformer stations are calculated using Equation (3) and (4) according to the nominal power. The unit cost of energy used as data in the equations (e_c) is the unit price given for the energy distribution by the Energy Markets Supervisory Authority (EPDK) for 2018. The cost of the facility of the step-down transformer station (Sd_f) includes fixed costs resulting from the material, assembly, and artisanship during the installation of the step-down transformer station. The data on fixed costs are TEDAS 2018 unit prices. We calculate the cost of the plant by adding the expenses resulting from one year of iron losses to these prices. The variable cost of the transformer is the cost of the lost energy resulting from the loss of copper because of the electrical properties in the step-down transformer station. The total annual cost of the step-down transformer station is calculated by collecting the cost of the facility and the cost of the loss, as stated in Equation (1).

Table 1 shows that the cost of the facility increases as the rated power of the step-down transformer stations increases and the unit cost for one year increases. However, Figure 4 shows that the cost of loss decreases as the transformer power increases, showing that transformer losses decrease as power increases.

Table 2 shows the cost findings for the distribution transformers. These values were calculated using Equation (4) and Equation (5). The loss cost decreases as the power value of the transformer increases.

When the findings of Table 1 are examined, the loss cost of a transformer with the same power value is greater than that of a transformer with 33 kV. Therefore, the low voltage level selection is appropriate in the first design phase, but as stated in the literature [14], when the voltage is increased from 10 kV to 20 kV:

* The voltage drop is reduced by 75%.

* The power transfer capacity increases. The transfer capacity is proportional to the voltage, and when the voltage is doubled, the capacity will double. The need for capacity to meet this energy demand is inevitable, especially in areas where energy demand is rapidly increasing. Therefore, increasing the voltage level will support further capacity increases.

Table 1. Cost findings for the downstream transformers

Rated Power (MVA)	Loss On Out Of Gear (KW)	Loss on Load (kW)	Energy Unit Cost (TL/kWh)	Mounted Cost (TL)	Disassembly Cost (TL)	Annual Total Cost (TL)
6.3	10.5	42	0.1266	369.167,52	33.375,43	379.729,58
10.0	14.0	52	0.1266	524.306,80	43.833,52	532.711,97
12.5	16.0	55	0.1266	769.378,87	47.706,11	776.650,01
16.0	21.0	68	0.1266	948.731,66	51.528,37	955.881,89
20.0	25.0	78	0.1266	1.052.496,48	51.527,48	1.059.133,90

Table 2. Cost findings of distribution transformers

Operating Voltage (kV)	Distribution Transformer Power (kVA)	Energy Unit Cost (TL/kWh)	Facility Cost(TL)	Loss Cost (TL)	Annual Total Cost (TL)
15	100	0.1266	11.610,29	25.765,86	37.376,15
33	100	0.1266	13.639,94	29.101,25	42.741,19
15	160	0.1266	15.370,25	21.940,59	37.310,84
33	160	0.1266	17.690,91	24.025,21	41.716,12
15	250	0.1266	19.102,43	19.512,01	38.614,44
33	250	0.1266	22.041,35	21.546,60	43.587,95
15	400	0.1266	23.741,74	17.302,32	41.044,06
33	400	0.1266	27.544,28	18.970,01	46.514,29
15	630	0.1266	31.964,14	15.485,72	47.449,86
33	630	0.1266	36.466,30	16.160,74	52.627,04
15	1000	0.1266	42.016,17	15.092,62	57.108,79
33	1000	0.1266	49.099,34	15.592,93	64.692,27

Table 3. Cost findings of conductors

Conductors Type	Voltage Level (kV)	Equivalent Resistance (Ω/km)	Line (km)	Facility Cost (TL)	Loss Cost (TL)	Annual Total Cost (TL)
1x95/16	15	0,32	2,387	185,65	753,06	938,725
1x95/16	33	0,193	2,387	299,19	206,45	505,637
Swallow	15	1,1365	5,865	116,65	3.820,53	3.937,19
Swallow	33	1,1534	5,865	116,65	1.762,47	1.879,13
Hawk	15	0,3229	5,600	67,59	2.611,81	2.679,40
Hawk	33	0,3575	5,600	67,87	1.314,55	1.382,36

* The network diameter of electricity distribution is expanding. The amount of space for distribution directly proportional to the voltage level also increases because the voltage drop is less.

* The power loss is reduced. When the voltage level is doubled, the energy losses are reduced by approximately 75%.

* The electrical distribution network is more accessible. It is advantageous regarding the operation as the number of step-

Table 4. Results obtained by the mixed-integer programming method

Transformer Information Selected By Algorithm	Transformer item	Total Cost (TL)
100 kVA	11	411.137,655
160 kVA	9	335.797,5519
250 kVA	9	347.529,9674
400 kVA	7	287.308,4011
630 kVA	4	189.799,4515
1000 kVA	2	114.217,5875
6,3 MVA	2	826.210,0
10 MVA	0	0
12,5 MVA	0	0
16 MVA	0	0
20 MVA	0	0
Line Cost		3.767,13 TL
Optimum Cost		2.515.767,74 TL

Table 5. Results obtained with the genetic algorithm method

Transformer Information Selected By Algorithm	Transformer Item	Total Cost (TL)
100 kVA	11	411.137,655
160 kVA	12	447.730,0692
250 kVA	9	347.529,9674
400 kVA	8	328.352,4583
630 kVA	3	142.349,5886
1000 kVA	2	114.217,5875
6,3 MVA	2	759.459,1543
10 MVA	0	0
12,5 MVA	0	0
16 MVA	0	0
20 MVA	0	0
Line Cost		3.767,13 TL
Optimum Cost		2.554.543,61 TL

down transformer stations and fibers will decrease in higher voltage. Furthermore, the simple radial electric distribution scheme preferred in the fiber structure also contributes to this situation.

*It provides a material advantage by performing transmission with lower cross-section cables. The cost of high cross-section cables is less than the cost of lower cross-section cables.

Therefore, the distribution line conductor cost is significant considering the total cost and reducing losses. Table 3 shows the cost findings for conductors used in the objective functions [15].

Findings on the Redesign of the Electrical Distribution Network without Voltage Configuration

The Results Obtained by Optimization Methods

We solved the mathematical models created by using data from a live electrical distribution network, such as in the double-stage electrical distribution activity shown in Figure 1, using the mixed-integer programming method and the genetic algorithm method in MATLAB. In the design, we used the objective function in Equation (10) and distribution network restrictions. In the first case, assuming that the existing system was redesigned with the step-down transformer station, transformer boxes, distribution line, and step-down transformer station, the approximate costs were calculated under the current power density of the network. Tables 4 and 5 show the costs and transformer numbers calculated using the program [15].

Redesign of the Network without the Step-Down Transformer Station

Findings on the Redesign of the Network in Case of Voltage Configuration

In the second case, assuming that the current system was redesigned with the voltage configuration as a single-stage and high-voltage level, transformer boxes, distribution lines, and step-down transformer station approximate costs were calculated using Equation (11) under the current power density of the network. Tables 6 and 7 shows the results obtained in MATLAB [15].

Table 8 summarizes the analysis of the results. In the case of the single-stage electrical distribution (voltage configuration), the results obtained from the genetic algorithm and mixed-integer algorithm increase by 12.9% because of the transformer cost. Although the voltage level increases, the total cost decreases because of the step-down transformer station cost of the transformer and, especially, the decrease in the line costs, resulting in an approximate 25% financial gain.

When the voltage drop is evaluated, the same power value voltage increase will cause a decrease in current. Because the voltage drop is directly proportional to the square of the current, the decrease in current will decrease the voltage drop. This decrease in voltage drop leads us to the conclusion that more customers can receive a conductor with the same cross-sectional value [15].

Both the financial and technical aspects of the voltage configuration in the case of the system would make it easier to operate

Table 6. Results obtained with the mixed-integer programming method

Transformer Information Selected By Algorithm	Transformer item	Total Cost (TL)
100	11	470.153,0561
160	9	375.445,0408
250	9	392.291,5191
400	7	325.600,0337
630	4	210.508,1663
1000	2	129.384,5435
Line Cost		7.555,32 TL
Optimum Cost		1.914.704,81 TL

Table 7. Results obtained with the genetic algorithm method

Transformer Information Selected By Algorithm	Transformer item	Total Cost (TL)
100	11	470153,0561
160	12	500593,3877
250	9	392291,5191
400	8	372114,3242
630	3	157881,1247
1000	2	129384,5435
Line Cost		7.555,32 TL
Optimum Cost		2.033.740,41 TL

Table 8. Cost comparison of designs according to algorithm results

	Dual-Stage Electricity Distribution		Single Voltage Stage Distribution	
	Genetic Algorithm Findigs	Mixed-Integer Algorithm Findings	Genetic Algorithm Findigs	Mixed-Integer Algorithm Findings
Step-Down Transformer Station Cost	826.210,0	826.210,0	0,00	0,00
Distribution Transformer Station Cost	1.791.317,33	1.685.790,61	2.022.417,96	1.903.382,36
Line Cost	3.767,13	3.767,13	7.555,32	7.555,32 TL
Total Cost	2.621.294,46 TL	2.515.767,74 TL	2.029.973,28 TL	1.910.937,68 TL

the structure. Besides, if all equipment used in the electrical distribution network is considered as a possible failure factor, the elimination of the step-down station will decrease the probability of failure.

Conclusion

Planning a distribution system should deliver quality and demanded energy to consumers at the least cost. The development of technology enables the optimum design of large electrical networks, especially with computer support. Many optimization techniques in the literature can be applied to several topics in this research. Choosing an appropriate algorithm allows you to design the electrical network without sacrificing quality energy and low cost.

In this paper, we examined the necessity of the distributing network voltage configuration by using genetic algorithms and mixed-integer programming. We compared the objective function, which is solved by the mixed-integer programming method, to the result of resolving by the genetic algorithm. Although the purpose of using two algorithms is to confirm the accuracy of the results, the mixed-integer programming method approaches achieve the optimum result closer than the genetic algorithm, unlike the integer-free objective functions in integer-containing objective functions.

Currently, the energy distribution joint-stock companies (EDAS) prefer a single-tier distribution of 33 kV in new distribution networks. However, multistage distribution at different voltage levels continues in some parts of the existing network, which had been designed in previous years.

This paper evaluated whether the EDAS should maintain the current state or switch to a single-stage system by raising the voltage level when it expands in a multistage multi-voltage power distribution network. It aims to guide planners and investors by examining the situation financially.

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Leyla AKBULUT is a teaching assistant in Electrıcal and Energy Department of Akseki Vocational School of Alanya Alaaddin Keykubat University. She has completed her undergraduate and graduate education (Master of Science) at Gazi University Faculty of Engineering, Electrical Electronics Engineering Department. Her research areas are energy distribution and power system analysis

Suleyman Sungur TEZCAN is an assistant professor in Gazi University Faculty of Engineering, Electrical Electronics Engineering Department. He has completed his undergraduate at Yıldız Technical University Electrical Engineering Department and graduate education (Master of Science and Doctor of Philosophy) at Gazi University Faculty of Engineering, Electrical Electronics Engineering Department. His research areas are high voltage technique and power system analysis.

Ahmet COSGUN is a Lecturer at Akdeniz University Technical Sciences Vocational School Electricity and Energy Department Air Conditioning Refrigeration Technology Program. He has completed his undergraduate at Yıldız Technical University Mechanical Engineering Department and graduate education (Master of Science) at Sakarya University Mechanical Education Department and (Doctor of Philosophy) at Balikesir University Faculty of Engineering, Mechanical Engineering Department. His research areas are alternative energy sources, energy and energy engineering.