International Journal of Engineering Innovation & Research
Volume 5, Issue 3, ISSN: 2277 – 5668

Using Fuzzy Quality Function Deployment in Improving Reliabality of Wind Power Systems

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***Abstract* – This paper used fuzzy quality function deployment to investigate customer requirements and technical requirements associated with wind power systems to figure out possible recommendations which result in optimizing design of wind power systems, increasing customer satisfaction, and enhancing reliability. In the same way, correlation among customers' requirements and technical requirements are discovered so prioritization of technical requirements have been analyzed to be considered for optimizing future designs of wind power systems.**

***Keywords* – Fuzzy Quality Function Deployment, Wind Power System, Customer Requirements, Technical Requirements.**

I. Introduction

It is clear that wind power systems have been developed in in the last few decades to get maximum benefit from using renewable energy sources and reduce usage of coal and gas. Since wind power systems are developing, it is still essential to analyze their performance, reliability, and capability in order to potentially redesign their systems. There are several tools and models that have been used so far to analyze quality and reliability of renewable energy systems [1] especially for wind and solar power systems [2-14]. However, many studies are still working on wind power systems to increase their reliability and meet customers' requirements. Apart from obvious factors such as fluctuating power output due to a variability of wind speed and climate changes that have huge impact of the reliability and performance of these systems, there are many factors in terms of customers' expectations and technical requirements that are explored in this paper.

In this paper, fuzzy quality function deployment has been used as a practical method that can find potential elements for improvement. Technically, this method could effectively correlate each customer requirement with associated technical requirement along with relationship among each technical requirement internally. The goal of this study was to determine which factors should be prioritized in order to satisfy customer requirements and increase reliability of wind power systems.

II. Fuzzy Quality Function Development

Quality Function Deployment (QFD) which was developed in Japan in 1966 [15] is a practical tool which correlates customer requirements (CRs) and technical Requirements (TRs) in order to prioritize TRs in the way that can be used to enhance quality of products and systems [16]. Many articles have employed this useful method as a quality management technique in different industries [15-19]. It is worth mentioning that main internal part of QFD is House of Quality (HOQ) which shows all the existing relationships among CRs and TRs. Basically, CRs are the benefits that customers expect a product or system brings to them. In other words, it is considered as "what" customer needs. On the other hand, TRs show "how" the product should be produced [20]. It is obvious that sometimes it is not easy to recognize the strength and weakness of relationships among CRs and TRs due to vagueness of model so fuzzy quality function deployment (FQFD) is a newer version of quality function deployment that deals with these imprecise and vague relationships. In fact, using fuzzy logic [21, 22] along with quality function deployment enabled us to use an accurate mathematical way of modeling to translate vague preferences, such as weighting performances and relationships among each CR and TR. As mentioned earlier, first core of HOQ is to demonstrate relations among CRs and TRs so according to Fuzzy-QFD, the relationships are expressed with 3 specific numbers which show degree of strength (weak, medium, strong). As a result, instead of previous model, QFD, which was based on 1 number, FQFD could make a better estimation of strength and weakness of relationships among CRs and TRs to obtain accurate results.

III. Fuzzy Quality Function Applied to Wind Power Systems

A. Method of Collecting Data

In order to gather information related to wind power systems including all customer requirements and technical requirements, several questionnaires and surveys have been received from electrical, mechanical engineers, industrial engineers, and wind power system consumers through email solicitations and telephone interviews. 2 different types of questionnaires and surveys have been received from 2 different groups of consumers and engineers. In reality, surveys from consumers have been received for the purpose of recognizing all the requirements that consumers expect from one wind power system, so process of weighing each customer requirement is performed. However, questionnaires from engineers have been obtained in order to list technical requirements and figure out the relationships among each technical requirement with customer requirements so that Fuzzy-HOQ could be developed. In order to facilitate the process, pair-wise comparison has been used along with questionnaires with linguistic variables for both experts and customers. Accordingly, linguistic variables have been converted to the form of fuzzy triangle numbers which their conversion rule is shown in Table I and II. Needless to say that process of receiving questionnaires and surveys were repeated several times in order to reduce bias in the data and bias of one person or one voice. Consequently, the data have been analyzed and evaluated in order to be used as usable information in the process of implementing fuzzy quality function deployment.

Table 1. Degree of relationships, and corresponding fuzzy number [Adapted from 23]

Degree of Relationships	Fuzzy Number
Strong (S)	(0.7; 1; 1)
Medium (M)	(0.3; 0.5; 0.7)
Weak (W)	(0; 0; 0.3)

Table 2. Degree of correlations and corresponding fuzzy numbers [Adapted from 23]

Degree of Correlation	Fuzzy Number
Positive (★)	(0.5; 0.7; 1)
Negative (▲)	(0; 0.3; 0.5)

B. Precedure

The procedure of implementing fuzzy quality function deployment includes 5 steps that are shown in Fig. 1.

1) Identify CRs and TRs of the wind power system: One key factor that plays a prominent role in heightening sale in a competitive market is to know the customers' voice. In other words, by recognizing customers' requirement, process of Fuzzy-QFD could be initiated. As long as customers' reqruirements are met, more rate of sale would be expected.

In the same way, technical requirements are crucial features of various techonolgies to satisfy customer's sasisfaction. Thus, learning more about technical requirements would help designers of wind power systems to meet customers' requirements in an appropriate way.

Customers' requirements and technical requirements are gathered and listed in Table III.

2) Prioritize CRs to obtain CRs' priority weigh (w_i): This step is performed by considering all surveys that were obtained from consumers and using Expert Choice software [24] which was based on a deicion-making theory. In reallity, the surveys which include pair-wise comparison nature were based on lingustic variables that contained nine scales with respect to expermental criteria such as cost, services, and improving product quality. The nine scale that have been used in both surveys and mentioned software are listed in Table 4. Consequently, obtained priority weights are shown in Fuzzy-HOQ, Fig. 3.

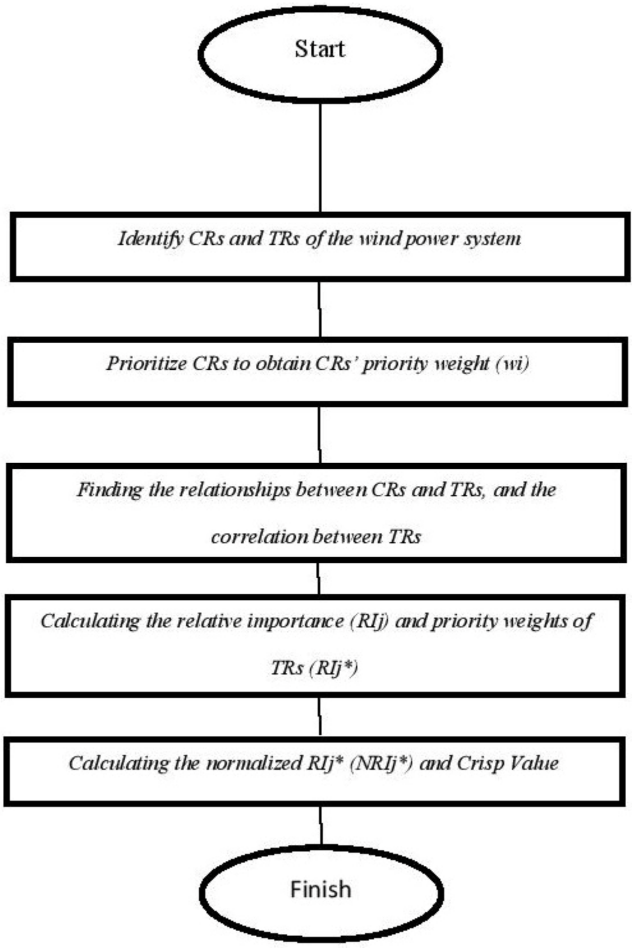

Figure 1. Schematic representation of the algorithm

Table 3. Customer requirements and technical requirements defined for wind power system

Code of CRs	Customer Requirements	Code of TRs	Technical Requirements
CR1	Durability	TR1	Height of tower
CR2	Energy saving	TR2	Cables
CR3	Low required space	TR3	Turbine dimensions
CR4	High efficiency	TR4	Blade design
CR5	Cost-effectiveness	TR5	Blade materials
CR6	User-friendly	TR6	Wind system performance
CR7	Usable for different hours	TR7	Wind charge controller
CR8	Low-noise wind turbine	TR8	Electrical generator
CR9	Using simultaneous energy options	TR9	Total weight
CR10	Regular current and voltage	TR10	Battery
CR11	Beautiful design	TR11	Invertor
CR12	Easy Installation	TR12	Air flow rate & velocity
CR13	Easy Portability	TR13	Over-speed protection system
CR14	Safe use		

International Journal of Engineering Innovation & Research
Volume 5, Issue 3, ISSN: 2277 – 5668

Table 4. Judgement scores based on expert choice software (retrieved from [24])

Option	Numerical value(s)
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect inputs	2,4,6,8
Reflecting dominance of second alternatives compared with the first	Reciprocals

3) Finding the relationships between CRs and TRs, and the correlation among TRs: In this section, it is shown that how each customer requirement can be correlated with technical requirement, and how each technical requiement is in relationship with the other TRs. As mentioned earlier, fuzzy logic has been considered in impplementing quality function deployment in order to translate imprecise and vague linguistic terms of relative importance of CRs, relationships, and correlation matrices to numerical valuses. In this step, the degree of relationship between technical requirements was expressed by triangle fuzzy numbers (TFNs) in Fuzzy-QFD which their scales are shown in Table 1 and 2.

According to Fig. 2., TFNs are considered which are denoted as a triplet (a, b, c) and non-fuzzy number [23, 25].

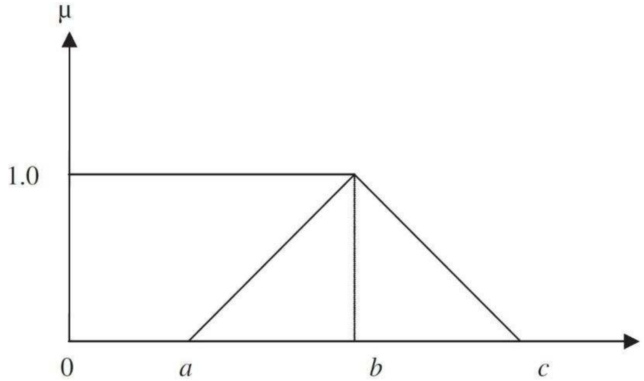

Figure 2. Triangle fuzzy number (TFN)

$$\mu_N(x): \begin{cases} (x-a)/(b-a), & x \in [a,b] \\ (c-x)/(c-b), & x \in [b,c] \\ 0 & otherwise \end{cases} \quad (1)$$

4) If M= (a_1, b_1, c_1) and N= (a_2, b_2, c_2) symbolize two Triangle Fuzzy Numbers, then the required fuzzy calculations are executed below [23, 25]:

Fuzzy addition:

$$M \otimes N = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \quad (2)$$

Fuzzy multiplication:

$$M \otimes N = (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2) \quad (3)$$

$$M \otimes 1/N = (a_1/c_2, b_1/b_2, c_1/a_2) \quad (4)$$

Fuzzy and natural number multiplication:

$$r \otimes M = (r.a, r.b, r.c) \quad (5)$$

5) Calculating the relative importance (RI_j) and priority weights of TRs (RI_j^*): In this section, relative importance (RIj) and priority weights of TRs (RIj*) are calculated as two parameters which was used to determine which TR has the most impact on improving reliability of wind power systems. RI_j was calculated by fuzzy multiplication of W_i to R_{ij}.

$$RI_j = \sum_{i=1}^{n} W_i \otimes R_{ij} \qquad j = 1, \dots, m \quad (6)$$

$$RI_j^* = RI_j \oplus \sum_{k=j} T_{kj} \otimes RI_K \qquad j = 1, \dots, m \quad (7)$$

6) Calculating the normalized RI_j(NRI_j^*) and Crisp Value:* In this part of process, normalization is done by dividing each RI_j^* by the highest one according to the fuzzy set algebra [23, 25]. Finally, in order to rank the TRs, the normalized scores of RI_j^* are de-fuzzified. Suppose M (a, b, c) is a Triangle Fuzzy Number; then, the Crisp Values are computed using the following equation.

$$\frac{(a+4b+c)}{6} \quad (8)$$

International Journal of Engineering Innovation & Research
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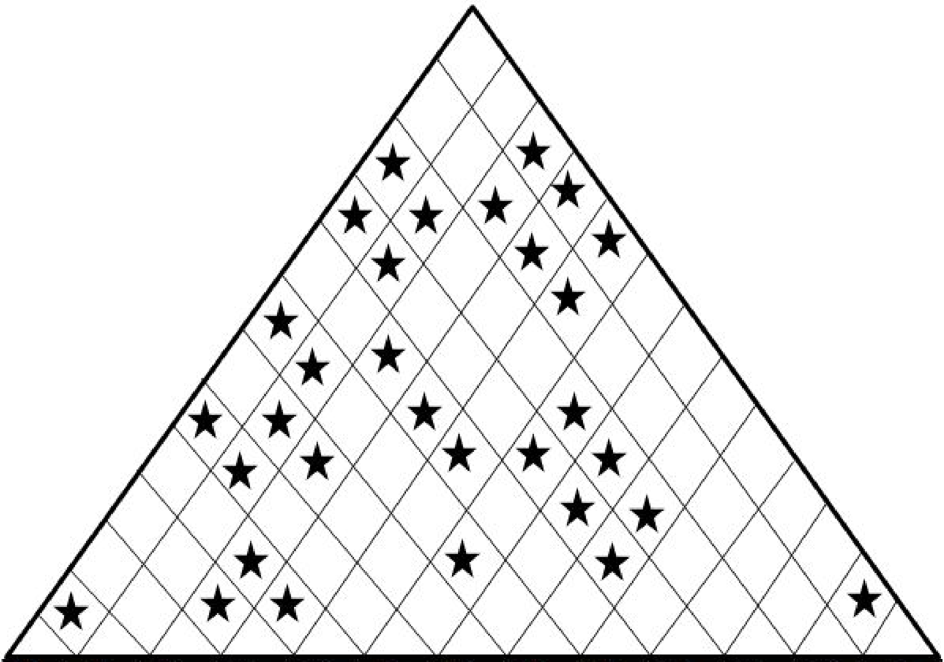

CR_n	Weight	TR_1	TR_2	TR_3	TR_4	TR_5	TR_6	TR_7	TR_8	TR_9	TR_{10}	TR_{11}	TR_{12}	TR_{13}
CR_1	0.056	W	M		M	S	S	M	M		S	M		S
CR_2	0.08	S	M	S	S	M	S	S	S		S	S	S	M
CR_3	0.016	W	W	S	S			W	W		W	W		
CR_4	0.042	S	M	S	S	M	S	S	S		S	S	S	M
CR_5	0.062	S	M	M	S	S	S	S	S		S	S		M
CR_6	0.025	M		M	S			M	M		M	M		W
CR_7	0.091	S		W	S	M	S	S	S		S	S	S	M
CR_8	0.023	M		M	S	S							M	M
CR_9	0.06	S		M	S	M	S	S	S		S	M	S	M
CR_{10}	0.193	S	S	M	S	M	S	S	S		S	S	S	S
CR_{11}	0.013	W	W	M	M	W								
CR_{12}	0.029	M		M				M	M		M	M		
CR_{13}	0.012			S	M	M				S				
CR_{14}	0.298	M	S	M	S	W	M	S	S		S	S	M	S
R_{ij}		0.48	0.41	0.31	0.65	0.24	0.50	0.61	0.61	0.01	0.63	0.59	0.42	0.49
		0.71	0.61	0.5	0.93	0.38	0.73	0.88	0.88	0.12	0.90	0.85	0.62	0.72
		0.81	0.67	0.67	0.95	0.57	0.79	0.90	0.9	0.01	0.92	0.89	0.69	0.80
RI_j^*		1.85	2.12	1.52	1.38	1.18	1.86	1.58	1.91	0.61	1.93	1.89	1.26	1.3
		3.49	4.07	3.05	2.57	2.40	3.49	2.88	3.54	1.39	3.56	3.51	2.39	2.42
		4.98	5.88	4.59	3.69	3.69	4.98	4.05	4.98	2.2	4.99	4.96	3.68	3.68
Normalized RI_j^* ($N\ RI_j^*$)		0.31	0.36	0.25	0.23	0.2	0.31	0.26	0.32	0.1	0.32	0.32	0.21	0.22
		0.85	1	0.74	0.63	0.59	0.85	0.70	0.86	0.34	0.87	0.86	0.58	0.59
		2.35	2.77	2.16	1.74	1.74	2.34	1.91	2.34	1.03	2.35	2.33	1.73	1.73
Crisp Values		1.01	1.18	0.89	0.74	1	1.01	0.82	1.02	0.41	1.03	1.01	0.71	0.72

The finalized Fuzzy-HQO for wind power system is illustrated in Fig. 3.

Figure 3. Proposed Fuzzy-HOQ for wind power systems

IV. Analyzing the Output Data

According to the output of Fig. 3, the obtained priority weights of CRs are illustrated in Fig. 4. The most important customer requirement based on received surveys from customers and analysis performed on Expert Choice software refers to safety with priority weight of 0.298. Also, the lowest priority weight of 0.012 shows that easy portability is the factor that was not crucial for wind power systems based on consumers’ surveys.

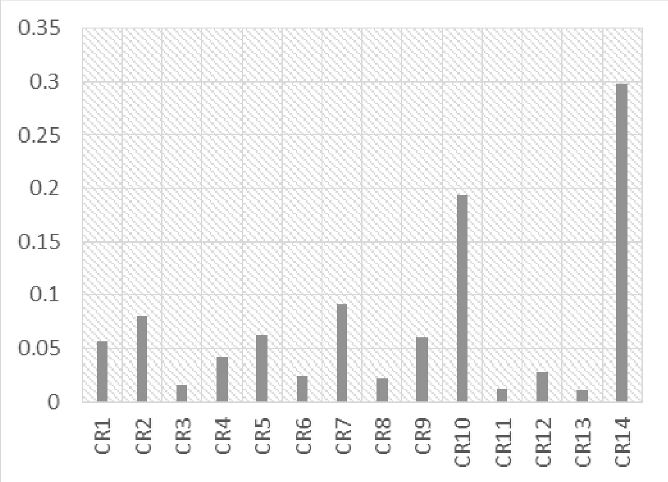

Fig. 4. Priority weight of CRs

According to Fig. 3, the gained crisp values of TRs are shown in Fig. 5. In fact, the highest priority of different TRs which allow designers to focus on them in order to increase reliability, customer satisfaction, and product quality refer to cables with the crisp value of 1.17. The main reason is that cables refer to safety of the wind power systems and many consumers have rated safety as one vital customer requirement. In reality, safety as a customer requirement with the highest priority weight has a strong correlation with cables as the highest crisp value of technical requirements. In the opposite way, the lowest priority of TRs refers to total weight with crisp value of 0.41 because this factor has a strong relationship with easy portability which had the least priority based on customers' surveys.

It should be noted that the rate of the wind power systems performance depends on different technical factors including turbine dimensions, batteries, blade design, and materials, etc. As it can be seen in Fig. 5, cables have the highest rate (1.17) in comparison to the other rates. However, the minimum rate refers to total weight (0.41). Since different components used for the wind power systems are in need of cables, this part is related to a large variety of electrical components. After cables, batteries, electrical generator, invertor, wind system performance, height of tower, and blade materials have the highest rate ranging from 1 to 1.03. It should not be left unmentioned that each component illustrated in Fig. 5 is important whereas high rate components on our list of priorities will draw attention to their importance. For instance, batteries have the highest rate after cables owing to the fact that batteries play a key role in wind power systems. It is conspicuous that without batteries, the system is not able to store electricity from wind sources. To improve TRs shown in Fig. 5, there are different ways in accordance with the advancement of technology. Some of the suggestions are noted in this study. Because different electrical components are used for a wind power system, using high quality cables is really noticeable. Besides, turbine dimensions are very important in wind power systems. The optimized dimension of turbine would increase the power that can be generated through wind and enhance the system efficiency. Therefore, providing accurate dimensions for turbines have a huge effect on the system. Moreover, electrical generators are utilized as the equipment to convert wind source to power source; as a result, a suitable electrical generator should be considered to convert the wind energy into electrical energy. There are many types of wind power technologies which are in development, but some of them are most commonly used. The effect of the electrical generators on the energy saving as a useful factor should not be neglected. Basically, it is a really indispensable part of a wind power system for the sake of producing electricity. To improve the mentioned part, different electrical components should be well-designed. It should not be neglected that blade materials and design following the aerodynamic rules affect the system efficiency undoubtedly as well.

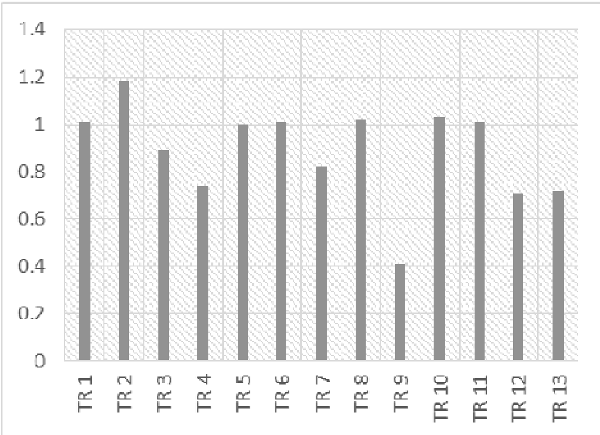

Fig. 5. Crisp values of TRs

V. Conclusion

It is obvious that using wind power systems plays a key role in reducing fossil energy usage since it consumes natural energy resources; however, they still need to be improved in terms of reliability and customer's satisfaction. The mentioned factors are inevitable elements that should be considered in developing renewable energy systems and one practical solution would be integration of electrical, mechanical and industrial sciences in long with practical quality management and reliability analysis tools. Since, no specific published record of using fuzzy quality function deployment in improving wind power systems have been found already, in this study, by recognizing all customers' requirements and technical requirements, we achieved the priority of TRs which should be considered in the process of design to enhance quality level of wind power systems.

According to findings of the current research, importance of each customer requirement has been shown in Fig. 4. The most important customer requirements such as safe use and regular current and voltage with the weights of 0.298 and 0.193 are achieved respectively. Similarly, obtained TRs depending on crisp value from Fuzzy-HOQ have been depicted in Fig. 5 to present the highest priority of different TRs which allow designers to focus on them in order to increase customers' satisfaction. Accordingly, the most crucial TR is the cables with the crisp value of 1.17. Similarly, the lowest priority of TRs refers to total weight with crisp value of 0.41. Thus, the most important CR would be safe use with priority weight of 0.298.

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Nomenclature			
A	Smallest possible value	R_{ij}	Relationship between the i-th CR and the j-th TR
B	Most promising value	RI_j	Relative importance of a TR
C	Largest possible value	RI_j^*	Priority weight of a TR
M and N	Triangular fuzzy numbers (TFNs)	RI_k	Relative importance of the k-th TR
W_i	Priority weight of a CR	T_{kj}	Degree of correlation between the k-th and j-th TRs

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