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OPTIMAL LOCATION AND SIZING OF HV/MV SUBSTATION USING THE BRANCH AND BOUND METHOD IN DISTRIBUTION NETWORK OF DEZFUL CITY (KHUZESTAN, IRAN)

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Abstract- Determination of the optimal location and capacity HV/MV substation in a scheduled program can be to reducing overall costs including the fixed costs (land cost, construction cost, equipment purchase cost, and installation cost) and variable costs (energy losses cost and power losses cost). This paper presents a different approach to determining optimal location and capacity HV/MV substation. For that reason the multiobjective function is formulated for solving problem so that the multiple objective functions has become a common objective function by using weighting method of Analytical Hierarchy Process. The solution method is based on analyzing a non-linear optimization problem and branch and bound algorithm is used to determine the optimal response. In order to evaluate the performance of the proposed algorithm, the distribution network has been studied in Dezful city. The results of simulation using Matlab software show effectiveness the proposed approach to reduce costs and determine the optimal capacity of HV/MV substation.

Keywords: HV/MV Substation, Optimal Location, Distribution Network, Branch and Bound Algorithm, Determining Optimal Capacity.

I. INTRODUCTION

Design and expansion of distribution systems seem inevitable in view of the need to satisfy the rise in energy consumption in a technical and economical way. Distribution substation planning is considered the most important step in the power system planning process and its planning model seeks to determine a strategy that will minimize the total costs associated with configuring and operating an electric power distribution system over a given planning horizon. In recent years a lot of mathematical models and algorithms have been developed [1-12]. Methods and procedures of the distribution system planning are varied according to the problem solution viewpoint. In [1], an approach to determine the sizing and timing of substations was proposed.

In this approach sizing and timing were effectively decoupled by using the Pseudo-Dynamic approach. This approach requires sequential applications of the single-time-period static planning model. In [2], a transportation approach for solving the substation location, sizing, and service area problem was developed. This approach assumed that the total demand is equal to the total supply and the objective was to determine a feasible flow pattern that minimizes the total transportation cost, while satisfying all demands. In [3], a fixed charge transshipment model for the problem of choosing an optimal substation location was developed. The objective function of the developed model included both the fixed and the variable cost components and was solved using an integer branch-and-bound technique.

In [4] and [5] a Heuristic Combinational Optimization algorithm was proposed to determine the optimum required substations capacities and then a Multisource Locating algorithm is used to allocate the substations by minimizing the cost of energy losses on the feeders. This procedure does not require the selection of candidate substation locations. In [6] an adaptive mutation particle swarm optimization algorithm was developed to solve for the optimal substation location and sizing. This approach does not require candidate substation location and it takes into account both the substation construction investment and the geographic information system (GIS).

Another substation expansion planning procedure was developed [7]. It proposed a mathematical clustering technique to determine the feasible candidates while considering the substation capacities, feeder capacities, and voltage regulations limitations. After that, a genetic algorithm is used to solve the optimization problem for expansion requirements for existing substations and new substation allocations and capacities determination. In [8], a probabilistic methodology for distribution substation location selection was presented. This methodology took into account the hourly (or daily) load cycle. For different hourly load scenarios, the load center locations are determined and weighted according to their load magnitude.

These locations are then used to develop a probability perimeter of the area where the substation should be located. The process also takes into account factors such as land availability and the cost of land. In [9] a new planning optimization model for distribution substation siting, sizing, and timing. The proposed model involves using linear functions to express the total cost function. The developed model includes different electrical constraints such as voltage drops, substation and transformer capacities, power flow, and radial flow constraints. The proposed problem formulation was modeled and solved using the General Algebraic Modeling Software (GAMS) solvers.

In [10], a technique for optimal planning of MV and LV segments of a distribution system is presented. A comprehensive optimal planning of distribution systems for the urban/semi-urban areas is presented. Both MV and LV networks are optimized and the optimal location and size of transformers and substations, as well as, the route and type of MV and LV feeders are obtained. This work is aimed at Greenfield sites where the location of specific loads or substations is not preassigned. In this work, the cost of the distribution system elements is not assumed to be continuous, but discrete. The employed objective function consists of the capital cost, loss cost and reliability cost.

This paper presents a non-linear mix-integer model for optimal locating, sizing and determining the service area of HV/MV substations in a scheduled program using weighting method of Analytical Hierarchy Progress. In problem formulation, cost function includes: construction and equipment costs, high voltage (HV) feeder cost, medium voltage (MV) feeder cost, power loss cost and energy loss cost. For optimization method, branch and bound algorithm (BBA) is used.

The service area under investigation is divided into some regions to obtain the load concentration point. In optimization procedure, splitting of each load point between the existing and candidate substations are considered. The effectiveness of proposed method is demonstrated by application on a real network (Distribution Network of Dezful City in Khuzestan, Iran) using Matlab software base on BBA algorithm.

II. MATHEMATICAL FORMULATION OF PLANNING MODEL

For determination of optimal locations, number, sizing and service area of substations from among candidate sites, the problem formulation and objective function are defined as follows:

$$F = k_1 \sum_{i=1}^{n} (FC_i E) + k_2 \sum_{i=1}^{n} (f_h S_i L_i) + k_3 \sum_{i=1}^{n} \sum_{j=1}^{N} (f_l d_{ij} S_j) + k_4 \sum_{i=1}^{n} \sum_{j=1}^{N} (f_P d_{ij} S_j^2) + k_5 \sum_{i=1}^{n} \sum_{j=1}^{N} (f_e f_{ls} d_{ij} S_j^2) \qquad (1)$$

subject to: $E = (1+r)^m$ (2)

where, n is number of all candidate and existing substations; n_l is number of load points that connected to ith substation; FC_i is construction and equipment cost; d_{ij} is distance between ith substation and jth load point; s_{ij} is load of jth load point connected to ith substation; s_i is capacity of ith substation; L_i is HV feeder length of ith substation; f_h is construction cast of HV feeder for each km; f_l is construction cost of MV feeder for each km; f_p is the peak power loss cost which is the saving per MW reduction in the peak power; f_e is energy loss cost which is per MWH; $k_1 \ldots k_5$ is weighting factors; E is economic factor; r is interest rate and m is the planning period.

III. WEIGHTING FACTORS

For problem solving, multi-objective function is converted to a single objective function by using Analytical Hierarchy process (AHP) model for determining the weighting factors $k_1 \ldots k_5$ to each normalized objective function [13]. AHP is a mathematical structured technique that includes matrices and their associated right eigenvector's. It involves building a hierarchy of decision elements and then the pair-wise comparisons are done in terms of which element dominates the other.

This gives a weighting for each element within a cluster and also a consistency ratio in order to checking the consistency of the data. The decision matrix A is defined as follows:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ . & \cdots & . \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \qquad (3)$$

where, a_{ij} is element corresponding to the relative importance of the ith objective function is as compared with jth objective function, A is the decision matrix ($n \times n$), and n is number of objective functions. The elements a_{ij} are governed by the following rules:

$$\begin{cases} a_{ij} = \dfrac{1}{a_{ij}} & a_{ij} > 0 \\ a_{ij} = 1 & \text{for all } i \end{cases} \qquad (4)$$

To determine elements in the matrix A, Table 1 is used.

Table 1. Scale of relative importance

Value	Description of comparison
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

The following steps are used for applying the AHP:

- Step 1: determine matrix A.
- Step 2: calculate $|A - \lambda I| = 0$ and obtain largest eigenvalue of the matrix $A(\lambda_{\max})$.
- Step 3: if inconsistency ratio < 0.1 then go to next step otherwise go to step 1 and set matrix A with review in determining the elements
- Step 4: obtain k_i by using the following equation:

$$(A - \lambda_{\max} I) \times K = 0 \quad , \quad \sum_{i=1}^{n} k_i = 1 \qquad (5)$$

IV. BRANCH AND BOUND METHOD

The branch and bound method is the basic powerful technique for solving integer and discrete programming problems [14]. The method is based on the observation that the enumeration of integer solution has a tree structure. The main idea in branch and bound is to avoid growing the whole tree as much as possible, because the entire tree is just too big in any real problem. Instead branch and bound grows the tree in stages, and grows only the most promising nodes at any stage. It determines which node is the most promising by estimating a bound on the best value of the objective function that can be obtained by growing that node to later stages.

The name of the method comes from the branching that happens when a node is selected for farther growth and the next generation of children of that node is created. The bounding comes in when the bound on the best value attained by growing a node is estimated. Pruning is one of the most important aspects of branch and bound since it is precisely what prevents the search tree from growing too much.

The node selection policy governs how to choose the next bud node for expansion. There are three popular policies for node selection:

- Best- first selection: choose the bud node that has the smallest value of the bounding function
- Depth-first: choose only from among the set of bud nodes just created. Choose the bud node with the smallest value of the bounding function. Depth-first node selection takes one step deeper into the branch and bound tree at each iteration, so it reaches the leaf nodes quickly. This is one way of achieving an early incumbent solution. If there was no possibility to proceed any deeper into the tree, back up one level and choose another child node from that level.
- Breadth-first: expand bud nodes in the same order in which they were created.

The algorithm stops when the incumbent solution's objective function value is better than or equal to the bounding function value associated with all of the bud nodes. In other words there are no more bud nodes left to consider for further growth.

V. DETERMINING THE LOAD GRAVITY CENTERS

The load concentration point is a dummy point, so we cannot find its path through the streets. Determination of the distance by radial and direct method is not a reasonable method because the covering such a distance is practically unlikely. For this reason, area under study is divided into several regions in which each region is supplied by several MV/LV transformers.

In order to consider load growth from base year to horizon year, power consumption of each region is determined by forecasting the load using an appropriate forecasting technique and power consumption of existing and new MV/LV transformers associated to each region is obtained for horizon year. Then with regard to the location of existing and new MV/LV transformers, load gravity center of each region is obtained using the following expressions:

$$X = \frac{\sum_{i=1}^{n} S_i X_i}{\sum_{i=1}^{n} S_i} \quad (6)$$

$$Y = \frac{\sum_{i=1}^{n} S_i Y_i}{\sum_{i=1}^{n} S_i} \quad (7)$$

where n is number of MV/LV transformers into the each region; x_j is longitude of ith MV/LV transformers; y_i is latitude ith MV/LV transformers; s_j is power consumption of each of ith MV/LV transformers for horizon year; X_i is longitude of load gravity center associated to ith region; and Y_i is longitude of load gravity center associated to ith region. Data of load and their growth rates for base years are shown in Table 2. So distance between substations and load gravity centers is obtained by using a GIS mapping software is called Mapsource (Figure 1).

Table 2. The objective function values for connection any load center to each of substations

	$L(1)$	$L(2)$	…...	$L(k)$
S (1)	F_{11}	F_{12}	…...	F_{1k}
S (2)	F_{21}	F_{22}	…...	F_{2k}
…...	…...	…...	…...	…...
S (n)	F_{n1}	F_{n2}	…...	F_{nk}
$New(1)$	F'_{11}	F'_{12}	…...	F'_{1k}
$New(2)$	F'_{21}	F'_{22}	…...	F'_{2k}
…...	…...	…...	…...	…...
$New(m)$	F'_{m1}	F'_{m2}	…...	F'_{mk}

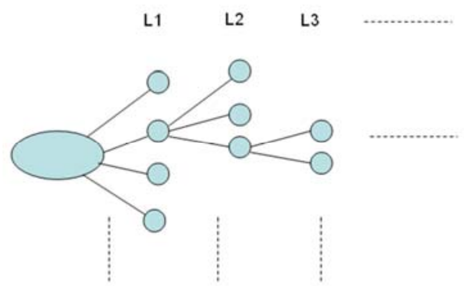

Figure 1. Tree structure of the proposed method

VI. OPTIMIZATION METHOD

The solution method is based on analyzing a non-linear optimization problem and we have used the BBA for performing optimization. Table 2 is used for the implement the branch and bound algorithm. This table shows the objective function values for connection any load center to each of substations so that $L(1)$ to L(k) are load centers and $S(1)$ to $S(n)$ and $New(1)$ to $New(m)$ are existing and candidate HV/MV substations, respectively.

The algorithm operates in such a way that a load center is allocated to a substation at any stage of tree growth. Figure 1 shows tree structure of the proposed method. We assume that load centers $L(1)$ to $L(k)$ are related to levels of i=1 to k, respectively and bud nodes j=1 to m are generated at each level so each node contains a complete solution for objective function value F.

The BB algorithm starts the search at the top of the tree (level 0), and all nodes at level-1 are analyzed. At each level, the successor node with the lowest F is analyzed, and the search continues until the bottom of the tree (level k) is reached; this gives one full path through the tree and an initial bound B for the criteria function F. The algorithm then backtracks to any unexplored nodes at level 2 and then those unexplored nodes at level 1.

If $F < B$ for a node (lower F values are better), its successor nodes are explored further (as long as their F values remain lower than B). If $F > B$ for a node, then F does not have to be evaluated for its successor nodes because F decreases as we proceed to the next higher level down the tree and its successor nodes (leaves) at the bottom of the tree cannot be the optimal subset. This causes the BB algorithm to be fast, as many sub-trees may be cut off. If a new deferent full path with a $F < B$ is found, the bound B is updated with the new lower value.

The search and backtracking continues until all nodes in the tree are either explored or cut off from the tree; thus, the BB algorithm gives the optimal solution. In optimization procedure the following subjects should be accounted:

- Each load center can be supplied with maximum two substations.
- Substation loading must be in acceptable margins.

VII. CASE STUDY

In order to evaluate the performance of the proposed algorithm, the distributed network of Dezful city in north Khuzestan, Iran is considered. In distributed network of Dezful city, existing substations include: Dezful ($S(1)$), Fatholmobin ($S(2)$), Dezhpol ($S(3)$), Modarres ($S(4)$), Shahrak-Sanati ($S(5)$), Roudband ($S(6)$) and Zibashahr ($S(7)$), and Candidate substations include: Jomhouri ($New(1)$), Ashrafi Esfahani ($New(2)$), Fath2 ($New(3)$) and Gholestan ($New(4)$).

Loads data and their growth rates from base year to horizon year are shown in Table 3 over the 5-year planning period. Program input data include load characteristics (location, magnitude and rate of load growth), the information of existing substation (location and capacity), the information of candidate substation (price of land, location and cost of upstream downstream lines) and costs of the loss of power and energy.

To determine the location and service area of HV/MV substations using the Branch and Bound algorithm, the simulation is done in Matlab software environment. According to Equation (3), to determine the weighting coefficients (K_i), the matrix A is formed on the basis of objective functions in Equation (8). In this matrix, rows 1 to 5 and columns 1 to 5 represent a fixed cost, upstream lines cost, downstream lines cost, cost of power losses and cost of energy losses.

According to equation (5), the weight coefficients of the objective function (1) can be obtained as follows:

$$A = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{5} & \frac{1}{8} & \frac{1}{8} \\ 5 & 1 & 4 & \frac{1}{4} & \frac{1}{4} \\ 5 & \frac{1}{4} & 1 & \frac{1}{6} & \frac{1}{5} \\ 8 & 4 & 6 & 1 & 2 \\ 8 & 4 & 5 & \frac{1}{2} & 1 \end{bmatrix} \qquad K = \begin{bmatrix} k_1 = 0.0311 \\ k_2 = 0.1444 \\ k_3 = 0.0740 \\ k_4 = 0.4314 \\ k_5 = 0.3191 \end{bmatrix} \tag{8}$$

Figure 2 shows the geographic location of the existing substations and distribution candidate substations and centers of gravity of the load related to Dezful city in MapSource software. Table 4 shows the results of simulations, while, the existing substations are not extensible.

In this case, The Jomhuri and Golestan substations are best candidates for feeding load in horizon year. Since the objective function has the lowest value and the best distribution of the load is carried on distribution substations with minimum cost while, load is not allocated to Fath2 and Ashrafi Esfahani substations. Thus according to the total loads allocated to Jomhouri substation (81.23 MVA) and Gholestan substation (74.55 MVA), 120 MVA capacity is offered to both Jomhuri and Gholestan substations that reserve capacity for load growth is also considered.

Table 4 shows that after optimization, Jomhuri substation is fed loads of L2, L13, L21, L25 and L27 as 100% and also Gholestan substation is fed loads of L10, L31, L36, L38, L51as 100% and is fed load of L47 as 16% with this explaining that 84% of the load L47 is fed by Zibashar substation.

In Table 5, the load distribution is considered with 50% increased capacity for the Zibashar substation. In this case, the Loads of 81/23 MVA and 53/55 MVA are allocated to Jomhuri and Gholestan substation, respectively, 120 MVA and 90 MVA capacities are offered to Jomhuri and Gholestan substations that reserve capacity for load growth is also considered.

In Table 6, the load distribution is considered with 100% increased capacity for the Zibashar substation. In this case, the Loads of 81.23 MVA and 32.55 MVA are allocated to Jomhuri and Gholestan substation, respectively, 120 MVA and 60 MVA capacities are offered to Jomhuri and Gholestan substations that reserve capacity for load growth is also considered.

Figure 3 shows objective functions values without and with increased capacity for Zibashar substation. With the increasing amount of capacity for Zibashr substation, the total cost is reduced.

VIII. CONCLUSIONS

This paper presents a new planning optimization model for distribution HV/MV substation allocation and sizing. The proposed model properly handles voltage profile in substations, loss of power, loss of energy and cost of area in cost function. The results in a real network show that proposed method is an efficient method, especially in large scale area with high number of load points and substations.

Table 3. Loads data and their growth rates from base year to horizon year

Load point	Load in base year (MVA)	Load in horizon year (MVA)	Load growth (%)	Load point	Load in base year (MVA)	Load in horizon year (MVA)	Load growth (%)	Load point	Load in base year (MVA)	Load in horizon year (MVA)	Load growth (%)
*L*1	3.84	6.1	9.68	*L*18	12.66	16.88	5.92	*L*35	16.03	23.31	7.58
*L*2	17.53	26.06	8.26	*L*19	9.40	14.63	9.24	*L*36	12.37	19.89	9.96
*L*3	5.03	7.68	8.84	*L*20	5.80	7.46	5.16	*L*37	8.16	13.14	10
*L*4	7.34	10.85	8.14	*L*21	5.69	7.59	5.92	*L*38	2.31	3.65	9.62
*L*5	5.08	8.12	9.82	*L*22	12.56	19.61	9.32	*L*39	12.57	20.13	9.87
*L*6	3.23	5.15	9.81	*L*23	14.60	23.14	9.64	*L*40	4.80	7.69	9.88
*L*7	7.97	12.70	9.75	*L*24	10.03	14.95	8.31	*L*41	1.01	1.30	5
*L*8	6.81	9.73	7.4	*L*25	3.42	5.50	10	*L*42	5.74	6.98	3.97
*L*9	6.32	10.09	9.81	*L*26	19.78	28.22	7.37	*L*43	3.56	4.73	5.88
*L*10	13.34	18.26	6.48	*L*27	12.81	18.11	7.16	*L*44	1.78	2.27	5
*L*11	2.41	3.20	5.81	*L*28	19.19	30.15	9.45	*L*45	0.40	1.50	5
*L*12	7.41	10.14	6.48	*L*29	2.89	4.00	6.75	*L*46	3.14	3.88	4.34
*L*13	9.30	13.86	8.31	*L*30	1.49	1.80	3.91	*L*47	4.05	4.81	3.5
*L*14	7.20	11.35	9.53	*L*31	13.09	20.53	9.42	*L*48	7.17	10.57	8.06
*L*15	6.31	8.59	6.37	*L*32	7.77	10.53	6.28	*L*49	6.69	7.29	1.73
*L*16	8.11	11.96	8.08	*L*33	2.19	3.47	9.66	*L*50	4.06	6.49	9.87
*L*17	3.14	4.19	5.91	*L*34	1.39	1.86	6.03	*L*51	7.17	11.45	9.81

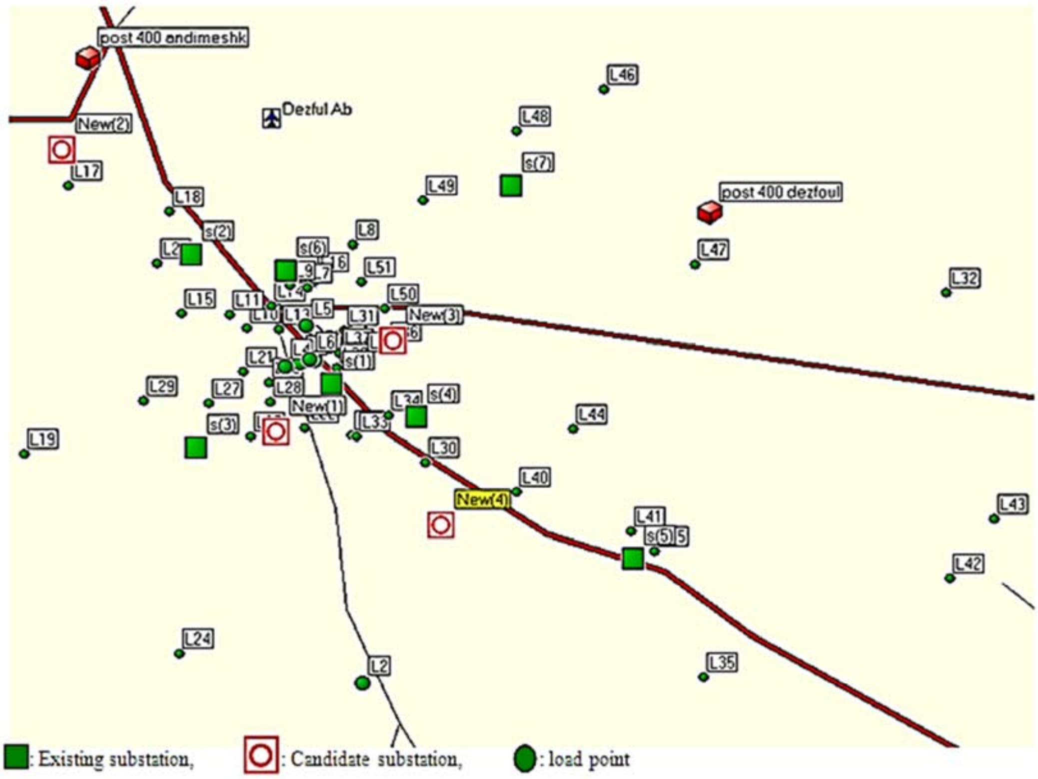

Figure 2. Location of substations and load gravity centers in MapSource software

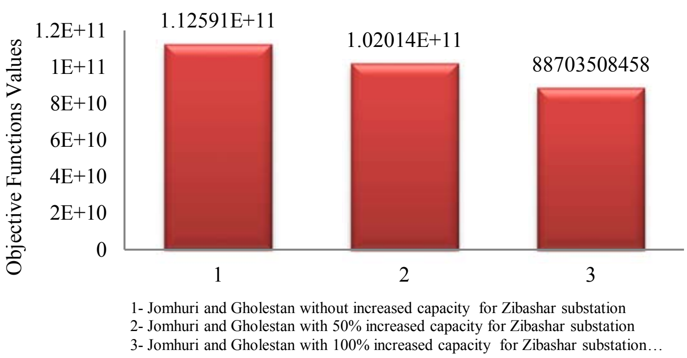

Figure 3. Objective Functions Values with and without increased capacity for Zibashar substation

Table 4. The loads distribution on existing and candidate substations without increased capacity for the Zibashar substation

	Station name	Capacity (MVA)	Allocated load point									
Existing substations	S(1)	60	L1	L3	L4	L5	L6	L22				
			100%	100%	100%	100%	100%	20%				
	S(2)	120	L9	L11	L12	L14	L15	L16	L17	L18	L19	L20
			18%	100%	100%	100%	100%	100%	100%	63%	100%	100%
	S(3)	120	L18	L22	L24	L27	L28	L29				
			37%	80%	100%	100%	77%	100%				
	S(4)	120	L23	L28	L30	L33	L34	L35	L37	L39	L40	
			100%	23%	100%	100%	100%	25%	100%	100%	100%	
	S(5)	60	L32	L35	L41	L42	L43	L44	L45			
			100%	75%	100%	17%	100%	100%	100%			
	S(6)	30	L7	L9								
			100%	82%								
	S(7)	60	L8	L46	L47	L48	L49	L50				
			100%	100%	84%	100%	100%	100%				
Proposed substations	New(1)	120	L2	L13	L21	L25	L26					
			100%	100%	100%	100%	100%					
	New(2)	120	L10	L31	L36	L38	L47	L51				
			100%	100%	100%	100%	16%	100%				

S(1) = Dezful Station	S(4) = Modarres Station	S(7) = Zibashar Station
S(2) = Fatholmobin Station	S(5) = Sharak Sanati Station	New(1) = Jomhouri Station
S(3) = Dezhpol Station	S(6) = Roudband Station	New(2) = Golestan Station

Table 5. The loads distribution on existing and candidate substations with 50% increased capacity for the Zibashar substation

	Station name	Capacity (MVA)	Allocated load point									
Existing substations	S(1)	60	L1	L3	L4	L5	L6	L22				
			100%	100%	100%	100%	100%	20%				
	S(2)	120	L9	L11	L12	L14	L15	L16	L17	L18	L19	L20
			18%	100%	100%	100%	100%	100%	100%	63%	100%	100%
	S(3)	120	L18	L24	L27	L28	L29					
			80%	100%	100%	77%	100%					
	S(4)	120	L23	L28	L30	L33	L34	L35	L37	L39	L40	
			100%	23%	100%	100%	100%	25%	100%	100%	100%	
	S(5)	60	L32	L35	L41	L42	L43	L44	L45			
			100%	75%	100%	17%	100%	100%	100%			
	S(6)	30	L7	L9								
			100%	82%								
	S(7)	90	L8	L31	L46	L47	L48	L49	L50	L51		
			100%	43%	100%	84%	100%	100%	100%	100%		
Proposed substations	New(1)	120	L2	L13	L21	L25	L26					
			100%	100%	100%	100%	100%					
	New(2)	90	L10	L31	L36	L38						
			100%	57%	100%	100%						

Table 6. The loads distribution on existing and candidate substations with 100% increased capacity for the Zibashar substation

	Station name	Capacity (MVA)	Allocated load point									
Existing substations	S(1)	60	L1	L3	L4	L5	L6	L22				
			100%	100%	100%	100%	100%	20%				
	S(2)	120	L9	L11	L12	L14	L15	L16	L17	L18	L19	L20
			18%	100%	100%	100%	100%	100%	100%	63%	100%	100%
	S(3)	120	L18	L24	L27	L28	L29					
			37%	100%	100%	77%	100%					
	S(4)	120	L23	L28	L30	L33	L34	L35	L37	L39	L40	
			100%	23%	100%	100%	100%	25%	82%	100%	100%	
	S(5)	60	L32	L35	L41	L42	L43	L44	L45			
			100%	75%	100%	17%	100%	100%	100%			
	S(6)	30	L7	L9								
			100%	82%								
	S(7)	120	L8	L31	L36	L46	L47	L48	L49	L50	L51	
			100%	100%	46%	100%	100%	100%	100%	100%	100%	
Proposed substations	New(1)	120	L2	L13	L21	L25	L26					
			100%	100%	100%	100%	100%					
	New(2)	60	L10	L36	L38							
			100%	54%	100%							

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