A Fuzzy Approach Used in Expert System for Optimal Neutral Grounding
Toader Dumitru, Lustrea Bucur*, Blaj Constantin, Borlea Ioan**, Haragus Stefan
Department of Physical Foundation of Engineering, * Department of Power Engineering
“Politehnica” University of Timișoara
Bd.Vasile Pârvan Nr.2 300223 Timișoara
ROMANIA
constantin.blaj@et.upt.ro  http://www.et.upt.ro

Abstract: - In this paper an expert system for selecting the appropriate neutral grounding method in medium voltage distribution network is presented. The grounding method should provide the best response in the case of a single-grounding fault. To fulfill this requirement, the fuzzy rules are based on a simple mathematical model of the fault, in conjunction with operation experience in medium voltage networks. The expert system is very easy to use even by medium level education operators.


1 Introduction
Medium voltage power networks may have the neutral isolated, or grounded, via a resistor or a reactor. If a nonsymmetrical fault occurs, the zero-sequence voltage on the transformer terminals, the voltages on the healthy lines and the fault current greatly depend on the adopted solution for grounding the network’s neutral. For an isolated neutral network, in the case of a single-grounding fault, the voltage on a healthy phase raises to the line voltage, stressing the phase isolation. Consequently, the single-grounding fault may develop into double-grounding fault, which is very dangerous for the power system. On the other end, if the neutral is zero-impedance grounded then a single-grounding fault does not affect the voltages on the healthy lines. In what concerns the modification of the phase voltages during a single-grounding fault, the grounding method via a reactor or a resistor is situated between those two methods before mentioned [1, 2, 3, 4, 5, 6]. In this paper an expert system is presented - Neutral Treatment Strategy Expert System (NTSES). This system allows the choosing of the optimal solution for grounding the neutral of a medium voltage power network based on the three classical methods, namely: isolated neutral, neutral grounded via a compensation reactor, respectively via a resistor. The main advantages offered by NTSES are the following:
-it is easily transferable to various locations;
-the recommended solution has a logical base;
-it is easy to use as a medium level knowledge for the people working in the field is necessary;
-it has low operation costs.
The NTSES utility resides from the following considerations:
-NTSES offers the necessary information needed to take the correct decision for the neutral grounding method;
-using the results provided by the NTSES the operation personnel may appropriately interfere with the power system, if necessary;
-during the design process of a medium voltage network, NTSES allows the selection of the optimal neutral grounding solution;
-NTSES helps to discriminate the situations in which modifications of the network structure, impose changing the way in which the network’s neutral is grounded.
The data provided by NTSES facilitates the maintenance activities scheduling, as the isolation stressing during a single-grounding fault do depend not only on the neutral grounding method, but as well on the specific fault conditions.

2 Basic Specification
2.1 General Specification
For choosing the appropriate neutral grounding method the following aspects should be taken into account [4, 7, 8, 9, 10]:
-the number of customer disconnections, due to grounding faults, should be as low as possible;
-the line types (overhead or underground);
-the fault nature (atmospheric discharge, internal overvoltage, etc.);
-the geophysical characteristics of the landscape (residential zone, rural zone, etc.)
-the length of the distribution lines;
-overvoltages on the healthy lines for single-grounding faults, which may lead to the occurrence of dangerous multiple-grounding faults;
-the value of the fault current for overhead lines;
-the existent protective devices for detecting and removal of single-grounding faults.
2.2 Isolated-neutral Networks
This method is recommended if the capacitive current of the network does not exceed 10 A. In this situation it is supposed that the fault arc extinction occurs naturally when the fault current crosses through zero and therefore is no need to disconnect the faulty line. If this does not occur, and the network stays under fault condition for a longer period of time, the single-grounding fault may turn into a multiple-grounding one, with all the unwanted consequences. Isolated neutral operations also occur in networks with the neutral grounded via impedance if the grounding is accidentally interrupted.

2.3 Neutral Grounded via a Compensation Reactor
The neutral is grounded via a reactor tuned to be at resonance with the equivalent capacity of the medium voltage lines connected to power transformer. In this case the current at the fault location will be zero. Practically, the reactor is tuned for a slightly overcompensated regime. This solution is recommended for networks with a capacitive current greater than 10 A. The operation experience shows that if this method is adopted, more than 80% of single-grounding faults are self-vanishing and consequently there is no need to disconnect the customers [7, 8, 9].

2.4 Neutral Grounded via a Resistor
If the capacitive current of the medium voltage network is greater than 100A, the active component of this current may exceed 10 A. In this case, single-grounding faults usually are not self-vanishing and the compensation reactor method becomes inefficient. In such situations the grounding of the neutral via a resistor may be more efficient, especially due to the possibility to detect the fault with the help of a directional zero-sequence current protective device [7, 8, 9]. The direct grounding of the transformer’s medium voltage windings neutral is not recommended as any single-phase short-circuit implies the disconnection of the faulty line and consequently of all the affiliated customers [4, 10].

2.5 Data Used by the Expert System
The expert system analyses only single-grounding faults in 20 kV distribution networks. The input data are:
(i) the total capacitive current \( I_c \) of all distribution lines connected to the medium voltage windings of the substation transformer;
(ii) the fault resistance \( R_f \) [11, 12, 13, 14]. The usual range for \( I_c \) is \((0...200) \) A. The self-vanishing of the fault arc is mainly determined by the active component \( I_{cs} \) of this current. It is considered that if \( I_{cs} < 5 \) A, the arc vanishes certainly. In the range \((5...10) \) A, a nonzero probability for self-vanishing also exists. If \( I_{cs} > 10 \) A, there are no conditions for the self-vanishing fault arc [1, 2, 3]. Very few distribution networks have a capacitive current greater than 200 A. Therefore the upper limit for \( I_c \) has been set to 200 A.

The fault resistance \( R_f \) value depends on a series of factors, many of them hard to quantify: the network type (overhead lines, underground cables), the characteristics of the fault arc, atmospheric conditions (snow, rain, heat, etc), and so on. The usual range is \((0...10) \) k\( \Omega \).

2.6 Quantities Computed by the Expert System
The expert system computes the following quantities:
- the zero-sequence current at the fault location;
- the zero-sequence voltage at the substation’s bars (on the medium voltage side);
- the relative overvoltage on the healthy lines, \( U_f/U_{in} \).

3 The Mathematical Model of the Single-Grounding Fault
A three phase network in which a single-grounding fault occurs, may be viewed as a nonsymmetrical network interconnected with other three symmetric networks as shown in Fig. 1, where the notations have the following meanings: \( A \) is the symmetric network representing the source and the line up to the fault location, \( B \) is the symmetric network representing the line behind the fault and the load, \( C \) is the symmetrical network modeling the earth, \([Z_2]\) is the matrix of the sequence impedances at the fault location, \([I]_s \) and \([I']_s \) are the matrices of the sequence currents at the fault location and toward the load, respectively [14].

\[
\begin{align*}
\text{Fig.1. Equivalent schematics for the single-grounding fault.}
\end{align*}
\]

At the fault location, the sequence voltages and currents satisfy the following system of equations:
\[
\begin{align*}
|U_0|_S &= (|Z_1|_S + |Z_2|_S)|U_0|_S + |Z_0|_S|U_0|_S \quad (1) \\
|0| &= -|Z_C|_S|U_0|_S + |Z_2|_S|U_0|_S \quad (2)
\end{align*}
\]

Equation (1) yields:
\[
|U_0|_S = |Z_1|_S^{-1}|Z_C|_S|U_0|_S \quad (3)
\]

Using (2) into (1) yields to:
\[
|U_0|_S = (|Z_1|_S + |Z_2|_S)|U_0|_S + |Z_0|_S|U_0|_S \quad (4)
\]

from which \([U_0|_S]\) can be determined.

At the fault location the sequence currents and voltages satisfy the following equations:
\[
I_0 = I_0^0, \quad U_0^0 + U_0^+ + U_0^- = 3R_I I_0^0 \quad (5)
\]
The zero-sequence current is given by the equation
\[
I_0^0 = \frac{U_f}{Z^+ + Z^- + Z^0 + 3R_I} \quad (6)
\]

where: \(Z^+, Z^-, Z^0\) are the medium voltage network’s sequence impedances as seen from the fault location.

The sequence voltages on the medium voltage transformer bars then become:
\[
U_0 = -Z_0^0 I_0^0, \quad U_0^+ = U_f - Z^0 I_0^0, \quad U_0^- = -Z^- I_0^0 \quad (7)
\]
The phase voltages on the medium voltage bars are given by the following equations:
\[
\begin{align*}
U_1 &= U_0^0 + U_0^+ + U_0^- \\
U_2 &= U_0^0 + a \cdot U_0^+ + a^2 \cdot U_0^- \\
U_3 &= U_0^0 + a^2 \cdot U_0^+ + a \cdot U_0^-
\end{align*}
\]

This model has been used to compare different neutral grounding solutions for a 20 kV radial network with 25 A capacitive current [14]. The single-line diagram of the network is shown in Fig.2. For this network the zero-sequence capacitive reactance has the value \(X^0 = 1386 \Omega\).

The values of the positive and negative-sequence of the power transformer \(T\) are \(Z^+ = Z^- = (0.1+j\cdot2.1) \Omega\)

For networks with capacitive currents of 50 A, 100 A and 200 A the results are also given in [14]. These results were used for establishing rules to select the optimum neutral grounding solution.
following quantities: the network’s capacitive current, the grounding resistance, the zero-sequence voltage and the phase voltage variation on the healthy phases. The fuzzy model has four linguistic terms, namely small, medium, high and very high. These terms correspond to four fuzzy sets, denoted $S$, $M$, $H$ and $VH$ respectively (Fig.6).

![Fig. 6. The fuzzy model.](image)

The fuzzy model for a generic quantity $A$ is described below. The linguistic terms are denoted as follows:

- fuzzy set of small values (small),
  $$S = \{(A, \mu_S(A)) | A < b\}$$
- fuzzy set of medium values (medium),
  $$M = \{(A, \mu_M(A)) | A \in [a,c]\}$$
- fuzzy set of high values (high),
  $$H = \{(A, \mu_H(A)) | A \in [b,d]\}$$
- fuzzy set of very high values (very high),
  $$VH = \{(A, \mu_{VH}(A)) | A > c\}$$

The membership functions are given by the following expressions:

$$\mu_S(A) = \begin{cases} 1, & A < a \\ \frac{b-a}{b-a}, & a \leq A \leq b \\ 0, & A > b \end{cases}$$

$$\mu_M(A) = \begin{cases} 0, & A < a \\ \frac{A-a}{b-a}, & a \leq A \leq b \\ \frac{a-A}{a-c}, & b \leq A \leq c \\ 0, & A > c \end{cases}$$

$$\mu_H(A) = \begin{cases} 0, & A < b \\ \frac{A-b}{c-b}, & b \leq A \leq c \\ \frac{d-A}{d-c}, & c \leq A \leq d \\ 0, & A > d \end{cases}$$

$$\mu_{VH}(A) = \begin{cases} 0, & A < c \\ \frac{A-b}{d-c}, & c \leq A \leq d \\ 1, & A > d \end{cases}$$

The parameters $a$, $b$, $c$ and $d$ depend on the modeled electrical quantity, according to Table 1.

Analysing the results shown in Fig. 3 to 5, a set of rules, corresponding to the different neutral grounding methods, can be identified. Those rules are shown in Tables 2 to 5. For example, in Table 5 the rule corresponding to cell $i=3, j=2$ is:

**IF** Rt = medium **AND** Ic = high **THEN**

Neutral treatment with Petersen coil

- $U_0$ - very high
- $U_t/U_{in}$ - very high
- $I_d$ - medium (self-vanishing).

### 5 The Description of the Proposed Expert System

NTSES was developed in Prolog, a language dedicated to expert systems development. With the advantage of the inference machine always present, Prolog insures a friendly environment, making it easy to build an expert system, as the programmer is charged only to build the interface, the rules and database.

NTSES works on any personal computer with Windows operating system platform. Maintenance tasks for the discussed expert system, as response to future changes, are easy to achieve thanks to the use of information representation rules.

As any expert system, NTSES has the following components:

- An inference machine for the expertise of the diagnosis problem solving. The Prolog environment insures this element.
- A knowledge base formed by a specific rule base
- An user interface that initiate a dialog with the user and presents the result of expertise.

The methodology used by the expert system for selecting an optimal neutral grounding solution goes through the following steps:

- Initiate a dialog to gather the necessary data;
- Fuzzificate the input data;
- Establish the quantities necessary for the analysis;
- Display the expertise results, based on the fuzzy rules corresponding to the decision matrix.

To establish the neutral grounding strategy, two input data are needed: the grounding fault resistance and the capacitive current of the analyzed medium voltage network.

<table>
<thead>
<tr>
<th>Fuzzy quantity</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive current [A]</td>
<td>10</td>
<td>30</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Grounding resistance [Ω]</td>
<td>125</td>
<td>300</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Zero-sequence voltage [p.u.]</td>
<td>0.10</td>
<td>0.2</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Phase voltage variation [p.u.]</td>
<td>1</td>
<td>1.1</td>
<td>1.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Table 1. Definition of the fuzzy quantities.
### Table 2. Resistor-grounded neutral.

<table>
<thead>
<tr>
<th>Crt. no.</th>
<th>Quantity Rule</th>
<th>IC</th>
<th>Rr</th>
<th>Uh</th>
<th>ΔUf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IF</td>
<td>small OR medium OR high OR very high AND</td>
<td>very high OR high OR medium OR small</td>
<td>THEN</td>
<td>small AND small</td>
</tr>
<tr>
<td>2</td>
<td>IF</td>
<td>small OR medium OR high OR very high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
</tbody>
</table>

### Table 3. Reactor-grounded neutral, overcompensation 10%.

<table>
<thead>
<tr>
<th>Crt. no.</th>
<th>Quantity Rule</th>
<th>IC</th>
<th>Rr</th>
<th>Uh</th>
<th>ΔUf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IF</td>
<td>small AND</td>
<td>very high OR high OR medium OR small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
<tr>
<td>2</td>
<td>IF</td>
<td>medium AND</td>
<td>very high OR high</td>
<td>THEN</td>
<td>medium AND medium</td>
</tr>
<tr>
<td>3</td>
<td>IF</td>
<td>medium AND</td>
<td>medium OR small</td>
<td>THEN</td>
<td>high AND very high</td>
</tr>
<tr>
<td>4</td>
<td>IF</td>
<td>high AND</td>
<td>very high</td>
<td>THEN</td>
<td>medium AND medium</td>
</tr>
<tr>
<td>5</td>
<td>IF</td>
<td>high AND</td>
<td>high OR medium</td>
<td>THEN</td>
<td>high AND very high</td>
</tr>
<tr>
<td>6</td>
<td>IF</td>
<td>high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
<tr>
<td>7</td>
<td>IF</td>
<td>very high AND</td>
<td>very high</td>
<td>THEN</td>
<td>small AND small</td>
</tr>
<tr>
<td>8</td>
<td>IF</td>
<td>very high AND</td>
<td>high OR medium</td>
<td>THEN</td>
<td>medium AND medium</td>
</tr>
<tr>
<td>9</td>
<td>IF</td>
<td>very high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
</tbody>
</table>

### Table 4. Isolated neutral network.

<table>
<thead>
<tr>
<th>Crt. no.</th>
<th>Quantity Rule</th>
<th>IC</th>
<th>Rr</th>
<th>Uh</th>
<th>ΔUf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IF</td>
<td>small OR medium AND</td>
<td>very high</td>
<td>THEN</td>
<td>medium AND small</td>
</tr>
<tr>
<td>2</td>
<td>IF</td>
<td>small OR medium AND</td>
<td>high</td>
<td>THEN</td>
<td>high AND medium</td>
</tr>
<tr>
<td>3</td>
<td>IF</td>
<td>small AND</td>
<td>small OR medium</td>
<td>THEN</td>
<td>high AND high</td>
</tr>
<tr>
<td>4</td>
<td>IF</td>
<td>medium AND</td>
<td>high</td>
<td>THEN</td>
<td>medium AND medium</td>
</tr>
<tr>
<td>5</td>
<td>IF</td>
<td>medium AND</td>
<td>medium</td>
<td>THEN</td>
<td>high AND very high</td>
</tr>
<tr>
<td>6</td>
<td>IF</td>
<td>high AND</td>
<td>very high</td>
<td>THEN</td>
<td>small AND small</td>
</tr>
<tr>
<td>7</td>
<td>IF</td>
<td>high AND</td>
<td>high</td>
<td>THEN</td>
<td>medium AND medium</td>
</tr>
<tr>
<td>8</td>
<td>IF</td>
<td>high AND</td>
<td>medium</td>
<td>THEN</td>
<td>high AND high</td>
</tr>
<tr>
<td>9</td>
<td>IF</td>
<td>high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
<tr>
<td>10</td>
<td>IF</td>
<td>high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
<tr>
<td>11</td>
<td>IF</td>
<td>very high AND</td>
<td>very high OR high</td>
<td>THEN</td>
<td>small AND small</td>
</tr>
<tr>
<td>12</td>
<td>IF</td>
<td>very high AND</td>
<td>medium</td>
<td>THEN</td>
<td>medium AND small</td>
</tr>
<tr>
<td>13</td>
<td>IF</td>
<td>very high AND</td>
<td>small</td>
<td>THEN</td>
<td>very high AND very high</td>
</tr>
</tbody>
</table>

### Table 5. Rules used by the expert system ntses.

<table>
<thead>
<tr>
<th>Rt. j→</th>
<th>Small</th>
<th>Medium</th>
<th>High</th>
<th>Very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic, i</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Small</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - small (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - small (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - small (self-vanishing)</td>
<td>Petersen coil or isolated U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
</tr>
<tr>
<td>Medium</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - high Uf/Ufn - high Id - small (self-vanishing)</td>
</tr>
<tr>
<td>High</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - medium (self-vanishing)</td>
<td>Petersen coil U0 - medium Uf/Ufn - medium Id - medium (self-vanishing)</td>
</tr>
<tr>
<td>Very high</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - very high</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - very high</td>
<td>Petersen coil U0 - very high Uf/Ufn - very high Id - very high</td>
<td>Petersen coil U0 - small Uf/Ufn - small Id - small (self-vanishing)</td>
</tr>
</tbody>
</table>
NTSES displays the following expertise results:
- the fuzzy values of the input data
- the recommended neutral grounding strategy
- the fuzzy values of the zero-sequence voltage, healthy phase voltage to nominal phase voltage ratio, and fault current, as shown in Fig. 6.

The expert system NTSES has been tested using different input data (Rt, Ic) from the usual range. In every case, NTSES provided the right results.

![Fig. 7. NTSES working interface](image)

6 Conclusion

The main advantage of applying NTSES to select a neutral grounding method for a medium voltage distribution network consists in the fact that it can be used by a large number of people with only medium level expertise in the field.

NTSES offers the essential information needed to take the right decision concerning the neutral grounding solution.

In the design process of a medium voltage network, NTSES allows to adequately choose the optimal neutral grounding solution.

During network’s operation, NTSES may discriminate the situations that impose the change of the neutral grounding method because of the changes in the network’s structure.

The maintenance services of medium voltage distribution network may also benefit form the use of NTSES as this system provides useful data concerning the possibility of overvoltage occurrence due to accidental groundings.

The expert system NTSES can be integrated into the informational system of the electrical substation, allowing to remote monitoring the way in which the chosen neutral grounding solution fits the specific operating conditions.

References:


