A FUZZY LOGIC APPLICATION TO REPRESENT LOAD SENSITIVITY TO VOLTAGE SAGS

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***Abstract*:** This paper presents a case study application of fuzzy logic in a power quality issue. It describes the computer-based load sensitivity to voltage sags, by using fuzzy sets and IF-THEN inference rules. The load sensitivity is based on the steady-state and transient voltage versus time profile according to the IEEE Std. 446, also referred to as the CBEMA (Computer Based Equipment Manufacturer Association) curve. Fuzzy logic allows the modeling of the inherent uncertainty of the load reliability. This expresses how the success or failure of computer based loads is correlated with short term voltage variations in the electric supply system. A fuzzy inference system is experimentally implemented for these cases, showing the general procedures of how to use this theory. It appears that fuzzy set theory can play an important role in diagnosing power quality disturbances, and hence it can offer insights towards the satisfaction of the needs of manufacturers, utilities and customers.

Keywords: fuzzy sets, fuzzy logic application, power quality, voltage sag, intelligent systems.

I. INTRODUCTION

The main objective of this research is to explore new possibilities to represent the reliability of computer-based loads, such as an electronically controlled equipment, with respect to transient phenomena in electric power systems, such as voltage sags. In recent years, it has been a big concern for the electric utilities to satisfy the expectations of the industrial, commercial and residential electricity customers with respect to the quality in the supplied electric energy. Due to the development of automated control systems, computer-based loads and other power electronic devices, their sensitivity to the quality of power has increased. Furthermore, the expectations are highly differentiated, reflecting the great variety of products and processes. Sometimes power electronic loads are also responsible for the electric "pollution" in the system, and are the source of power quality problems.

Voltage sags, voltage swells, outages, cold load pick-up, transient impulses, waveshape faults, harmonic distortions, flicker, frequency deviations are examples of disturbances related to power quality problems. These variations can originate and/or manifest themselves at various places in the network. Some of these power quality concerns are associated with design, operation and random environmental events in the electric power system, for example, a fault caused by lightning. Many of them are associated with the operation and design of customer facilities, e.g., concerns associated with wiring and grounding problems, switching transients, load variations, harmonic generation. Most of the power quality cases are due to the incompatibility between the susceptibility of electronic based loads, with the present power systems normal operation [1].

To analyze the voltage magnitude and duration sensitivity of a specific computer-based load it is important to consider its intrinsic manufacturing characteristics. Sometimes this is not known by the customers who complain about some power quality problems to the utilities. The load voltage sensitivity varies depending on the manufacturer, differences in equipment or application, life-time, previous conditions, etc. These real uncertainties make hard the decision task of forecasting the success or failure of computer-based loads against possible power quality related problems by the utilities. Therefore, fuzzy logic [2] seems to be appropriate to represent load sensitivity to voltage sags. An example of such application will be described in this paper.

The proposed fuzzy logic application to represent load sensitivity to voltage sags is based on the CBEMA (Computer Business Equipment Manufactures Association) computer tolerance envelope presented by the IEEE Std. 446-1987 [3]. Some necessary practical knowledge was also used as reference from realistic power quality monitoring from Brazilian utility CESP (Companhia Energetica de São Paulo, São Paulo, Brazil). This real experience was developed through some power quality troubleshooting within customers installations and also within power system facilities [4], [5].

This paper is composed of five sections. Section II of the paper presents some of the fuzzy sets fundamentals. A

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description of the load voltage sensitivity as a power quality issue is discussed in section III. The formulation of the load voltage sensitivity case study based on the fuzzy set theory is shown in section IV. Section V presents the conclusions.

II. FUZZY SETS FUNDAMENTALS

The mathematical representation of vagueness or uncertainty is not an easy task. Usually for real problems, there is a lack of complete and reliable information on things that are supposed to be given or known. Typically, the modeling criteria to be taken into account for this representation are neither precisely known nor remain constant with time, context nor situation, i.e., forecasts proved to be wrong, random disturbances occurring, subjective judgments, and so on [1].

Fuzzy logic is a technique to handle such uncertainties. A fundamental element of fuzzy logic is the *"membership function"*, which describes the degree of a certain variable "x", belonging to a *fuzzy set* "**A**". This degree of membership, expressed in an interval of [0, 1], is a measure of proximity to this set. A membership value of 1 for a particular value "x_0" means that the variable is completely satisfactory for the fuzzy set "**A**", whereas a value of 0 means that it is completely unacceptable in that fuzzy set, i.e., it doesn't belong to the set "**A**" at all. Any deviation is acceptable with an intermediate degree of satisfaction between 0 and 1. This is a special property that is very useful to model some real world uncertainties, that are linguistically expressed by experts.

IF-THEN logic rules can be used to combine membership values for fuzzy variables, trying to mimic the human reasoning process. All the consequences for each defined rule are aggregated to give the result, that is expected to be a real value, which is supposed to be the closest to the real knowledge being modeled.

When fuzzy set theory is used to solve real problems, the following steps are generally followed [6]:

1) Description of the original problem in a linguistic or mathematical form;
2) Definition of the input and output variable for the fuzzy inference system, whose range and thresholds can be based on empirical knowledge;
3) Appropriate definition of the number and shape of membership functions for each input and output variables. The membership functions express the degree of satisfaction of a certain variable value into a defined fuzzy set;
4) Definition of IF-THEN inference rules, that must represent the system practical behavior being modeled by an expert;
5) Selection of the fuzzy operators for the defuzzification process in order to assure that the results obtained are similar to those observed in the real world;
6) Tuning the fuzzy inference system by feedback to the previous steps.

III. DESCRIPTION OF THE LOAD VOLTAGE SENSITIVITY AS A POWER QUALITY ISSUE

Usually, voltage sags, that are short term depressions in supply voltages, are responsible for the majority of distribution power quality problems [1]. An appropriate way to express voltage sags disturbances is through a graph of rms voltage magnitude in percentage of the nominal voltage versus the time duration in cycles (60 Hz) or milliseconds. A commonly used voltage duration profile for power line disturbance is presented in Fig. 1. This typical Automatic Data Processing power requirements profile from IEEE Std. 446-1987 [3] is a computer tolerance envelope, which is also referred to as CBEMA curve.

IV. FORMULATION OF THE LOAD VOLTAGE SENSITIVITY CASE STUDY BASED ON FUZZY SETS

Because most of the power quality problems are related to voltage sags, for this project only this type of voltage variation will be considered for modeling the load sensitivity. Fig. 2 shows a set of waveforms of the magnitude versus duration of voltage disturbance taken from monitoring a 138 kV substation, supplying a pulp and paper industry customer.

A common sense about electronic or computer-based load reliability, expressed as success or failure, regarding voltage magnitude depression and time duration can be stated linguistically in general terms as follows:

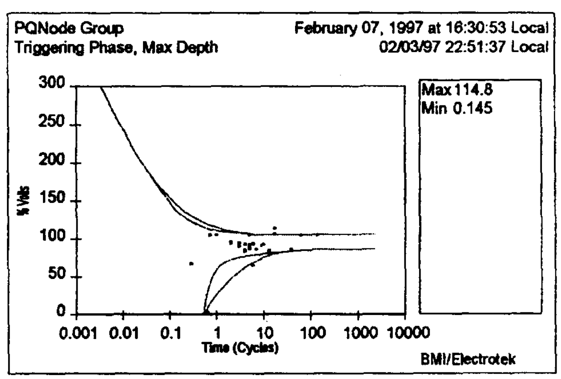

Fig. 1: Typical Automatic Data Processing Power Requirements Profile from IEEE Std. 446-1987 (CBEMA curve).

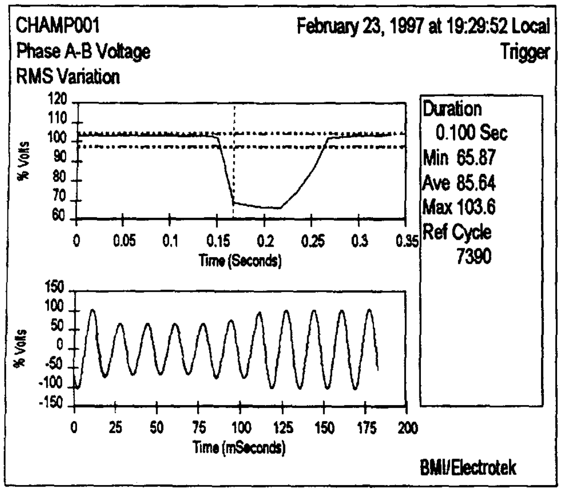

Fig. 2: Voltage Sag Disturbance in a 138 kV substation, supplying a pulp and paper industry customer

IF the voltage is normal and time duration has no effect,
THEN the load always will succeed;
IF the voltage is low and the duration is very short,
THEN the load may fail;
IF the voltage is extremely low and the duration is long,
THEN the load certainly will fail.

A fuzzy logic application was developed to represent load voltage sensitivity according to the steps presented above. The software MATLAB, version 5.1, with a fuzzy logic toolbox, was used to implement the case studies.

For this fuzzy inference system, the two input variables chosen are the ***voltage magnitude*** expressed in percentage of the load nominal voltage, in a range from 0 to 106%, and the ***time duration*** of this undervoltage, expressed in cycles (60 Hz), in a range from 0 to 60 cycles, or milliseconds. The one output variable chosen is the ***reliability***, expressed in percentage, in a range from 0 to 100% (Note that although the reliability measure is expressed by percentage, those figures do not necessarily represent the probability of occurrence). Table 1 explains the meaning of each defined fuzzy set for each of the input and the output variables.

Four trapezoidal membership functions are defined for each of the input variables as shown in Fig. 3 and Fig. 4. The thresholds are defined based on the CBEMA curve and from practical experience. The output variables are defined by five membership functions as shown in Fig. 5. Success is interpreted as "100% reliability", whereas failure is interpreted as " 0% reliability".

To represent the phenomena or practical knowledge, IF-THEN rules must be stated to form a fuzzy inference system. For each possible combination of the fuzzy sets belonging to two input variables, there is one fuzzy set output variable. Examples of rules are shown in Fig. 6.

Table 1. Fuzzy Sets defined for the fuzzy inference system

Membership function	**Input 1: Voltage** (%)	**Input 2: Duration** (cycles)	**Output: Reliability** (%)
1	**EL** Extremely Low	**ES** Extremely Short	**F** Failure
2	**VL** Very Short	**VS** Very Short	**AF** Almost Failure
3	**L** Long	**S** Short	**A** Average
4	**N** Normal	**L** Long	**AS** Almost Success
5			**S** Success

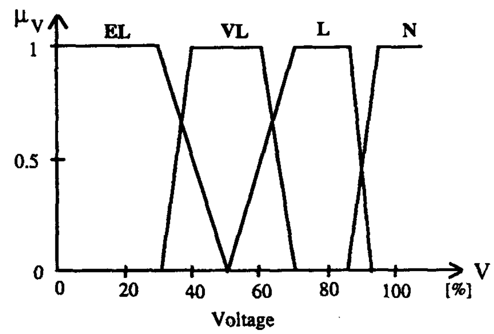

Fig. 3: Voltage Magnitude Input Membership Function

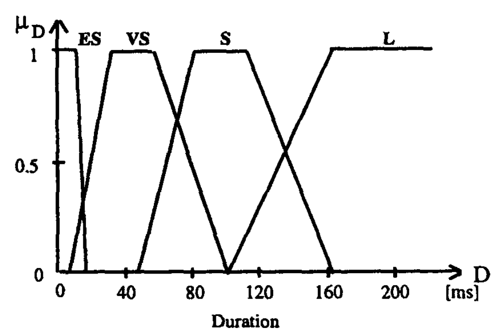

Fig. 4: Time Duration Input Membership Function

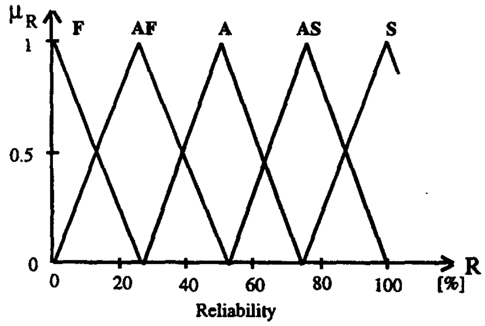

Fig. 5: Reliability Output Membership Function

It is important to note that, because four fuzzy sets were defined for voltage input variables, and four other fuzzy sets for the time duration input variables, this combination resulted in 16 inference rules. Generally, the number of rules increases as the product of the number of defined input fuzzy sets. This could be a concern if a large number of fuzzy sets are defined. The fuzzy inference process is illustrated in Fig. 7.

The selection of the fuzzy operators and the defuzzification method was made as shown in Table 2.

1: IF (Voltage is EL) and (Duration is ES) THEN (Reliability is S)
2: IF (Voltage is EL) and (Duration is VS) THEN (Reliability is AF)
3: IF (Voltage is EL) and (Duration is S) THEN (Reliability is F)
4: IF (Voltage is EL) and (Duration is L) THEN (Reliability is F)
5: IF (Voltage is VL) and (Duration is ES) THEN (Reliability is S)
6: IF (Voltage is VL) and (Duration is VS) THEN (Reliability is A)
7: IF (Voltage is VL) and (Duration is S) THEN (Reliability is AF)
8: IF (Voltage is VL) and (Duration is L) THEN (Reliability is F)
9: IF (Voltage is L) and (Duration is ES) THEN (Reliability is S)
10: IF (Voltage is L) and (Duration is VS) THEN (Reliability is AS)
11: IF (Voltage is L) and (Duration is S) THEN (Reliability is A)
12: IF (Voltage is L) and (Duration is L) THEN (Reliability is AF)
13: IF (Voltage is N) and (Duration is ES) THEN (Reliability is S)
14: IF (Voltage is N) and (Duration is VS) THEN (Reliability is S)
15: IF (Voltage is N) and (Duration is S) THEN (Reliability is S)
16: IF (Voltage is N) and (Duration is L) THEN (Reliability is S)

Fig. 6: Inference rules for voltage sags

Table 2. Fuzzy Operator and Defuzzification Method

AND	min
OR	max
Implication	min
Aggregation	max
Defuzzification	centroid

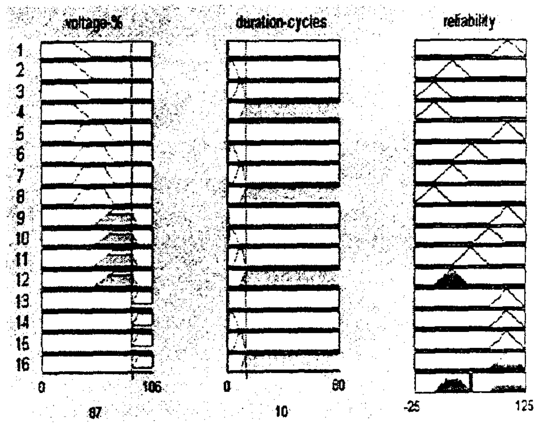

Fig. 7: Process of the fuzzy inference

The simulation results of this fuzzy logic application in representing load sensitivity to voltage sags is presented in the following figures. Fig. 8 shows the surface view quantifying the load reliability expressed in percentage. Success is interpreted as 100%, whereas failure is 0%. Fig. 9 illustrates the same resulting reliability in a two-dimensional chart resembling the CBEMA curve for the voltage sag cases (lower half of Fig. 1).

V. CONCLUSIONS

This paper has presented a case study application of fuzzy logic to a power quality issue. It describes the computer-based load sensitivity to voltage sags, by using fuzzy sets and IF-THEN inference rules. Using a typical computer voltage tolerance envelope as a standard reference (IEEE Std. 446 or CBEMA curve), a fuzzy reasoning process was developed to decide about the reliability ("how much" success or failure) of computer-based loads, when voltage disturbances occur in the neighborhood of the electric supply system.

This type of sensitive load has an inherent uncertainty, i.e., power quality tolerance varies according to differences in equipment manufacturers, device application, and so on. This uncertainty was formulated by fuzzy logic theory through membership functions, which usually do not use strict boundaries, and such feature was found suitable in dealing with the vagueness associated with the power quality problem. The results presented show the potential of intelligent system techniques for diagnosing power quality disturbances, giving answers to the needs of manufacturers, utilities, and electric energy customers.

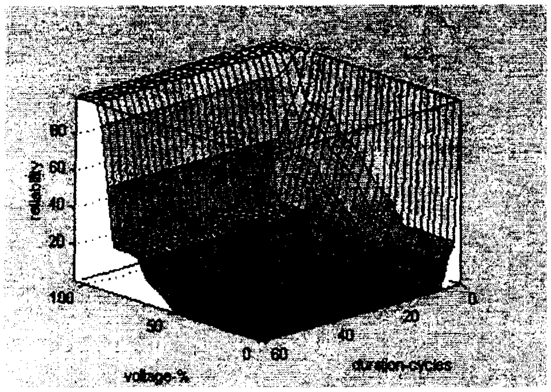

Fig. 8: 3D Surface view of voltage sag load sensitivity

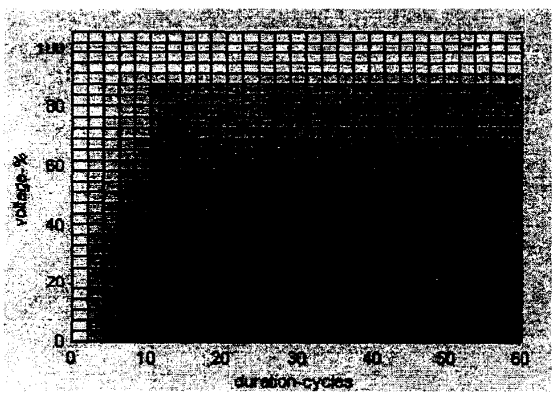

Fig. 9: Two-dimensional view of voltage sag load sensitivity

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BIOGRAPHIES

Benedito Donizeti Bonatto was born in Conchal, Brazil, on August 05, 1966. He received the B.S. in Electrical Engineering with honors from the Federal School of Engineering of Itajuba· (EFEI), Itajuba·, Brazil, 1991, and the M.A.Sc. in Electrical Engineering from the State University of Campinas (UNICAMP), Campinas, Brazil, 1995. He joined CESP - Companhia Energetica de São Paulo, Brazil, in 1994, at the Distribution Planning and Protection Divison, where his main tasks were power quality measurements, diagnosis and proposal of solutions for distribution customers. He also joined CEETEPS - The State Center of Technological Education Paula Souza, Brazil, in 1995 as a teacher for the electrotechnical and electroelectronics technical high school courses. Currently, he is on a leave absence from CESP and CEETEPS to pursue his Ph.D. degree at the Department of Electrical and Computer Engineering of The University of British Columbia (UBC), Vancouver, Canada. His field of interests includes simulation and analysis of electromagnetic transients phenomena in electric power systems and power quality issues. He is a student member of the IEEE.

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