FUZZY DECISION BASED FAULT LOCATION IN SHIPBOARD POWER DISTRIBUTION SYSTEMS

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ABSTRACT

In this study, a fuzzy decision based method is proposed to estimate the faulted section of the shipboard power system. The membership functions describe the degree of the possibility of being a faulted line section. One of the membership functions is based on the magnitude of the fault currents measured from generator switchboard. Another membership function type is based on the geographical location of line sections on ship. By combining the results of various membership functions, a priority list of possible faulted line sections is obtained. In the paper, proposed method is applied on an example shipboard electric power distribution system and the simulation results are presented.

I. INTRODUCTION

Usage of electrical energy in ships is getting increasing day by day. The electrical power systems in naval ships supply energy to sophisticated systems for weapons, navigation, operation, and communications. Moreover, merchant ships use electrical energy for big cranes, and systems of navigation, communications etc. Shipboard electrical systems have their own characteristics.

Shipboard electrical distribution systems have special features and some differences from their commercial terrestrial counterparts. Nautical conditions are harder than terrestrial conditions. Moisture on sea, variable ship swing/trim because of sea conditions, continuous vibration on ships etc. can be given as examples of these nautical conditions. Electrical energy is vital for ships. Generators support electrical energy, and shipboard power distribution system distributes energy to the loads. Generally naval ships use 450V 60Hz three phase main electric energy. The traditional shipboard power distribution system is a type of radial electric power distribution system. Shipboard power distribution system has two geographically separated power sources to supply energy for mission critical loads. Mission critical loads are vital loads. The other types of loads are non-vital. Usually ungrounded delta configuration is used to ensure continuous operation of the power systems in the presence of a single phase to hull fault in navy ships [1]. The most popular topology used in shipboard power systems is a ring configuration of the generators, since any generator can provide energy to any loads in this configuration.

Electrical power systems of today's navy ships are designed with reliability of power for vital loads. Architecture of radial distribution systems is almost impossible to protect and keep functioning during and after casualty [2]. Today's studies for shipboard power distribution are conducted to determine new architecture. The demand is that the future ships are more affordable while maintaining their existing performance capabilities. New architecture is named zonal electric distribution system in ships [2]. This new method modifies architecture of current power cable between electrical power generators and the vital bus transfer or non-vital electrical panel on all switchboard feeder circuits [2]. The new distribution technique is separated into two parts. One is AC zonal electrical system and the other is DC electrical system [2].

Network reconfiguration for restoring a naval power system is a critical task performed to restore loads resulting from battle damage or system faults [3]. To maintain the availability of energy connected with loads that keep all systems operational, protection devices are used. After a fault occurs in a shipboard electrical system, protection devices isolate faulty section to prevent or limit damage during abnormalities and to minimize their effect on the remainder of the system. Since a continuous power supply must be provided to the vital loads for maintaining safety on sailing under battle damage and certain major failure conditions, it is important to locate and fix fault as soon as possible. Especially on war ships, we have to locate and fix fault, which can be caused by causality, collision, to be hit at war etc., very quickly to execute the mission. The restoration/reconfiguration can be expedited if the location of the fault is either known or can be estimated with reasonable accuracy.

In this study, a fuzzy decision based method is proposed to estimate the faulted section of the shipboard power system. The problem is handled in fuzzy environment and various membership functions are used to model the knowledge such as measured fault currents, locations of lines on the ship. In this paper, the fault location and basic principles of fuzzy set theory are briefly introduced in section 2 and section 3, respectively. Then the proposed method is discussed in detail in section 4. The application results and the conclusions are given in section 5 and section 6, respectively.

II. FAULT LOCATION

When the fault occurs, protection relays isolate faulty portion of the system but after that some loads, which are free of problems in faulty section, cannot be supplied. Since some of these loads may be vital, faulty system has to be reconfigured/ restored as soon as possible.

In order to restore and reconfigure the shipboard electrical system that is under fault, first of all fault location should be determined. During this process, the available data from the feeders can be used to apply analytical methods, and the operators' experience can also be included in this process to identify possible fault locations [4].

There are many kinds of fault location and diagnosis techniques in the literature and these techniques were generally developed for transmission lines and they are not suitable for radial distribution networks [5-6]. The fault location methods can be divided into three categories: the method that uses fundamental frequency, voltages and currents measured at the line terminals, the method that uses traveling waves, and the impedance based method, which uses high frequency components of current and voltage. When some of these methods are used for distribution lines, the fault location error can occur because of non-homogeneity of lines, presence of laterals and load taps [6].

A shipboard power distribution system is generally a type of radial distribution. Radial distribution has many branches or laterals. We can find a number of possible fault places that have the same electrical distance from the supply, if the faulted feeder has several laterals and branches.

Some areas of the ship are very likely to have a fault. Some part of a warship has high radar or thermal cross section areas and so a guided missile can hit this part with the highest possibility at the battle. Some feeder and devices are located on board and they are affected from the bad sea and weather conditions. Therefore using the information about the location of electrical devices, feeder or branches in the ship can help operator during the fault location process. Moreover, it can be useful to take into consideration the operator's experience in the fault location method. Consequently, the fault location problem of shipboard power systems is very fuzzy. So, we can handle the fault location problem of a shipboard electrical distribution system in the fuzzy environment.

III. FUZZY SET THEORY

Fuzzy set theory offers new methods for modelling the inexactness and uncertainty concerning decision-making [7]. It is a natural and appropriate tool to represent inexact relations. Each uncertainty is associated with a membership function $\mu(x)$ that represents the degree of certainty for that relation [4]. Fuzzy set theory defines set membership as a possibility distribution. In Fuzzy set theory the grade of membership function $\mu(x)$ is between 0 and 1 although in the normal case of set theory the grade can be taken only as 0 or 1. The membership function is defined by the user considering fuzziness.

There are several applications of fuzzy system theory to some areas of electric power engineering such as power system stability control, power system optimization, fuzzy pattern recognition for power system stability assessment etc. [7-9].

If X is a collection of objects denoted generically by x, then a fuzzy set A in X is a set of ordered pairs as follows [8].

$$A = \{(x, \mu(x)) | x \in X\} \quad (1)$$

where membership function $\mu(x)$ describes the degree to which the element x belongs to the fuzzy set A. The set of elements that belongs to the fuzzy set A at least to the degree α is called an α-level set [10],

$$A_\alpha = \{x \in X | \mu_A(x) \geq \alpha\} \quad (2)$$

Operations with a fuzzy set are defined via their membership functions. Basic set operations are defined as follows;

$$\text{Intersection: } \mu_{A\cap B}(x) = \min(\mu_A(x), \mu_B(x)) \quad (3)$$

$$\text{Union: } \mu_{A\cup B}(x) = \max(\mu_A(x), \mu_B(x)) \quad (4)$$

$$\text{Complement: } \mu_{\tilde{A}}(x) = 1 - \mu_A(x) \quad (5)$$

The algebraic sum can be used to reflect the effects of all inputs and it can be defined as follows [10],

$$\mu_{A\cup B}(x) = \mu_A(x) - \mu_A(x) \cdot \mu_B(x) + \mu_B(x) \quad (6)$$

IV. PROPOSED METHOD

The proposed method uses fuzzy sets to model the uncertainty in the estimation of the faulted section of the shipboard power distribution system. The various membership functions are used to handle the problem in fuzzy environment. The membership functions describe the degree of the possibility of being a faulted line section. One of membership functions is based on the magnitude of the fault currents measured from generator switchboard. Another membership function type is based on the geographical location of line sections on ship since the lines on ship are installed on different sections and some sections have greater possibility to cause line fault.

The faulted section can be estimated using the measured fault current. The fault current is larger when the fault is closer to the generator switchboard. But the fault impedance can cause the uncertainty in where the fault is. Also there can be a number of possible places for the fault, because there are many branches or laterals in the system. A membership function, which has trapezoidal form, can be used to model the knowledge about measured fault currents, and it is given in figure 1. This membership function is formed for the lines in shipboard power distribution system. Horizontal axis contains currents value along the line.

The membership functions are formed using the fuzzy number *UF*,

$$UF = \left[a, b, c, d\right] \tag{7}$$

where *a*, *b*, *c*, *d* are defined parameters, and determined based on the operator's experience (or simulations). The current values between *b* and *c* have maximum membership grade for the line. The range between *a* and *b* (*c* and *d*) represents the range of fuzziness. The membership function of fault current $\mu_C(I)$ is

$$\mu_C(I) = \begin{cases} 0 & I \le a \\ \dfrac{(I-a)}{(b-a)} & a \le I \le b \\ 1 & b \le I \le c \\ \dfrac{(d-I)}{(d-c)} & c \le I \le d \\ 0 & I \ge d \end{cases} \tag{8}$$

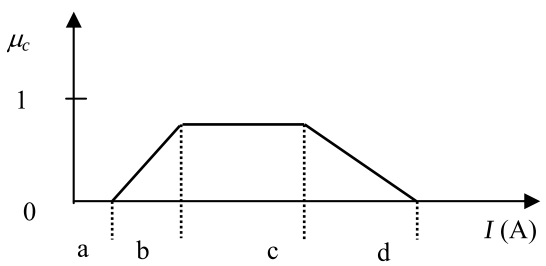

Figure 1. The membership function of the measured fault current.

The membership function of the measured fault current gives us a value of possibility of the faulty lines in our system. As mentioned earlier, more than one feeder section may have same membership grade because of the branches that have same electrical distance from the measuring point. By considering additional membership functions that represent the experience in the shipboard power system, the number of candidates can be reduced.

Another membership function type can be defined according to the operator's experience as in figure 2, and it is based on the geographical location of line sections on ship since the lines on ship are installed on different sections and some sections have greater possibility to cause line fault. In figure 2, the horizontal axis shows the line section and vertical axis is membership value. All lines have their individual location membership function.

The number of the membership functions that represents operator experience can be increased, if there is enough knowledge. As a third membership function, the experience based on the ship's mission can be used. A ship operates under various conditions. For example, a warship operates under five conditions and these are anchor, shore, cruising, functional, and emergency. The power demand depends on ship's mission, and some loads and some feeder lines may not be on service. Therefore the possibility of being faulted line can be affected by the mission. This effect can be reflected by a membership function. A membership function as in figure 2 can be used to represent this experience.

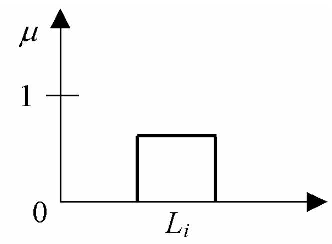

Figure 2. The membership function based on the geographical location.

By combining the results of various membership functions, a priority list of possible faulted line sections is obtained. In combining membership functions the algebraic sum, equation (6), can be used to calculate the possibility of being faulted line.

The final result of the fault location (possible places) can be determined using both maximum and α-level selection on the set that includes the candidate sections.

V. APPLICATION

The proposed method is applied on an example shipboard electric power distribution system. The system, we tackle, belongs to a warship which is a fast attack boat, and it is a radial system. System has three generators (one of them is an emergency generator and not energized), and the voltage and frequency level are 450 V and 60 Hz, respectively. In addition to 450V 60Hz, a warship uses various voltage and frequency levels such as 115V 60Hz and 450V 400Hz, 115V 400Hz for weapons, fire control systems etc. In this study, we considered only 450V, 60Hz systems to reduce our complicated shipboard electrical distribution system. Figure 3 shows the example shipboard electric power distribution system. The switchboard and the feeders can also be seen from the figure.

To apply the proposed fault location method, first the membership functions must be defined for the lines. One way to define membership function based on the measured fault current is to use our experience. However, we have no experience for our modelled system in figure 3. So simulations performed on Matlab [11] environment were used to define the membership functions. Simulations were repeated for all line sections of the example shipboard electrical system, and the fault current data that measured in the switchboard during the simulation are saved. The peak value of the membership function based on measured fault current was taken as 0.8. After forming the membership functions for each line, the measured fault current in a fault case will give a membership value for each section in the faulted feeder. This membership value is a degree of the possibility of being faulted line.

The geographical location membership functions μ_G (figure 2) are formed by assigning a fault possibility degree to each bulk. All line sections in a bulk have same membership degree. In figure 3, the line sections in same bulk are shown within dashed-line boxes. For example, the line sections, L27, L28 and L29 are in bulk B3 and their membership degree is defined as 0.5 which is a low degree because B8 is an inner bulk. The membership degree of line sections L22 and L23 in bulk B1 is 0.8 which is a high degree because these line sections supply devices on afterdeck and they can be easily affected from sea conditions. The proposed method was tested for randomly generated fault scenarios, and the results for 10 cases are presented in table 1. Second column of the table shows the actual fault location. For example “L12, 84 %” means that the fault is occurred in 84 % of L12’s length from generator side. It can be seen from the table that if fault location is close to middle of the line such as case 3, case 4, case 5 and case 10, using only membership values based on measured fault current may give satisfactory results. The priority list of possible faulted line sections obtained by combining membership functions is given in last column. Often this list is much more satisfactory than the list obtained by only current membership function. The operator can locate the fault by using a method like maximum selection or α-level selection.

VI. CONCLUSION

We have to locate and fix fault, which is caused by a combat hit or causality or collision etc., very quickly to execute the mission. The restoration/reconfiguration can be expedited if the location of the fault is either known or can be estimated with reasonable accuracy. So the location of the fault should be found as soon as possible.

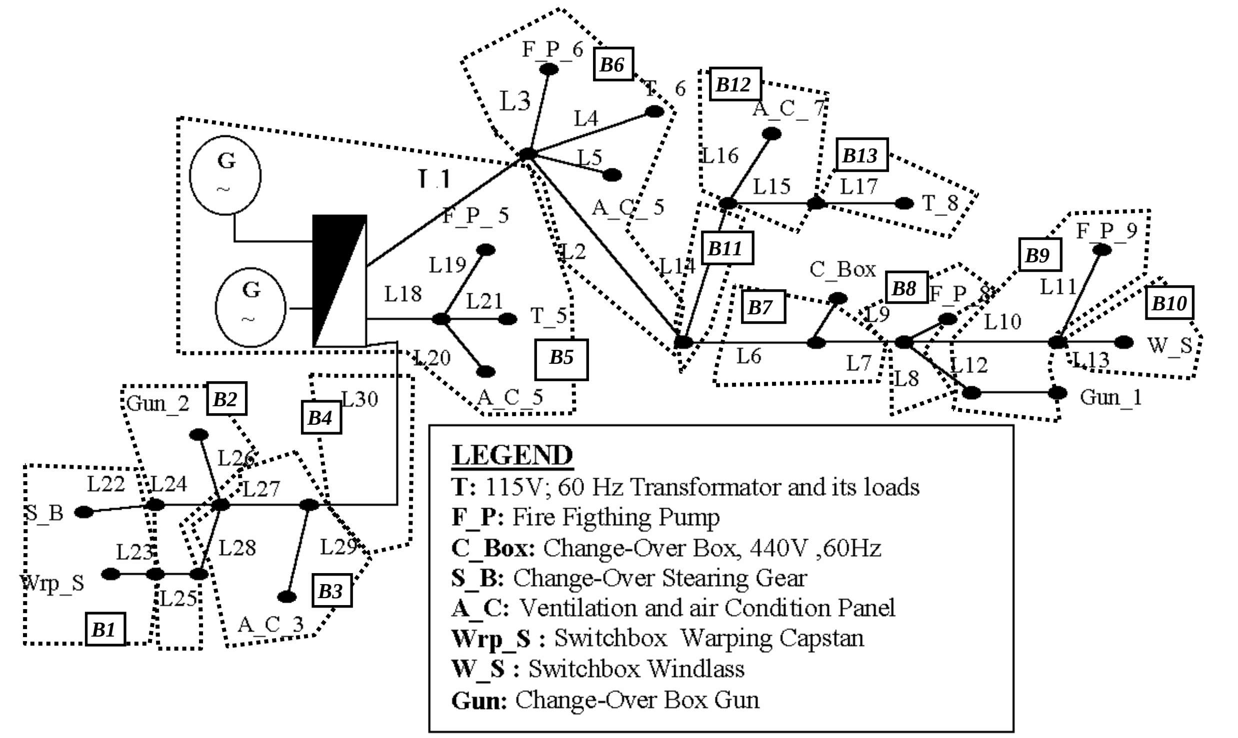

Figure 3. The example shipboard electric power distribution system.

Table 1. The obtained results for the example system

Case #	Fault location	μ_C	μ_G	Final Decision μ_D	Priority ordering of possible fault locations
1	L12, 84 %	0.8 for L4 0.8 for L10 0.8 for L15 0.7205 for L12	0.6 for L4 0.8 for L10 0.65 for L15 0.8 for L12	0.92 for L4 0.96 for L10 0.93 for L15 0.9441 for L12	L10 L12 L15 L4
2	L11, 86%	0.7283 for L13 0.6812 for L11	0.6 for L13 0.8 for L11	0.8913 for L13 0.9362 for L11	L11 L13
3	L13, 50%	0.8 for L13	0.6 for L13	0.92 for L13	L13
4	L27, 41%	0.8 for L27 0.5085 for L29	0.5 for L27 0.5 for L29	0.9 for L27 0.75425 for L29	L27 L29
5	L24, 62%	0.8 for L24 0.8 for L28	0.6 for L24 0.5 for L28	0.92 for L24 0.9 for L28	L24 L28
6	L19, 20%	0.8 for L20 0.7985 for L19 0.5468 for L21	0.75 for L20 0.75 for L19 0.75 for L21	0.95 for L20 0.9496 for L19 0.8867 for L21	L20 L19 L21
7	L23, 89%	0.6217 for L23	0.8 for L23	0.9243 for L23	L23
8	L28, 94%	0.5320 for L28 0.2699 for L25	0.5 for L28 0.6 for L25	0.766 for L28; 0.7079 for L25	L28 L25
9	L11, 6%	0.5720 for L11 0.4757 for L13 0.4002 for L10	0.8 for L11 0.6 for L13 0.8 for L10	0.9144 for L11 0.7903 for L13 0.88 for L10	L11 L10 L13
10	L15, 61%	0.8 for L4 0.7865 for L15 0.7392 for L10	0.6 for L4 0.65 for L15 0.8 for L10	0.92 for L4 0.9253 for L15 0.9478 for L10	L10 L15 L4

The proposed method that uses fuzzy set theory to estimate the faulted section of the shipboard power system is very flexible, because the problem is handled in fuzzy environment and various membership functions are used to model the knowledge such as measured fault currents, geographical locations of lines on the ship and ship's mission etc. These membership functions can be used together to obtain better fault location results.

Since the determination of membership functions is important and the results vary depending on available measurements and network information, by having more data and a better network model, more accurate fault locating can be possible.

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