ANALYSIS OF TRANSIENT PROCESSES DURING SHORT CIRCUIT USING TRAVELLING WAVE APPROACH IN THE PRESENCE OF AUTOTRANSFORMERS

By

I.I.Mansy  A.M.M.Aly

Mansoura University, Faculty of Engineering, Electrical Power & M/Cs Dept.

ABSTRACT

A general methodology is presented for the node equation approximation. The developed methodology is applied to the phase modeling of an autotransformer. The approach makes it possible to perform short circuit transient calculations in the presence of an autotransformer.

The aim of this paper is to compute short circuit transients using the travelling wave approach, for different types of faults and different configurations of autotransformer windings.

On the basis of travelling wave approach and Rung-Kutta, a proposed program is constructed. Also, this work discusses the reasons of errors in obtained results. The results and input data are enumerated.

INTRODUCTION

Travelling wave approach (TWA) is used for determining electromagnetic transient processes in networks for different faults and configurations [1]. The development of mathematical model for obtaining frequency characteristic of transmission line (TL) is represented in [2].

In [3], TWA is used for solving transient processes on basis of node equations recorded in the form of finite difference equations. This procedure permits to use one description for any network node.

In this paper, autotransformer (AT) is considered as the main part of research to calculate the transient process (TP) using TWA. Due to magnetic circuit saturation the danger of electrodynamic effects on windings and system elements is reduced [4], especially in the

Accepted March 16, 1998.
case of short circuit (SC). Then, according to the consideration taken in the proposed problem, analysis of SC current and their effect on AT magnetic saturation are not considered as developing the algorithm of electromagnetic transient (EMT) process calculations.

**AUTOTRANSFORMER MODEL**

AT, in considered network, is modeled by the help of winding inductive reactance and active resistance of interconnected lines with the calculating leakages and without current of magnetoization\(^{[11,12]}\). The positive direction of currents and voltages in AT circuits are shown in Fig. 1. The AT equations are formulated in the following matrices:

\[
\begin{align*}
V_1' - V_3' &= - \left[ R_{k12} + X_{k12} \frac{d}{dt} \right] I_3' - \left[ R_1 + X_1 \frac{d}{dt} \right] I_3; \\
V_1 - V_3 &= - \left[ R_{k13} + X_{k13} \frac{d}{dt} \right] I_3 - \left[ R_1 + X_1 \frac{d}{dt} \right] I_3; \\
V_1 &= V_{1B} \\
V_3 &= \left[ V_{3A} - V_{3C} \right] \\
V_3' &= \left[ V_{3A} - V_{3C} \right]
\end{align*}
\]

\[\text{Where:}\]

\[
\begin{align*}
V_1 &= \begin{bmatrix} V_{1A} \\ V_{1B} \\ V_{1C} \end{bmatrix}; \\
V_2 &= \begin{bmatrix} V_{2A} \\ V_{2B} \\ V_{2C} \end{bmatrix}; \\
V_3 &= \begin{bmatrix} V_{3A} \\ V_{3B} \\ V_{3C} \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
R_{k12} &= \begin{bmatrix} R_{k12} & 0 & 0 \\ 0 & R_{k13} & 0 \\ 0 & 0 & R_{k13} \end{bmatrix}; \\
X_{k12} &= \begin{bmatrix} X_{k12} & 0 & 0 \\ 0 & X_{k13} & 0 \\ 0 & 0 & X_{k13} \end{bmatrix}; \\
R_{k13} &= \begin{bmatrix} 0 & R_{k13} & 0 \\ 0 & 0 & R_{k13} \end{bmatrix}; \\
X_{k13} &= \begin{bmatrix} X_{k13} & 0 \end{bmatrix}; \\
R_{k23} &= \begin{bmatrix} 0 & 0 & R_{k23} \\ 0 & 0 & 0 \\ 0 & 0 & R_{k23} \end{bmatrix}; \\
X_{k23} &= \begin{bmatrix} X_{k23} \end{bmatrix}; \\
R_1 &= \begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_1 & 0 \\ 0 & 0 & R_1 \end{bmatrix}; \\
X_1 &= \begin{bmatrix} X_1 \end{bmatrix}
\end{align*}
\]
\[ X_{1c} = \frac{(X_{k12} + X_{k13} - X_{k23})}{2}; \]
\[ R_{1c} = \frac{(R_{k12} + R_{k13} - R_{k23})}{2}; \]
\[ \tau = \omega t, \text{ where } R_{k12}, R_{k13}, X_{k13}, R_{k23} \text{ and } X_{k23} \text{ are SC resistances and reactances of AT.} \]

Eq. (1) is the basic equation. This equation can be modified for any AT operation condition. The preceding equation demonstrates the relationship between currents and voltages in the windings.

For computing EMT process, the system is modeled at first. The investigated system involves generators, transformers, TL with distributed parameters and AT. Computation of the algorithm used in solving our problem depends on the application of TWA [1]. Reactive linear elements concentration in [1] may be changed by lines with their distributed parameters. The errors in currents are analyzed in [3].

**PROBLEM STATEMENT:**

In this paper, the AT is represented by a system with concentrated parameters. At formulation of a problem the recording of equations, which are combined with wave values, is very important. These wave values are derived from line with AT basic equation (1). The currents and voltages of the AT are described in Fig. 2. The SC occurred at the nodes 1, 2 and 3 (AT leads). The AT can be operated as three or double windings regime. The dead earth neutral of the AT is considered. But, as necessary, considered system (Fig. 2), permits to connect a regulator or current limiting device in neutral of AT.

The following expressions demonstrate operation characteristics of the AT, when it operates as three windings regime with dead earth neutral:

\[ V_1 = V_{d1} - Z_{d1} \cdot i_1; \]
\[ V_2 = V_{d2} - Z_{d2} \cdot i_2; \]
\[ V_3 = V_{d3} - Z_{d3} \cdot i_3; \]
\[ V_1' = V_1 - \left( R_{e1} + X_{e1} \frac{d}{dt} V_1 \right) \]
\[ V_2' = V_2 - \left( R_{e2} + X_{e2} \frac{d}{dt} V_2 \right) \]
\[ V_3' = V_3 - \left( R_{e3} + X_{e3} \frac{d}{dt} V_3 \right) \]
\[ i_1 = \left[ I_o + \frac{d}{dt} i_1 \right]; \]
\[ i_2 = \left[ I_o + \frac{d}{dt} i_2 \right]; \]
\[ i_3 = \left[ I_o + \frac{d}{dt} i_3 \right]. \]

(2)

The first three equations of this system indicate the voltages at AT terminals (\(V_1, V_2\) and \(V_3\)). After reflection of \(V_1, V_2\) and \(V_3\), the voltages in circuit can be determined. They consist...
Fig. 1. Considered Model of Autotransformer.

Fig. 2. Considered Model for determining Current and Voltage in AT Elements.

Where \( V_a \), \( I_a \), and \( J_a \) are voltage, current, and current in the AC transformer.

Fig. 3. Principle Network of Single Phase SC.
of wave resistances of TL. The fourth and fifth equations are basically differential equations of AT operation regime. These two equations are solved using 4th order Runge-Kutta method in combination with TWA. Sixth equation reflects acceptance of the assumption that the open circuit current equals zero. The other equations reflect coupling of currents in lines with currents in AT windings in the presence of AT dead earth neutral and connection of AT windings become Y/Y/Δ.

The operation of the AT in double windings regime is represented by the following equations:

\[
V_1 = V'_{1\text{st}} - Z_{eq1}I_{eq1} \\
V_2 = V'_{2\text{st}} - Z_{eq2}I_{eq2} \\
V_1 - V_2 = -[R_{k12} + X_{k12}] \frac{d}{dt}I_1 - [R_1 + X_1] \frac{d}{dt}I_1; \\
V_1 - V_3 = -[R_{k13} + X_{k13}] \frac{d}{dt}I_2 - [R_1 + X_1] \frac{d}{dt}I_2;
\]

\[
I_0 = I_{eq1} + I_{eq2} \\
\]

Where:

\[
\begin{bmatrix}
I_{\text{eq1}} \\
I_{\text{eq2}} \\
I_0
\end{bmatrix}
\]

(3)

Fig. 2. depicts that the SC occurred in the nodes 1, 2, and 3. When the SC occurs at node 1, equation of this node is rewritten as follows:

\[
\begin{align*}
K_{VA} & = 0; \\
H_{VA} & = 0;
\end{align*}
\]

(4)

where: \( k \) - square matrix, which contains phases A, B, and C = 1 in the presence of SC and C = 0 in the absence of SC;

\[
H = 1 - K \\
1 - Unity matrix \\
V, V_{eq} - Column matrices of voltage and current in node 1.
\]

Substituting the SC constraints (4) in Eqs. (3) and (3) as follows:

\[
K_{VA} Z_{eq1} I_{eq1} = 0
\]

Subtract: \( H_{VA} I_0 = 0 \) from this equation
\[ K V_{\text{out}} - K Z_{\text{out}} I_{\text{out}} - H I_{a} = 0 \]  
(5)

or substitute by \( I_{\text{out}} = I_{a} + I_d \) in Eq. (5)

\[ K V_{\text{out}} - K Z_{\text{out}} I_{a} - K Z_{\text{out}} I_d - H I_{a} = 0 \]  
(6)

Eq. (6) may be written in the following expression:

\[ I_a = \frac{F}{K} \pm |K V_{\text{out}} - Z_{\text{out}} I_{\text{out}}| \]  
(7)

where \( F = K Z_{\text{out}} + H \)

Because of absence of node 3 in Eq. (3), SC constraints in AT winding \( HH \) are given zero value of column matrix \( V_3 \). For computing three phase SC current at \( HH \), assume \( V_3 = 0 \) and eliminate two ultimate equations in Eq. (3).

**PROCEDURE OF SOLUTION**

On the basis of the proposed method, the computer program is used to compute the SC transient currents and the overvoltage in the superhigh voltage network. In general, the proposed program is used to calculate the unsymmetrical, commutation phase cut out, SC and breaks. We consider that the system constitutes the following three phase elements: section of super high voltage TL, generators nodes, transformers, AT, reactors, arrestors, switches and active resistances.

On evaluating the results obtained from the proposed program, we compare them with the experimental out. The data have been determined from experience of SC in the system shown in Fig. 3 [9]. which shows long TL parameters of sources, reactors and AT. When the switch \( S_5 \) is closed, single phase SC occur in time \( t = 1.26 \) rad. The experimental curves of single phase SC current, experimental data from[9], are shown in Fig. 4. From this figure, we note that the two curves in the first period coincide, but in the second and the third periods, the two curves deviated with each other. In this paragraph, the reason of increasing computed error is discussed. As known, TL parameters, generators and transformers depend on the current frequency. In this work, the frequency dependence of TL parameters is calculated in sufficient wide range from 0 to 1000 Hz [2]. Generators and transformers parameters are taken into account during the computation of frequency. Inductive scattering of transformers in the range 0 - 1000 Hz changes within 15-20%, i.e. relatively small dependency on frequency. Therefore, the active resistances of transformers increase from 30 to 40 times in the indicated range of frequency. Applied aspects of the given problem have purpose evaluate firstly dangerous types of electrodynamic effects on AT’s windings. These dangerous types are developed to large degree at initiation of SC in voltage phase. Transient SC current in these cases consists of suddenly and aperiodical components of transient process. For computing equivalent constant time of damping aperiodical SC current components, active resistance of winding is determined through SC losses. These losses specified in [7] are 1.6 times less than its value at operating frequency. In these losses different additive losses are appeared, in result which constant time of transformer is underrated [8].

In the experiment of switching \( S_5 \) on single phase, SC is performed in moment \( t = 1.26 \) rad. For circuit with distributed parameters at indicated phase voltages in SC current, beside suddenly and aperiodical components are observed too periodical components, decrement
Fig. 4. Considered and Experimental Values of Single Phase SC Currents
1: Considered Curve
2: Experimental Curve.

Fig. 5. Principal Network of Calculated SC Currents with AT.

Fig. 6. SC Current Values in AT: Winding at 2-Phase SC (High Voltage Side) in the Case of Triple Winding. 1: Current in Second Winding of AT, 2: Current in General Winding of AT & III: Current in Low Voltage of AT.
damping which at adoption in the operating active resistance of transformer. These
preceding analysis show the reasons of increasing errors in second and third periods.

ILLUSTRATIVE EXAMPLE

For checking the derived expressions and that determining the accuracy of TWA, the circuit
for calculating SC in TL and AT is considered. This circuit is shown in Fig.5. All data of this
network are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Block 300 MW</th>
<th>Block 1000 MW</th>
<th>AT 1000 MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>Generator</td>
<td>V_{tn} = 759 kV</td>
</tr>
<tr>
<td>$x_d' = 0.196$</td>
<td>$x_d = 0.3$</td>
<td>$e_{Vth} = 28.2%$</td>
</tr>
<tr>
<td>$V_{Oa} = 20$ kV</td>
<td>$V_{Oa} = 24$ kV</td>
<td>$e_{LBC} = 10%$</td>
</tr>
<tr>
<td>Transformer</td>
<td>Transformer</td>
<td>$e_{kCH} = 17.1%$</td>
</tr>
<tr>
<td>$S_{tn} = 400$ MVA</td>
<td>$S_{tn} = 3\times 417$ MVA</td>
<td>$\Delta P_{LBC} = 580$ kW</td>
</tr>
<tr>
<td>$V_{tn} = 347$ kV</td>
<td>$V_{tn} = 787$ kV</td>
<td>$\Delta P_{kCH} = 255$ kW</td>
</tr>
<tr>
<td>$e_{L} = 11%$</td>
<td>$e_{L} = 14%$</td>
<td>$\Delta P_{kCH} = 235$ kW</td>
</tr>
</tbody>
</table>

For measurement, three phase SC current which flows through AT winding at SC in node L.
SC losses are written as:

1) Parameters of Generator I:
   $X_G = X_L V_n \cos \delta_0 / P_{Gn} = 312.37 \Omega$;
   $X_T = \phi \delta_0 / S_{tn} = 154.7 \Omega$;
   $X_G + X_T = 467.07 \Omega$;
   $X_L = (X_G + X_T) / n = 70.06 \Omega$;
   $X_p = X_T / n = 23.2 \Omega$;

Where: $n = P_T / P_{Gn}$; $I_1 = \sqrt{3} V_n / (\sqrt{3} X_L) = 8.816$ kA.

Also, the parameters of the other generators may be computed.

2) Parameters of generator II:
   $X_L = 95.3 \Omega$; $X_C = 284.47 \Omega$; $I_1 = 6.395$ kA;

3) Parameters of generator III:
   $X_L = 57.9 \Omega$; $X_C = 15.7 \Omega$; $I_1 = 10.57$ kA;

4) Parameters of generator IV:
   $X_L = 70.9 \Omega$; $X_C = 12.3 \Omega$; $I_1 = 8.86$ kA;

5) Parameters of AT:
   $X_{LBC} = \phi \delta_0 V_n^2 / S_{tn} = 56.25 \Omega$;
   $X_{kCH} = 158.6 \Omega$;
   $X_{kCH} = 96.19 \Omega$ and $X_{th} = (X_{kBH} + X_{kBC} - X_{kCH}) / 2 = 59.34 \Omega$.

Losses:

$\Delta P_{LBC} = \Delta P_{kBH} / \alpha^2 = 813.14$ kW;
$\alpha = (V_{TBD} - V_{TCA}) / V_{TBD}$;
$\Delta P_{kCH} = \Delta P_{kCH} / \alpha^2 = 749.36$ kW;

Active Resistances:

\[ R_{BC} = \Delta P_{BC} \frac{V_{10}^2}{1.6 \cdot S_{10}^2} = 0.0204 \Omega; \]
\[ R_{AB} = \Delta P_{AB} \frac{V_{10}^2}{1.6 \cdot S_{10}^2} = 0.0286 \Omega; \]
\[ R_{CH} = \Delta P_{CH} \frac{V_{10}^2}{1.6 \cdot S_{10}^2} = 0.0326 \Omega; \]
\[ R_H = \frac{R_{ABC} + R_{AB} - R_{CH}}{2} = 0.0113 \Omega. \]

5) Parameters for calculating damping by positive and zero sequences of TL are determined as:

i) TL (Q30 kV):

**Wave Impedances**: \( Z_a = 290 \Omega \) and \( Z_a = 740 \Omega \);

**Conductor resistances**: \( R_a = 0.054 \Omega \) and \( R_a = 0.0137 \Omega \);

\[ C = \frac{15.5 \text{ mF}}{6.666 \text{ mF}} = \frac{16.682 \mu F}{66 \text{ mF}} = \frac{8.2672 \mu F}{73.6 \text{ mF}} \]

ii) TL (Q30 kV):

\[ Z_a = 220 \Omega ; \]

\[ Z_a = 630 \Omega ; \]

\[ C_a = 43.2 \mu F ; \]

\[ C_a = 0.1866 \mu F \]

\[ C_a = 0.0249 \mu F ; \]

\[ C_a = 0.0759 \mu F \]

\[ C_a = 0.0622 \mu F \]

\[ C_a = 0.052 \mu F \]

**Parameters of Sources from low tension side of AT**:

\[ X^* = X_a = 112.5 \Omega ; \]

\[ Y = 5.443 \text{ kA.} \]

The resulted transient currents in AT windings in the case of three phase SC in node 1 are plotted in Fig.6. The results obtained from TWA and that obtained from [18,10], in case of occurring SC in nodes 1 & 2 in Fig. 5 [10], are recorded in Table 2. From this table, we note that the obtained results are consistent.

<table>
<thead>
<tr>
<th>Program of Computation</th>
<th>SC in Low Voltage Side of AT</th>
<th>SC in High Voltage Side of AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation in Triple-Regime</td>
<td>SC</td>
<td>SC</td>
</tr>
<tr>
<td>3-ph</td>
<td>3-ph</td>
<td>1-ph</td>
</tr>
<tr>
<td>On base of TWA</td>
<td>8.5</td>
<td>18</td>
</tr>
<tr>
<td>On base of Exp.</td>
<td>7.93</td>
<td>17.02</td>
</tr>
</tbody>
</table>

From these results, it is remarked that large values of SC current take place at faults on middle tension side in general winding of AT. The reason of this fault in AT is that one of basic types of faults at SC is radial losses of AT general winding stability [10].

**CONCLUSIONS**

From the preceding analysis and computing SC currents, we can conclude the following:

1. TWA can be used in general, for calculating the SC transient in any node and configuration.

2. In any method, high accuracy approximation requires a high model order. This, however, may not be warranted if the data are not very accurate.

3. The error levels should, therefore, be determined according to the precision of the input data as reflected in the step responses.
4- The presented procedure is compared with the experimental method in terms of accuracy and computation time.
5- A general methodology is represented for the node equation approximation of proposed system.
6- This paper represents AT by triple or double windings model. Also, this paper presented mathematical equations of two models of AT.
7- The results presented show that the proposed program can provide satisfactory accuracy.

REFERENCES