A New Look on the Automation of Medium Voltage Substations in Power Distribution Systems

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***Abstract*--With the expansion of electricity networks, increasing operational complexities, improved knowledge of the system operators, all with the subsidies elimination in some countries such as Iran and experiencing the real price of electricity by then, it necessitates a more reliable power to be delivered to the system customers. Power system automation is regarded as an efficient solution and the effective key to this problem. However, the great number of substations in power distribution systems has led to the fact that it is neither feasible nor economic to automate all of them. This calls for a comprehensive scheme on the placement of the distribution substations to be automated. In this paper, a practical glance is followed on the calculation of outage times which follows a practical approach for the substations placement. Some reliability-oriented indices are also proposed with which, together with their suitable fuzzy membership functions, the optimal location of substations for automation would be identified. The presented approach is finally applied to a real part of a distribution system in Tehran, Iran. And the results, as expected, show the applicability and effectiveness of the proposed algorithm.**

***Index Terms*—Optimal Placement, distribution automation (DA), reliability, outage time, substation, fuzzy sets theory.**

I. Introduction

EXPANSION of nowadays power distribution systems has led to the fact that providing the customers with a more reliable power has become more and more difficult. Subsidies elimination and experiencing the real price of electricity, in Iran, has also expanded the people's expectations on their power delivery policies [1]. As a result, interruption duration has been of a tremendous interest and is not acceptable and even tolerable if is more than a threshold. The reason lies in the fact that not only the distribution utility will lose, due to the not sold energy, but also the customers have to tolerate the interruption costs. However, this cost is of different value and effect for different types of customers. Industrial customers would be more sensitive, while the interruption costs for residential loads are low and these interruptions experienced by the residential sector mainly last into their dissatisfaction [2].

Distribution automation (DA) includes the monitoring and remote controlling of distribution system and has been proved to cause a significant saving in outage duration and outage cost, and as a result will last into a great increase in the system reliability. On the other hand, DA has been also regarded as the first step toward the Smart Grid implementation. Remote terminal units, whose roles are going to be explored later in this paper, are the main parts and of the essential requirements of automation in a power distribution system [3].

To the best of the authors' knowledge, there are a relatively low number of papers or researches on the RTU placement problem in power distribution systems. However, researches on this area have seen a tremendous growth recently. Some papers in this respect are organized in such a way that the placement process can be accomplished by extracting the experts' knowledge and operators' expertize [1], [3]. In [3], a decision making approach, called analytical hierarchical process (AHP) is used to deal with the most suitable substations for automation. Reference [4] employs the fuzzy sets theory in the placement process of RTUs in power distribution systems. In comparison with [3], the fuzzy AHP could well In [5], a comprehensive approach is presented to not only find the appropriate locations and substations of the system for RTU placement and automation, but also employs the reliability cost/worth analysis to find the optimal number of RTUs to be located in the previously found substations through Fuzzy AHP. In [2], and for the placement process, a cost function has been proposed for the distribution system which has to be minimized. The costs are associated with the power interruption which takes both the utility losses due to not selling the energy and the customer damages into consideration. These cost components have to be calculated separately for different load types, e.g. residential, industrial, commercial and special important loads, and they are finally summed up. The new added cost component related to the installed RTUs and the associated placements are also considered and finally did find the optimal number and location of RTUs.

This paper not only does consider the expected energy not supplied (EENS), but also take a special glance at the other index, i.e., load type importance. A practical approach, once accompanied by a proposed algorithm to simply evaluate the reliability of an automated system (no matter how expanded it is), is the main contribution of the paper. The paper is mainly concentrated on the outage time calculation of the automated systems versus the non-automated ones. The proposed method is to investigate the placement problem of RTUs in some MV

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substations in this view and copes with making the calculation process of reliability indices easier once confronting with the complicated power networks.

The rest of the paper is organized as follows. In Section II, an introduction to the automation is presented and the role of RTUs is highlighted there. Section III is devoted to the proposed methodology. Section IV deals with outlining the implementation process as the paper case study; the applicability and robustness of the proposed algorithm is then investigated. And finally comes the conclusion in Section V.

II. Automation of Power Distribution Systems

Power distribution system, although being in a looped structure, usually operated radially. Therefore, once a fault occurs in the system, an isolation process in clearing the fault can provide the possibility of supplying the loads from the other parts of the distribution system. In a non-automated distribution system, when a fault occurs, a breaker has to disconnect the supply source of the whole feeder. Once the fault occurrence detected, the operators have to find its location and after a manual switching and cleaning the fault, have to supply the customers through the other parts of the system or via the distributed generations (DGs). This procedure may take them several hours. The major part of this time is associated with the manual switching which can be minimum through automation. However, this reduction in the outage duration can be only reached once a cost is devoted to the required equipment for the automation implementation. Among the cost functions related to the automation process, the costs of Remote Terminal Units (RTUs) that are going to be installed in the target substations are of considerable amounts and importance.

RTUs are the essential units which are used to remotely control and monitoring of different parts of the system. They are regarded as the main part of system automation.

Automating a power distribution system would have some significant benefits to the system operation, management, and control. Among these positive impacts are:

- Reliability improvement of the system.
- Providing a better competition environment for the Discos.
- Increasing the customer satisfaction.
- Prolonging the equipment ages.
- and so on.

On the other hand, automating all the substations in a distribution system is neither affordable nor reasonable. In response, it calls for a cost/benefit analysis to compromise the imposed costs of the automation equipment and the technical and economic benefits gained.

In some rural areas in which there is no support supply system, DGs can be regarded as an efficient alternative. In [6], the effective factors on the reliability index, system average interruption duration index (SAIDI) have been discussed. In this paper, some proposals are presented to have this index minimized. Among these proposals are:

- Variations in the system topology.
- Installment and replacement of re-closers.
- DG integration as an alternative source.

The noteworthy in this respect is that the calculations performed to get this index in the automated cases of power systems need to be reorganized once the network topology changes. In other words, once the network topology changes in response to the restoration process, performing the computational-demanding procedure of the reliability index computation would be again necessary. This is the main shortcoming attributed to the past studies on the automation and RTU placements.

III. The Proposed Methodology on the Calculation of Outage Times

Due to the fact that the automation process has considerable effects on only the outage duration, but not outage frequency, only the reliability indices which have considerable dependency to the time and duration, has to be employed. One of the commonest time-based reliability indices employed in many distribution utilities worldwide is the energy not served (ENS) index of reliability [7]. This index is going to play a major rule in the RTU placement procedure proposed in this paper and can be calculated through (1).

$$\mathrm{ENS} = \sum_i L_i \sum_j r_{ij} \lambda_j \quad (1)$$

where the following nomenclature can be applied.

L_i	Total load connected to substation *i*.
r_{ij}	The outage time of the load *i* due to the outage occurrence in line *j*.
λ_j	Failure rate of the j^{th} line.
i	Substation number.
j	Line number.

In this equation, L_i and λ_j are among the network data while r_{ij} has to be calculated.

In order to calculate the outage times associated with different load of the system, the automation of only one substation is, at first, considered. One matrix is assign to this case. Then, for the cases in which the automation of several substations has been considered, another matrix is assigned which can be built from the previously-obtained matrices. In this way, the computational burden will decrease to a minimum. The proposed algorithm is generically presented in Fig.1.

A. Case I: The System with Just One RTU Installed

The location of RTUs in different substations in a distribution system is of considerable effects on the outage duration and interruption time of the loads. This will have significant effects on the ENS index of reliability, too.

In this case, one RTU has to be located in each system substation respectively, and then for the outages in all the lines of the system understudy, the outage times should be calculated.

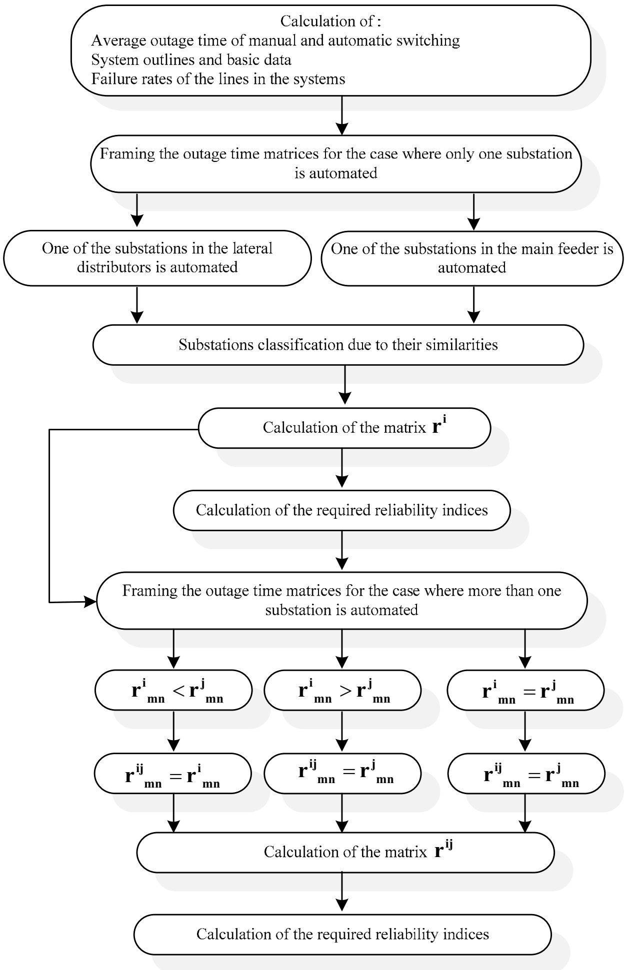

Fig. 1. The flowchart associated with the proposed methodology on the calculation of outage time

For example, assume the following distribution system. As shown in Fig.2, this system has eight substations. For an RTU to be located in each substation, a 8×8 matrix is defined, as shown in (2).

$$\mathbf{r^i} = \begin{bmatrix} r_{11}^i & . & \cdots & . & r_{1n}^i \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ r_{m1}^i & . & \cdots & . & r_{mm}^i \end{bmatrix} \tag{2}$$

where r^i denotes to the i^{th} substation where the RTU is located, and r_{mn}^i is the outage time associated with the n^{th} substation once a fault is experienced on line *m* and there is an RTU only in the i^{th} substation.

The manual switching time is assumed to be 1 hour and the automatic switching time is supposed to be 0.1 hour. The following two cases are scrutinized:

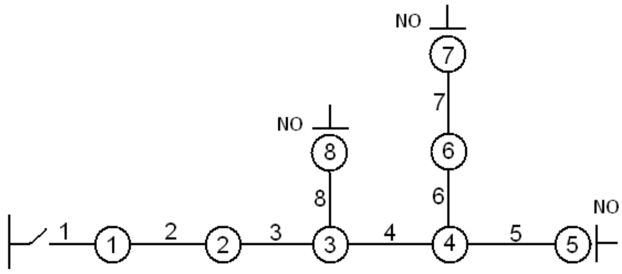

Fig. 2. A hypothetical test system with 8 substations.

a) RTU is located in one of the substations in the main feeder (substation 1 to 5)

For instance, the matrix r^4 whose elements are representative of the outage times when the RTU is located in the forth substation is explained. In such situation, the network can be divided into three different parts. The first part includes substations 1, 2, 3 and 8; and the second part consists of substation 5; and the third part contains both substations 6 and 7. When an interruption occurs in each section, the switching process has to be done to restore the loads of the associated section manually, while this process has to be done automatically for the other sections.

$$\mathbf{r^4} = \begin{bmatrix} 1 & 1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \\ 1 & 1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \\ 1 & 1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \\ 1 & 1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 1 & 0.1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 & 1 & 0.1 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 & 1 & 0.1 \\ 1 & 1 & 1 & 0.1 & 0.1 & 0.1 & 0.1 & 1 \end{bmatrix} \tag{3}$$

b) RTU is located in the lateral distributors (substations number 6, 7 or 8)

In such circumstances, the network is divided into two different parts. For example, for *i*=6, the first part consists of the substations 1 to 5 and 8; and the second part includes only substation number 7.

The proposed algorithm in the aforementioned two cases could be effectively and simply implemented in MATLAB environment.

B. Case II: The System with More Than One RTU (n>1)

In the previous section, a matrix $\boldsymbol{r^i}$ was proposed for an RTU located at each substation. In this section, using the obtained matrices before, the associated matrix for the case where more than 1 RTU has to be installed, could be obtained ($\boldsymbol{r^{ij}}$).

$$
\mathbf{r}^{ij} = \begin{bmatrix} r_{11}^{ij} & . & \cdots & . & r_{1n}^{ij} \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ r_{m1}^{ij} & . & \cdots & . & r_{mm}^{ij} \end{bmatrix} \quad (4)
$$

where $\boldsymbol{r}_{mn}^{ij}$ is the outage time of substation n when the line m is interrupted and there are two RTUs in substations i and j.

Assume that the substations i and j are automated. So, the following two cases can be studied:

a) $\boldsymbol{r}_{mn}^{i} = \boldsymbol{r}_{mn}^{j}$

This means that the separate automation of each of the substations i and j have the same effects on the outage time ($\boldsymbol{r}_{mn}$). As a result, their simultaneous automation will have also the same influence on the outage time and so, we have $\boldsymbol{r}_{mn}^{ij} = \boldsymbol{r}_{mn}^{i} = \boldsymbol{r}_{mn}^{j}$.

b) $\boldsymbol{r}_{mn}^{i} \neq \boldsymbol{r}_{mn}^{j}$

first suppose $\boldsymbol{r}_{mn}^{j} < \boldsymbol{r}_{mn}^{i}$ .this means that in the case of automating substation j, the outage time ($\boldsymbol{r}_{mn}$) is equal to the remote automatic switching and in the case of automating substation i, the outage time is equal to the manual switching. As a result, with the simultaneous automation of both substations i and j, and benefiting from the RTU located in substation j, the outage time would be the equal to that of remote automatic switching ($\boldsymbol{r}_{mn}^{ij} = \boldsymbol{r}_{mn}^{j}$). With the same discussion for the case where $\boldsymbol{r}_{mn}^{i} < \boldsymbol{r}_{mn}^{j}$, the result would be $\boldsymbol{r}_{mn}^{ij} = \boldsymbol{r}_{mn}^{i}$.

Investigating different cases, we can reach to the following general condition, as is introduced in (5).

$$
r_{mn}^{ij} = \min\{r_{mn}^{i}, r_{mn}^{j}\} \quad (5)
$$

So, for the matrix $\boldsymbol{r}^{ij}$, we have:

$$
r^{ij} = \min\{r^{i}, r^{j}\} \quad (6)
$$

where, $\min\{r^{i}, r^{j}\}$ denotes to the matrix whose elements are equal to the minimum of the associated elements of matrices i and j.

Using these matrices ($\boldsymbol{r}^{ij}$), the reliability indices can be calculated.

C. Incorporating the Importance of Substations in the Proposed Algorithm

Once calculating the ENS index of reliability, some criteria such as outage frequency on a line within a year, each substation's load, and the network topology are of great importance. To find the optimum location of the RTUs, some other criteria are also important. Amongst are load type which can be of residential, industrial, commercial and special types. The other consideration-demanding criterion is the substation accessibility. In considering so, a new factor is proposed to deal with the importance of different load types, and is introduced through (7).

$$
\mathrm{IM} = \frac{\sum_i A_i \sum_j r_{ij}\lambda_j}{\sum_i A_i} \quad (7)
$$

where, the following nomenclature can be adopted:

IM	The importance criterion of each substation.
A_i	The weight of substation i with respect to its load types importance.
r_{ij}	The outage time of the load i due to the outage occurrence in line j.
λ_j	Failure rate of the j^{th} line.
i	Substation number.
j	Line number.

In the following, both the proposed criterion and the ENS index of reliability are incorporated in the placement procedure of RTUs in power distribution systems.

D. Fuzzy Treatment of the Defined Criteria

In this section, using the fuzzy sets theory, some suitable membership functions are proposed for the aforementioned criteria, as shown in Fig 3 [8].

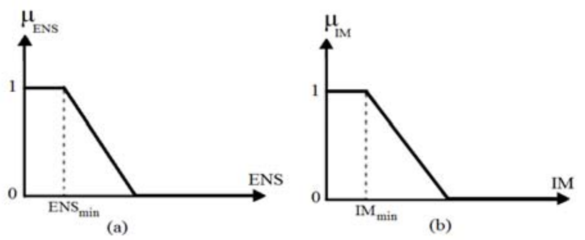

Fig 3. Membership functions assigned to the ENS index of reliability and the importance criterion of substations.

As can be seen in Fig. 3(a), the employed membership function for the ENS index of reliability is a trapezoid membership function. A same figure is also shown in Fig. 3(b) which is attributed to the substation importance criterion. Finally, the final membership function can be obtained with the multiplication of these two membership functions. In this respect, this final membership function would be the final decision factor.

$$
\mu = \mu_{ENS} \times \mu_{IM} \quad (8)
$$

IV. Implementing the Proposed Method in a Typical Practical Power System

In this section, the proposed algorithm in the placement process of RTUs in power distribution systems is simulated in a real distribution system which is a part of the distribution system, located in the East of Tehran, Iran. The system employed as the case study is depicted in Fig. 4.

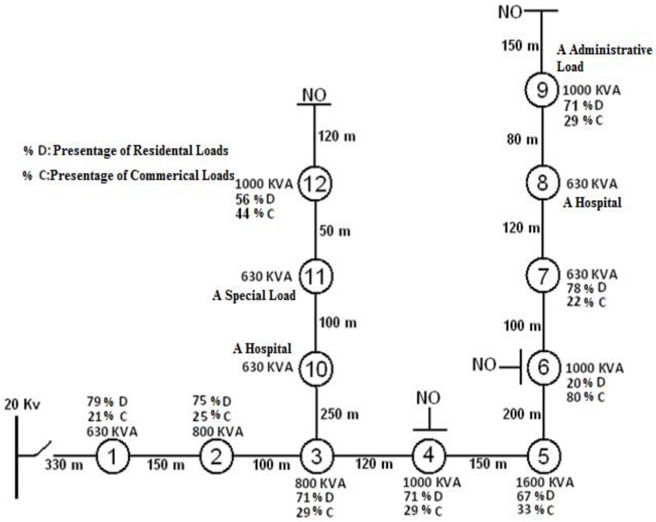

Fig. 4. The test system, a real part of the distribution system, located in the East of Tehran, Iran.

Table I presents the results associated with the case of *k*=2 (placement of 2 RTUs in the system). Accordingly, it can be seen that once just the ENS criterion is considered, substations number 3 and 5 are the solutions; however, once just the importance criterion is at the point, automation of substations number 3 and 8 is the optimal plan to be adopted.

The considered weights for the system various loads are in accordance with those of Table II. Table III presents the membership functions associated with the two considered criteria as well as the final decision criterion for the case of *k*=2. Using this table and taking into account that the optimal solution corresponds to the case where μ is maximum, substations number 3 and 6 are reached as the final optimal results. The associated diagrams are illustrated in Fig. 5.

TABLE I
THE ENS INDEX AND IMPORTANCE CRITERIA FOR THE CASE OF K=2

Substations	ENS(KWh)	Importance
3 , 5	**2365**	0.273
3 , 8	3128.3	**0.198**
3 , 6	2398	0.218
5 , 10	3549.2	0.238
5 , 4	4302.5	0.530

TABLE II
THE CONSIDERED WEIGHTS FOR DIFFERENT LOAD TYPES

Load Types	Residential	Commercial	Industrial	Special
Weight	0.004	0.139	0.225	0.398

TABLE III
THE MEMBERSHIP FUNCTION EMPLOYED IN THE CASE STUDY (K=2)

Substations	μ_{ENS}	μ_{IM}	μ
3 , 5	**0.991**	0.870	0.863
3 , 8	0.896	**0.974**	0.873
3 , 6	0.986	0.942	**0.933**
5 , 10	0.833	0.918	0.765
4 , 5	0.733	0.514	0.376

Table IV presents the results due to the variations of *k* (number of RTUs to be installed). The improvements in the reliability indices in the case of *k*=3, compare to the case of *k*=2, is not in such a way that can justify the imposed costs of automating a third substation; whereas when comparing the cases of *k*=1 and *k*=2, it can be concluded that the imposed costs of automating the second substation can be afforded and reasonable. As a result, the optimal number of RTU will be reached as two.

The offered methodology, so, seems to be efficient enough in constructing the required matrices as soon as possible and with minimum computational burden. It can be also well integrated with the programming environments, such as MATLAB environment.

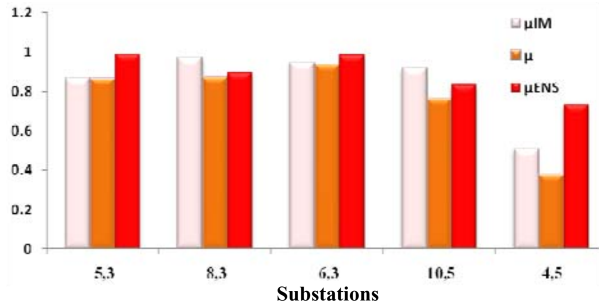

Fig. 5. The results diagram of the membership functions associated with the employed criteria (consistent with Table III).

TABLE IV
DIFFERENT VALUES OF THE CRITERIA FOR VARIOUS NUMBERS OF K

No. of RTUs	Optimal Location	ENS	Assigned Importance
k=1	3	4071.3	0.366
k=2	3 , 6	2398	0.218
k=3	3 , 6 , 10	1962.8	0.122

V. CONCLUSION

Moving toward smarter grid environments, subsidies elimination and the need for a more reliable power have increased the need for the automation of power distribution systems. On the other hand, automating all the system substations is not reasonable and affordable. So, it calls for a comprehensive scheme for the placement of RTUs. Practically approached, a methodology is proposed in this paper on the basis of reliability indices. In this method, the criterion, ENS, is taken into account by which the other parameters such as network topology and load amount, failure rates and mean outage times can be all considered. Two other factors namely load types of a substation and substation accessibility are also proposed as the main factors concerning the placement problem. In the first step, the outage time of a system under automation could be reached and then, the importance weights of load types would be mathematically reached. Finally, these two criteria were combined through fuzzy sets theory. A sensitivity analysis was finally conducted on the number of RTUs to be installed and a compromising was performed on the achieved technical benefits and financial imposed costs of new RTUs. The propose approach was applied in a real part of a distribution system located in Iran and the optimal number of substations were obtained.

REFERENCES

[1] A. A. Razi Kazemi, P. Dehghanian, G. Karami, “A probabilistic approach for remote terminal unit placement in power distribution systems,” *2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC)*, pp.1-7, 9-13 Oct. 2011.

[2] D. Kirschen and G. Strbac, *Fundamentals of Power System Economics*, John Wiley and Sons, 2004.

[3] P. Dehghanian, A. A. Razi Kazemi, and M. Fotuhi-Firuzabad, “Optimal RTU placement in power distribution systems using a novel method based on analytical hierarchical process (AHP),” *2011 10th International Conference on Environment and Electrical Engineering (EEEIC)*, pp.1-4, 8-11 May 2011.

[4] P. Dehghanian, A. A. Razi Kazemi, and G. Karami, “Incorporating experts knowledge in RTU placement procedure using fuzzy sets theory-a practical approach,” *2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC)*, pp.1-10, 9-13 Oct. 2011.

[5] A. A. Razi Kazemi and P. Dehghanian, “A Practical Approach on Optimal RTU Placement in Power Distribution Systems Incorporating Fuzzy Sets Theory”, *International Journal of Electrical Power and Energy Systems*, vol. 37, pp. 31-42, May, 2012.

[6] K. Zou, W. W. L. Keerthipala, S. Perera, “SAIDI minimization of a remote distribution feeder,” *Australasian Universities Power Engineering Conference*, pp.1-5, 9-12 Dec. 2007.

[7] R. Billinton and R.N. Allan, *Reliability evaluation of power systems*, Plenum Press, New York, 2nd edition, 1996.

[8] R. M. Rodriguez, L. Martinez, and F. Herrera, “Hesitant Fuzzy Linguistic Term Sets for Decision Making,” *IEEE Transactions on Fuzzy Systems*, vol.20, no.1, pp.109-119, Feb. 2012.

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