Evaluation of Hurricane Impact on Failure Rate of Transmission Lines Using Fuzzy Expert System

Yong Liu, Chanan Singh
Department of Electrical and Computer Engineering
Texas A&M University
College Station, USA
liuy0004@neo.tamu.edu, singh@ece.tamu.edu

Abstract—**Adverse weather, such as hurricanes, can have severe effects on power system reliability. Incorporating weather effects in power system reliability evaluation has drawn more and more attention in recent years. In past decades, many methods have been proposed to evaluate power system reliability considering weather effects. Some of the earliest methods used the two-state weather model. These have been later expanded into multi-state weather model, regional weather model (RWM) and statistical regression method. In this paper, a fuzzy expert system (FES) is proposed and is combined with RWM to assess hurricane impact on the reliability parameters of transmission lines. Firstly, according to the computation requirements the composite system is partitioned into different regions. Then, the FES maps the nonlinear relationship between the hurricane parameters (indicator of hurricane severity) and the increment multipliers of failure rates (IMFR) of the transmission lines in different regions. In this step, the possible case that transmission lines traverse adjacent regions is investigated by using weighted average method (WAM). Finally, the results obtained by using the proposed method can be used in analytical or simulation method to evaluate composite system reliability considering hurricane impact. The proposed method is applied to the IEEE Reliability Test System (RTS). The implementation demonstrates that the proposed method is effective and efficient and the FES is convenient to construct.**

Keywords- Adverse weather, composite system reliability, fuzzy expert system, IEEE RTS

I. INTRODUCTION

Any power system components, such as transmission and distribution lines, are exposed to weather environment. It is well known for a long time that the failure rate of a transmission or a distribution line is a function of the weather environment that it is exposed to and the failure rate of the transmission (distribution) line can be much higher in adverse weather than that in normal weather [1]. The severe weather like a hurricane is an extreme weather condition and can seriously jeopardize power system operation. In recent years, the hurricanes in US have caused hundreds of thousands of customers losing power supply and even brief power interruption may affect communication, water distribution, traffic signaling, and other lifeline systems [2]-[4]. Incorporating weather effects in power system reliability evaluation has drawn more and more attention in recent years. More accurately predicting hurricane impact can help utilities manage better preparedness and restoration arrangement [2]-[3]. In past decades, many methods have been proposed to evaluate power system reliability considering weather effects. In [5] each transmission line was assumed to operate in a two-state fluctuating weather environment and full Markov method was used to evaluate transmission system reliability. In [6] an improved three-state weather model was proposed to include major adverse weather conditions such as heavy storms, freezing rain and tornadoes, and minimal cut-set (MCS) method was used to evaluate transmission and distribution system reliability. In [6]-[7] RWM was used to recognize the regional effects of weather environment that the transmission lines are exposed to and Monte-Carlo simulation was used to evaluate composite system reliability. In [3]-[4] statistical regression method was used to predict the hurricane-related outage number in each geographic unit in distribution system and in [2] it was pointed out that there is rough correspondence between hurricane severity and power outage number.

To assess the impact of hurricanes on composite system reliability the challenge is to determine the functional relationship between the severity level of a hurricane and the variation of the reliability parameters (e.g. the failure rate) of transmission lines. Regression method and Bayesian network have been used to solve this problem in [10]-[11]. In this paper, a FES is proposed and is combined with RWM to assess the hurricane impact on the failure rates of transmission lines. The implementation of the proposed method is as follows:

- According to the computation requirements, the composite system is partitioned into different regions. It is pointed out that the number of the partitioned regions should be determined in terms of accuracy and computation burden.
- The FES is used to map the approximate nonlinear relationship between the hurricane parameters and the IMFR of the transmission lines in different regions. This fuzzy rule-based inference system consists of a set of ‘if-then’ rules that describe the relationships between the input and output variables. Here, the input variables are the defined hurricane parameters (representing the severity of the hurricane) and the

---

This work is supported in part by NSF Grant EECS-0725823.

output variables are IMFR of transmission lines. In each region, the input and output of the FES are assumed to be identical. Since a long transmission line may traverse different regions, its overall IMFR is determined by using WAM.

- The failure rates of transmission lines can be used in analytical or simulation method to evaluate composite system reliability considering hurricane impact.

The proposed method is applied to the IEEE RTS [8]. The implementation demonstrates that the proposed method is effective and efficient and the FES is convenient to construct.

This paper is organized as follows: Section II briefly introduces the basic concepts of fuzzy sets; in Section III, all functional modules of the proposed FES are described in detail; in Section IV, the full scheme of composite system reliability evaluation considering hurricane impact is presented; in Section V, the proposed method is applied to the IEEE RTS; finally is the conclusion part.

II. FUNDAMENTALS OF FUZZY SETS

In this section, the basic concepts of fuzzy sets and fuzzy rule-based system [9] are briefly reviewed to facilitate the understanding of subsequent discussion.

A. Crisp Set and Fuzzy Set

The concept of fuzzy set is a generalization of the crisp set, i.e. the classic set. Usually, whether an element x is a member of a crisp set A or not is classified by using the characteristic function (CF) as follows:

$$CF_A(x)=\begin{cases}1, x\in A\\0, x\notin A\end{cases}, \text{ i.e. } CF_A: X\rightarrow\{0,1\} \quad (1)$$

where X is the universe of discourse of x, i.e. all possible values that x can take: discreet or continuous. However, for a fuzzy set B the degree of whether or not an element x is its member can be between 0 and 1 and it is described by using the membership function (MF) as follows:

$$MF_B: X\rightarrow[0,1] \quad (2)$$

Apparently, the expression of MF is more flexible than that of CF and this makes MF more descriptive of how the real world is perceived. Actually, we always encounter many objects that partially belong to a category and maybe belong to other categories at the same time. In practice, MF can be any function that satisfies the above relationship. They can be in triangular, trapezoidal, Gaussian, and many other forms.

B. Operations of Fuzzy Sets

Correspondingly, the operations of fuzzy sets are the generalization of those of crisp sets. For instance, the CF of intersection of two crisp sets C and D can be expressed as follows:

$$CF_{C\cap D}(x)=\min(CF_C, CF_D) \text{ for } x\in X \quad (3)$$

Using MF instead of CF, the intersection of two fuzzy sets E and F can be expressed as follows:

$$MF_{E\cap F}(x)=\min(MF_E, MF_F) \text{ for } x\in X \quad (4)$$

Similarly, other operations of crisp sets can be extended to fuzzy sets. Here, it should be pointed out that the laws of noncontradiction and excluded middle are applicable in crisp sets but not in fuzzy sets. These are listed in Table I where usually the universe of discourse of interest is the set of real numbers. More generally, the intersection operation of fuzzy sets can be realized using triangular norms (t-norms). It presents a group of operators, e.g. minimum and product. In the same way, the union operation of fuzzy sets can be realized by using t-conorms (s-norms), e.g. maximum and probabilistic sum.

TABLE I. COMPARISON OF CRISP SET AND FUZZY SET

Operation	**Crisp Set**	**Fuzzy Set**
Noncontradiction	$A\cap\overline{A}=\varnothing$	$A\cap\overline{A}\neq\varnothing$
Excluded Middle	$A\cup\overline{A}=X$	$A\cup\overline{A}\neq X$

C. Fuzzy Relation and Rules System

Relation captures the association between objects. Generally, a relation R defined over the Cartesian product of X and Y is a collection of selected pairs (x, y) and $x\in X$, $y\in Y$. Here, the two-dimensional case is illustrated and this is also applicable in the multi-dimensional case. Mathematically, R is a mapping as follows:

$$R(x,y)=\begin{cases}1, x, y \quad related\\0, x, y \quad unrelated\end{cases}, \text{ i.e. } R: X\times Y\rightarrow\{0,1\} \quad (5)$$

Fuzzy relation generalizes the above concept by recognizing the partial degree of association between objects, i.e. fuzzy relation R_F is a mapping such that:

$$R_F: X\times Y\rightarrow[0,1] \quad (6)$$

Actually, a fuzzy relation is a multi-dimensional fuzzy set. Fuzzy relation is closely linked with fuzzy rules that form the core part of a rule-based system.

III. FUZZY EXPERT SYSTEM

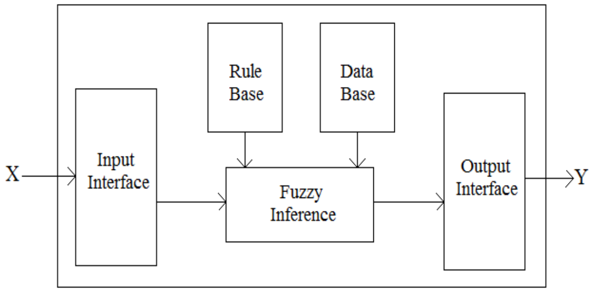

Figure 1. Architecture of FES

In this section, the proposed FES is described in detail. It consists of five parts: input interface, rule base, data base, fuzzy inference and output interface [9]. The relationships among these parts are shown in Figure 1. Here X and Y are the input and output of the FES. For each part, its basic function and realization are presented.

A. *Input Interface*

The input X can be a single numeric value or a fuzzy set. It can be one-dimensional or multi-dimensional. If the input is a numeric value, it needs to be converted into the form that the FES can deal with. This process is usually called *fuzzification*, i.e. to find the corresponding membership value of the input. This is shown in Fig. 2.

In the proposed FES, the input variables are the hurricane parameters in different regions of the composite system and they indicate the severity of the hurricane.

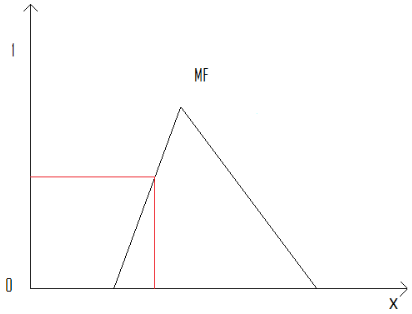

Figure 2. Fuzzification

B. *Rule Base*

Rule base consists of a set of fuzzy rules that describe the relationships between input X and output Y. Generally, a fuzzy rule is in the following form:

R: If X is A then Y is B

The left-hand side of the rule is called *antecedent* and the right-hand side is called *consequent*. Usually they are linguistic variables and antecedent is in multi-dimensional form and consequent is one-dimensional, i.e. the previous rule is in the following form:

If X_1 is A_1 and X_2 is A_2 and $\cdots$ and X_n is A_n then Y is B

In the proposed FES, the output variable is the IMFR of the transmission lines in different regions. For instance, a rule can be as follows:

If H_1 is High and H_2 is Medium and $\cdots$ and H_n is High then IMFR is High

where H_1, H_2, $\cdots$, H_n are hurricane parameters.

C. *Fuzzy Inference*

This is the most important part of the FES. It processes the input data and implements reasoning function by using the information of rule base and data base. The detailed description of the inference is as follows:

- Input matching: For each rule, use fuzzification to determine the membership value of each input.
- Input aggregation: For each rule, use any *t*-norm to compute the rule activation degree, i.e. the intersection of all obtained membership values of the inputs in step (1). Here, the minimum operation is used.
- Output derivation: For each rule, use any *t*-norm to compute the intersection of the rule activation degree and the output. Here, the minimum operation is used.
- Output aggregation: use any *s*-norm to compute the union of all obtained outputs in step (3). Here, the maximum operation is used.

D. *Data Base*

Data base stores the parameter values of the FES, e.g. the definitions of variable universes, the types and parameters of the MF of input and output variables. Basically, there are two methods to construct the rule base and data base (i.e. building a FES): knowledge-based and data-driven. The proposed FES is built by using expert knowledge. Generally, when sufficient historical data is available, the data-driven method can be used to build a fuzzy inference system (FIS); if the data is not available or is insufficient, the knowledge-based method can be used. The details of the proposed FES are given in Section V.

E. *Output Interface*

The output Y also can be a single numeric value or a fuzzy set. In the proposed FES, the outputs are the IMFR of the transmission lines in different regions. Thus, the output in the form of a fuzzy set needs to be converted into a numeric value by using *defuzzification*. Here, the numeric output is the representative of the inferred fuzzy set. There are many methods to implement defuzzification. In this paper, the centroid method is used [9]. Basically, it determines the gravity center of the inferred MF of the output and is as follows:

$$y = \frac{\int_Y y \cdot B(y) d(y)}{\int_Y B(y) d(y)} \tag{7}$$

IV. EVALUATION OF FAILURE RATE

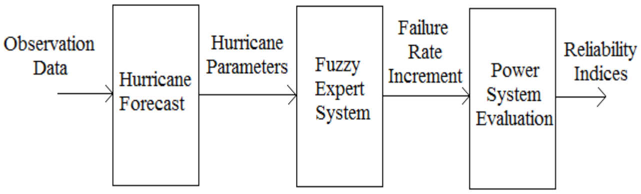

Figure 3. Reliability Evaluation Scheme

The proposed FES can be combined with analytical or simulation to evaluate composite system reliability considering hurricane impact. As shown in Fig. 3, the whole evaluation process consists of hurricane forecast, assessment of hurricane impact, and composite system reliability evaluation. As mentioned previously, according to the computation requirements the composite system is partitioned into different regions. The possible case that a transmission line traverses different regions is solved by using WAM. This is also described in this section.

A. Evaluation Scheme

1) Hurricane forecast

The incoming hurricane is forecast by using observation data and prediction model. The hurricane forecast usually includes the forecast of hurricane track and intensity. The track forecast can determine the movement path of the hurricane and thus the affected parts of the composite system can be identified. The intensity forecast can determine the effects of a hurricane. Due to the development and dissipation of the hurricane, its impact on the composite system may be different in different regions. Therefore, according to the tradeoff of accuracy and computation burden the composite system should be divided into different regions. In each region, the hurricane impact is represented by using defined parameters that indicate its severity and are identical. A hurricane can cause large waves, heavy rain, and high winds. Here, wind speed and rainfall are selected as two hurricane parameters.

2) Fuzzy expert system

The hurricane parameters obtained in Step (1) are input into the FES to assess the hurricane impact on the failure rates of the transmission lines in different regions. Here, the output is the IMFR of the transmission lines in different regions. In each region the multiplier is the same for all transmission lines belonging to this region. As mentioned before, generally there are two methods to build a FIS: expertise-based and data-driven. Here, the expertise-based method is used, i.e. the experts quantify knowledge about the basic concepts and variables essential to the problem and relate them in the form of some rules. The formed FES is described in detail in the next section.

3) Composite system evaluation

The output of the FES (the regional IMFR of the transmission lines) is input into the reliability evaluation model of composite system to evaluate hurricane impact. Here, analytical or simulation method can be used.

B. Regional Weather Model

As mentioned before, the composite system is partitioned into several regions according to the computation choice and the corresponding model is shown in Fig. 4.

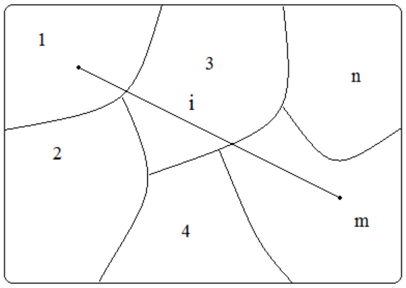

Figure 4. Regional Weather Model

For a long transmission line, it is possible that it belongs to different regions. This problem is solved by using WAM. If transmission line traverses different regions, its overall IMFR is calculated as follows:

$$n_i = \sum_{j\in M} \frac{l_j}{l} n_j = \sum_{j\in M} w_i^j \cdot n_j \tag{8}$$

Where set M represents all the regions the transmission line i traverses; l is the overall length of transmission line i and l_j is its length in region j; n_j is the IMFR of transmission line i in region j; w_i^j represents the corresponding weight. If the individual weight is interpreted as the probability of the transmission line i being in region j (p_i^j), the above equation can be rewritten as follows, i.e. the expectation of random variable $N_j = \{n_j\},\ j \in M$.

$$n_i = \sum_{j\in M} p_i^j \cdot n_j = E(N_i) \tag{9}$$

V. NUMERICAL EXAMPLES

In this section, the proposed method is applied to the IEEE RTS [8]. Firstly, the input data, data base and the rule base of the FES are given; then, the results of the proposed method are listed.

A. Input data

In this paper, the IEEE RTS is divided into two parts and the split basically follows along the voltage levels of the IEEE RTS. This is shown in Fig. 5. The tie lines between 230KV part and 138KV part are four transmission lines: line from bus15 to bus24, line from bus11 to bus14, line from bus12 to bus23, and line from bus13 to bus23. The split is assumed to pass through the middle points of these lines.

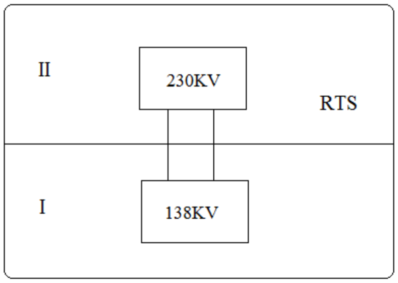

Figure 5. Partition of RTS

TABLE II. INPUT DATA

Input Data	Region 1	Region 2
Wind Speed (mph)	120	105
Rainfall (in)	20	15

As mentioned before, the hurricane parameters that indicate its severity are wind speed and rainfall of each region. Since a hurricane develops and dissipates with time, suppose that during a short time interval the hurricane parameters are as in Table II.

B. *Data base and rule base*

The MF of input and out variables are shown in Fig. 6-8.

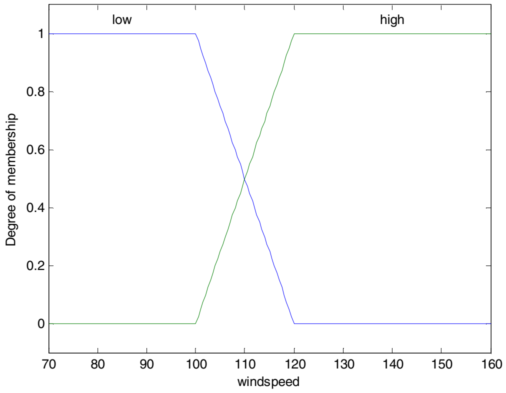

Figure 6. MF of Wind Speed

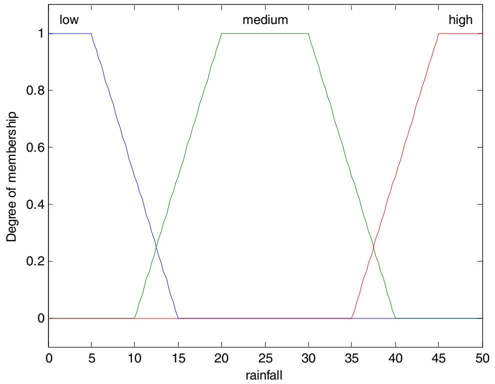

Figure 7. MF of Rainfall

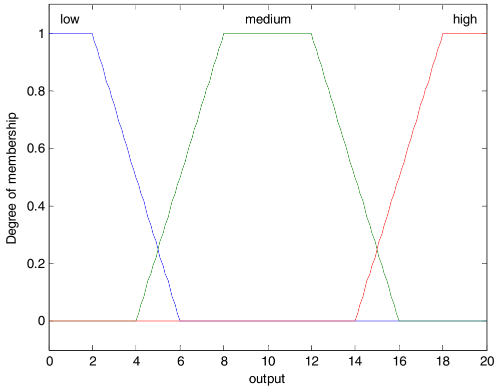

Figure 8. MF of IMFR

All rules in the rule base are listed in Table III:

TABLE III. RULE BASE

IMFR		**Rainfall**		
		High	Medium	Low
Wind Speed	High	High	High	Medium
	Low	Medium	Low	Low

C. *Results of the Proposed Method*

The outputs are regional IMFR of transmission lines. They are listed in Table IV.

TABLE IV. OUTPUT DATA

Output	**Region 1**	**Region 2**
IMFR	17.888	7.7316

VI. CONCLUSION

A hurricane has significant effects on composite system reliability. The challenge of assessing its impact is to find out the functional relationship between its severity and the increment of the failure rates of transmission lines. In this paper, a FES is proposed and is combined with RWM to solve this problem. The FES maps the approximate nonlinear relationship between hurricane parameters and the IMFR of the transmission lines in different regions. Here, the defined hurricane parameters indicate its severity. Then, the failure rates of transmission lines can be used in analytical or simulation method to evaluate composite system reliability considering hurricane impact. During this process, the possible case that transmission lines traverse different regions is investigated by using WAM. The proposed method is applied to the IEEE RTS. From the implementation, the following conclusions are obtained:

- The proposed method is effective. It can evaluate the hurricane impact on composite system reliability. The numeric results demonstrate that a hurricane can increase the failure rates of transmission lines and consequently worsen the reliability of power system.
- The proposed FES is efficient. Once the FES is built, its inference time is almost negligible.
- It is convenient to build a FES by using the knowledge-based method.

REFERENCES

[1] D. P. Gaver, F. E. Montmeat, A. D. Patton, "Power system reliability I – Measures of reliability and methods of calculation", *IEEE Trans. PAS*, vol. 83, no. 7, pp. 727-737, July 1964.

[2] R. A. Davidson, *et al*, "Electric power distribution system performance in Carolina hurricanes", *Nat. Hazards Rev.*, vol. 4, no.1, pp. 36-45, Feb. 2003.

[3] H. Liu, *et al*, “Negative binomial regression of electric power outages in hurricanes”, J. Infrastruct. Syst. 2005; 11(4): 258-67.

[4] S. Han, *et al*, “Estimating the spatial distribution of power outages during hurricanes in the Gulf coast region”, Reliab. Eng. Syst. Safety, to be published.

[5] C. singh, R. Billinton, *System Reliability Modeling and Evaluation*, Hutchinson, London, 1977.

[6] C. Singh, T. P. Chander, M. P. Bhavaraju, M. Lauby, "A Monte Carlo tool for estimating contingency statistics", *Proc. Power Tech 1993*, Athens, 1993.

[7] M. R. Bhuiyan and R. N. Allan, “Inclusion of weather elects in composite system reliability evaluation using sequential simulation”,

IEE Proc.-Gener. Transm. Distrib., Vol. 141, No. 6, pp. 575-584, Nov. 1994.

[8] RTS Task Force, “IEEE reliability test system”, *IEEE Trans. PAS*, vol. 98, no.6, pp. 2047-2054, 1979.

[9] W. Pedrycz and F. Gomide, *Fuzzy Systems Engineering-Toward Human-Centric Computing*, John Wiley & Sons, New Jersey, 2007.

[10] F. Xiao, J. D. McCalley, Y. Ou, J. Adams, and S. Myers, “Contingency probability estimation using weather and geographical data for on-line security assessment”, 9th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), KTH, Stockholm, Sweden, June 11-15, 2006.

[11] Y. Zhou, A. Pahwa, and S.-S. Yang, “Modeling weather-related failures of overhead distribution lines”, IEEE Trans. Power Systems, vol. 21, no. 4, pp. 1683-1690, Nov. 2006.