Optimal RTU Placement in Power Distribution Systems Using a Novel Method Based on Analytical Hierarchical Process (AHP)

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Abstract— **In a practical power system, automating all the substations is neither affordable nor economically justifiable. On the other hand, the trend for electric power subsidies elimination in some regions, such as Iran, aggravates this situation. To enhance the cost effectiveness of distribution automation system, this paper proposes a novel applicable qualitative-quantitative method using analytical hierarchical process (AHP) to find the optimum placement of remote terminal units (RTU). Entire attempt is to contribute all the crucial technical and practical parameters related to this problem in order to find the most reliable solution. Optimum number of RTUs is determined using the concepts of reliability cost/worth taking into account the total cost of customer interruption and investment cost of RTUs. The effectiveness of the proposed technique is validated on a real distribution feeder of Iran's power grid.**

Keywords-component; AHP, Automation, Placement, Remote Terminal Units, Cost/Worth Analysis

I. Introduction

Nowadays, advances in science and technology, industries development, increasing growth of urban population and emergence of privatization process and deregulation have deteriorated one of the most important problems in distribution of electrical power, its continuity accompanied by its quality [1]. Large numbers of interruptions in addition to their long durations make a great number of manpower be engaged to resolve the problem. With the postponed equipment services, equipments failure rates will increase and consequently, the high statistics of interruptions will be reported. To achieve a remedy to this problem, it is necessary for distribution systems to be control automated. In non-automated power distribution girds, after each interruption, a lot of time will be spent to find the fault location and its isolation from the rest of the network [2]. This time may further increase to several hours in large scale networks or because of some operation limitations such as traffic and population crowds; however, in today's industries, power outages even for a few seconds will cause irreparable damages to the country economy [3].

On the other hand, distribution system improvements lead to the fact that it is not possible to use the traditional methods of maintenance, operation and protection. Therefore, data acquisitions of distribution systems and also benefiting from an automation system that can remotely monitor and coordinate commands to enable immediate response and switching are obviously inevitable. Proper performance of SCADA systems relies on an accurate and high-security communication between control center and remote terminal units. Hence, a remote operation is possible within a few seconds and consequent troubleshooting time will decrease to a minimum by sending commands remotely to control the devices via control center and the remaining grid is then isolated promptly [3]. So, it seems necessary to find the proper location of the terminals and to determine the beneficial number of them due to the available financial resources.

There are some placement methods proposed in the literature. References [4, 5], considered power system observability as the sole parameter in the placement process. A method for RTU placement is proposed in [6] regarding observability, critical measurements, and loss of RTUs as its basis. Reference [7] presented a placement method that combines cost, accuracy, reliability, and bad data processing requirements.

Finding the appropriate numbers and locations of remote terminals is very difficult in today's complex power distribution networks. Distribution companies may use their past experiences, experiential data from customers, and some political and economical considerations to choose the appropriate number and location of RTUs. As far as the authors' knowledge, these realistic points are not considered in any of the past literature. In an attempt to overcome such shortcomings, this paper is to introduce a method to sensibly and meanwhile systematically solve the problem taking a robust decision making method called AHP as basis. Hence, all the practical factors which are involved in the problem can be effectively considered and via the reliability cost/worth analysis, the optimum solution will be reached then.

II. ANALYTICAL HIEARARCHICAL PROCESS

The Analytical Hierarchy Process Model designed by TL Saaty [8] is a multi-criteria decision-making (MCDM) technique which has been widely used to make complex decisions. The method of AHP makes people's thinking process hierarchical and consequently is a qualified method that carries out weight analysis with the combination of qualitative and quantitative aspects. It involves the comparison of decision elements which are hardly quantifiable by building the hierarchy of them and then making comparisons between each possible pair in each cluster. This gives a weighting factor for each element within a level of the hierarchy. The interested readers who may follow the details are referred to references [8, 9].

III. METHODOLOGY

A. AHP and RTU Location Candidates

a) Criteria Definition

In complex environments consisting of multiple options and criteria (quantitative and qualitative), decision makers are faced with several options that should be investigated by different criteria, which stem from their internal and external environment. In this paper, to prioritize the installation location of the RTUs, an applicable method of decision making based on characteristics of AHP is proposed. The first step of AHP for evaluating the goal is to develop some criteria and then find a hierarchy of the problem. In this regard, after several meetings with distribution experts, several criteria presented in Table I were found and discussed.

TABLE I. CRITERIA DEFINED TO RANK THE CANDIDATE SUBSTATIONS

CRI. 1	Load Types and Their Total Number of Customers
CRI. 2	Load Capacity
CRI. 3	Substation Accessibility
CRI. 4	Grid Topology and Maneuverability

According to the first criterion, load type and total number of its customers can be a criterion for deciding whether related substation to be automated or not. Customers are assumed to be commercial, residential, and special (hospitals, military, political and so on) or a combination of the above. Load capacity is also assumed to be another criterion. It's almost equal to transformers capacity. Certainly, a substation that has a bigger number of customers is in a different priority level for automation than those which feed the lower number of customers and thus lower load capacity. The third criterion is defined as substation accessibility. There are substations that are placed somewhere which are difficult to access; for example, when a substation in a market is such that its door is closed till a specific time or where heavy traffic is common. In such circumstances, where a fault occurs, the time to access will increase and consequently will lead to more energy not supplied. It's of great importance to consider the grid topology and maneuverability as a criterion to this problem. As shown in Fig. 2, substation No. 3 is topologically important.

b) Hierarchy Modeling and Weighting

This is shown in Fig. 1 and allows the visualization of the interrelationships between the factors of different levels. In modeling, the goal, the chosen alternatives and criteria form the hierarchy. The goal is placed at the top. In intermediate levels, there are criteria and sub-criteria that cause the same impact on the goal [8]. Next, we have to form a judgment matrix. The value of elements in the judgment matrix reflects the user's knowledge about the relative importance between every pair of the factors. Once the pair-wise comparisons have been made for the four criteria, each alternative is compared against other alternatives with respect to the corresponding criterion at a time. Comparisons of main criteria are shown in Table II. For example, may be according to the research and assumption, the first criterion is C_{12} times as important as the second criterion and so on. Final weights of the criteria are reached then which is denoted here by C_i.

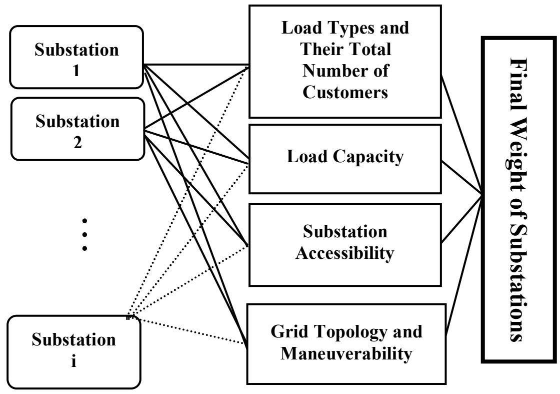

Figure 1. The analytic hierarchy process (AHP) scheme

TABLE II. PAIR-WISE COMPARISON OF CRITERIA

	CRI. 1	CRI. 2	CRI. 3	CRI. 4
CRI. 1	1	C_{12}	C_{13}	C_{14}
CRI. 2	C_{21}	1	C_{23}	C_{24}
CRI. 3	C_{31}	C_{32}	1	C_{34}
CRI. 4	C_{41}	C_{42}	C_{43}	1
Final Weight	C_1	C_2	C_3	C_4

AHP adopts the 1-9 marking method to constitute the judging matrix, which are nine fuzzy linguistic variables [8]. The 1-9 scales are illustrated in Table III.

c) Qualitative and Quantitative Criteria Decomposition

In order to achieve more accuracy, the four proposed criteria are decomposed into two categories of qualitative and quantitative. The pair-wise comparison tables for quantitative criteria should be completed more precisely; e.g. for the criterion, load types and their total number of customers, a table is framed to compare all the load types qualitatively as shown in Table IV where CL, RL and SL denote, respectively, commercial loads, residential loads and special loads.

After determining the total weight of each load type due to Table IV, an equation to quantitatively considering the total number of customers is proposed as expressed in (1):

$$W_{s,i} = C_i \bar{r}_1 + R_i \bar{r}_2 + S_i \bar{r}_3 \quad (1)$$

Where C_i, R_i and S_i are the total number of commercial, residential and special loads, respectively, and $\bar{r}_i$ and $W_{s,i}$ are the geometric mean value of the i^{th} row of Table IV and total weight of i^{th} substation according to this criterion, respectively.

TABLE III. SCALE METHOD OF AHP COMPARISONS

1-9 scale	The Relative Importance of the Criteria
1	Equally Important
3	Moderately Important with One Over another
5	Strongly Important
7	Very Strongly Important
9	Extremely Important
2,4,6,8	Intermediate Values

TABLE IV. PAIR-WISE COMPARISON OF DIFFERENT LOAD TYPES

	CL	RL	SL	Total Weight
CL	1	r_{12}	r_{13}	r_1
RL	r_{21}	1	r_{23}	r_2
SL	r_{31}	r_{32}	1	r_3

The second criterion, load capacity, has been taken into consideration such that normalized capacity of each substation transformers based on the biggest one is attributed to each substation. For the last two criteria, the same procedure as Table II will be done for each substation. Finally, the total weight of each substation, W_i, can be traced by (2):

$$W_i = \sum_{j=1}^{4} W_{i,j} . W_j \qquad (2)$$

in which W_j is the normalized weight of the j^{th} criterion and W_{ij} is the weight of i^{th} substation according to j^{th} criterion.

B. Reliability Cost/Worth and Determination of the Number of RTUs

In a deregulated market and restructured situation, automation of all the substations is not at all affordable. Power system planners struggle to determine the optimum balance between investment costs and system reliability to meet the operational and economical necessities. So, the concept of reliability cost/worth [10] is used to determine the total number of RTUs to be installed. The basic distribution system reliability indices are the three load point indices of average failure rate λ, the average repair time r and the annual outage duration U. The system expected energy not supplied is obtained using (3):

$$ENS = \sum_i L_{ai} . U_i \ (kWh/yr) \qquad (3)$$

Where L_a is the average load. In this paper, the total cost of reliability (TCR) to be minimized is defined as (4):

$$TCR = CIC + AINVC \ (\$/yr) \qquad (4)$$

Where CIC is customer interruption cost and AINVC is the annual investment cost of RTUs. CIC is calculated as follows:

$$CIC = \sum_i IC_i = \sum_i \sum_k IC_{ik} \ (\$/yr) \qquad (5)$$

Where IC stands for interruption cost and i is the number of load points and k is the customer type. The CIC in (5) represents the aggregated interruption costs of different types of customers, which have been derived for the residential, commercial, and special customers, respectively. The higher hierarchy level of customers denotes the more critical is the power service and so different electricity prices. AINVC assumed to be defined as (6):

$$AINVC = C_{RTU} . m . \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (6)$$

Where, C_{RTU} is investment cost of RTU, m is the number of RTUs, n is its expected life, and i is the interest rate.

IV. EMPRICAL STUDY

A. Discription of the Test Distribution Feeder

The proposed method is applied to a feeder of Iran's distribution network shown in Fig. 2. The related data is available in Table V in which H and M represent the hospital and military station, respectively. Power factor for all the transformers is assumed to be 0.9.

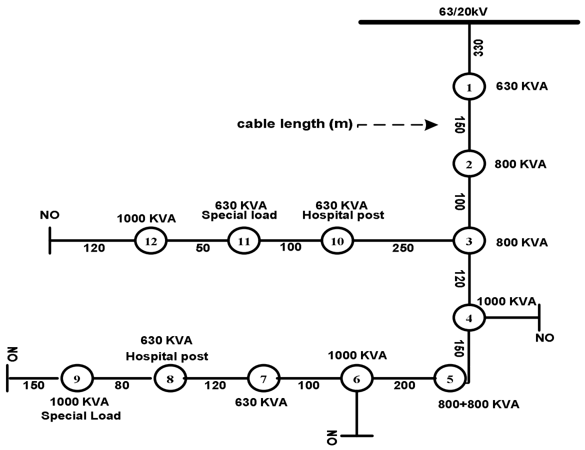

Figure 2. Distribution test feeder

TABLE V. TEST FEEDER DATA

SUBSTATION	1	2	3	4	5	6	7	8	9	10	11	12
COMMERCIAL CUSTOMERS	80	100	100	120	150	400	70	0	100	0	0	200
RESIDENTIAL CUSTOMERS	300	300	250	300	300	100	250	0	250	0	0	250
SPECIAL CUSTOMERS	0	0	0	0	0	0	0	1H	0	1H	1M	0

B. AHP Implementation on Finding the Optimum RTU Location

An RTU is required to be located at a substation in regards with the proposed qualitative- quantitative method. The final weight of each criterion is depicted in Fig. 3. Accordingly, the final weight of each substation is demonstrated in Fig. 4 by implementing the proposed procedure. Hence, the technically important and topologically critical candidates for RTU placement are found and efficiently ranked.

C. Cost/Worth Analysis on Finding the Optimum Number of RTUs

To implement the cost/worth analysis, all the required data are shown in Tables VI and VII. The results of system reliability analysis are shown in Table VIII in which ENS_C, ENS_R, and ENS_S, are representatives of the energy not supplied of commercial, residential and special loads, respectively and so are for CIC.

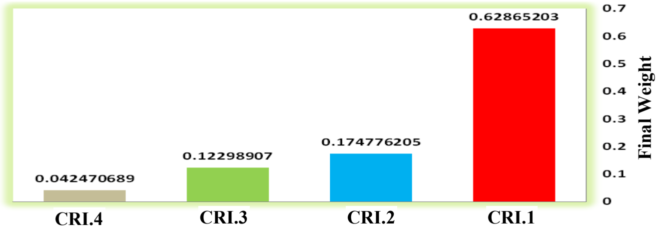

Figure 3. Final weight of the proposed criteria

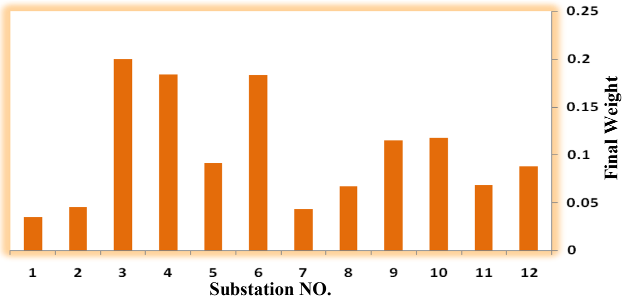

Figure 4. Final ranking of the substations

TABLE VI. REQUIRED DATA FOR RELIABILITY ANALYSIS

λ (failure/yr/km)	Repair time (hrs)	$t_{sw,}$ manual (hrs)	$t_{sw,}$automatic (hrs)
0.7	3	2	0.2

TABLE VII. AVERAGE ELECTRICITY PRICE FOR DIFFERENT KINDS OF LOADS

Load Types	Commercial	Residential	Special
Price ($/kWh)	0.0134	0.055	0.1

TABLE VIII. ENS AND CIC RESULTS IN THE NON-AUTOMATED TEST FEEDER

#	ENS_C	ENS_R	ENS_S	IC_C	IC_R	IC_S
1	378188.6	891891.4	-	198	120	-
2	570284.5	1042516	-	298	140	-
3	609855.2	899264.8	-	318	121	-
4	814692.1	1201308	-	425	161	-
5	1520759	1704841	-	794	229	-
6	2016000	-	-	1052	-	-
7	392961.6	877118.4	-	205	118	-
8	-	-	12700.8	-	-	13
9	814692.1	1201308	-	425	161	-
10	-	-	12700.8	-	-	13
11	-	-	12700.8	-	-	13
12	1267299	748701.2	-	662	100	-
Sum	$\sum ENS_{C,D,S}$=207619.2(kWh)			$\sum IC_{C,R,S}$=5563.04($)		

Having done the same analysis as in Table VIII for the automated test feeder according the top-ranked locations achieved before, for the interest rate of i=0.17 and RTU expected life time of n=25 years, and with an assumption of RTU price of 10,000$, AINVC of an RTU is calculated as 1700$. The related results are shown in Table IX. According to the cost/worth diagram depicted in Fig. 5, it can be construed that in the test feeder, one substation, which is substation NO. 3 must be automated to make an economically justifiable decision.

V. COCLUSION

Automating all the substations is neither affordable nor economically justifiable in an electric power system. A new qualitative-quantitative approach by taking AHP as basis to solve the optimal placement of remote terminal units for distribution systems has been proposed. The objective function is formulated by considering the main practical criteria qualitatively by means of AHP and the customer interruption cost and investment cost of RTUs quantitatively. The interruption cost of each load point is determined by the load composition of different customer classes and special customers such as hospital, military station, etc. It is concluded that the optimal placement of RTUs by the proposed AHP-based algorithm can therefore lead to a more efficient decision making and effectively promotes the previous works in which some practical points are ignored. The proposed method was successfully applied to a real test feeder of Iran's power grid.

TABLE IX. RESULTS OF COST/WORTH ANALYSIS FOR DETERMINING THE NUMBER OF RTUS

Number of RTUs	CIC($/yr)	AINVC($/yr)
0	5563.04	0
1	2519.33	1700
2	2519.33	3400
3	1263.572	5100

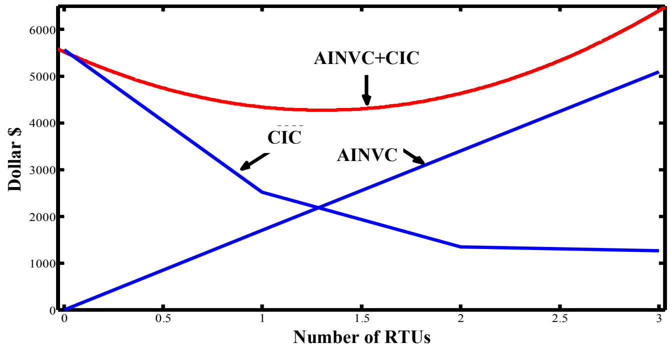

Figure 5. Cost/Worth analysis diagram

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