

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

تحليل الحالات العابرة أثناء القصر بطريقة الموجة العابرة في وجود المحولات الذاتية

By

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

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

ملخص البحث: طريقة الموجة المتحركة تستخدم لحساب تيار القصر في دوائر القوى الكهربائية. وبناء على هذه الطريقة وطريقة رونج-كوتا المستخدمة لحل المعادلات التفاضلية بنى خوارزم لحساب تيارات القصر العابرة في حالة حدوث قصر ثلاثي الوجه أو أحادي الوجه عند استخدام محول ذاتي ثلاثي أو ثنائي الملف. وتم تعميم هذا الخوارزم للحصول على النتائج المرجوة. وتم في هذا البحث نمذجة المحول الذاتي بحالتيه وتقديم نموذج رياضي استخدم في الحل وتم تطبيقه على مثال عددي.

وأيضاً تم في هذا البحث عمل مقارنة بين الطريقة المقترحة والطرق العملية المستخدمة لحصل مثل هذه المعادلات وبناء على نتائج المقارنة تم دراسة وشرح الأسباب التي أدت إلى الإنحرافات في بعض القيم. وقد توصلت بالبحث إلى نتائج كالمية لحل المشكلة في حالة استخدام المحولات الذاتية من تطبيق الخوارزم على دائرة مركبة.

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 numerated.

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

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 at 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 magnetization[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 :

$$\begin{aligned} V_1 - V_2 &= -[R_{k12} + X_{k12}d/dt]I_2 - [R_1 + X_1d/dt]I_3; \\ V_1 - V_3 &= -[R_{k13} + X_{k13}d/dt]I_3 - [R_1 + X_1d/dt]I_2; \end{aligned} \quad (1)$$

Where:

$$V_1 = \begin{bmatrix} V_{1A} \\ V_{1B} \\ V_{1C} \end{bmatrix};$$

$$V_3 = \begin{bmatrix} V_{3A} \\ V_{3B} \\ V_{3C} \end{bmatrix};$$

$$V_2 = \begin{bmatrix} V_{2A} \\ V_{2B} \\ V_{2C} \end{bmatrix};$$

$$V_3' = \begin{bmatrix} V_{3A} - V_{3C} \\ V_{3B} - V_{3A} \\ V_{3C} - V_{3B} \end{bmatrix};$$

$$R_{k12} = \begin{bmatrix} R_{k12} & 0 & 0 \\ 0 & R_{k12} & 0 \\ 0 & 0 & R_{k12} \end{bmatrix};$$

$$X_{k12} = \begin{bmatrix} X_{k12} & 0 & 0 \\ 0 & X_{k12} & 0 \\ 0 & 0 & X_{k12} \end{bmatrix};$$

$$R_{k13} = \begin{bmatrix} R_{k13} & 0 & 0 \\ 0 & R_{k13} & 0 \\ 0 & 0 & R_{k13} \end{bmatrix};$$

$$X_{k13} = \begin{bmatrix} X_{k13} & 0 & 0 \\ 0 & X_{k13} & 0 \\ 0 & 0 & X_{k13} \end{bmatrix};$$

$$R_{k23} = \begin{bmatrix} R_{k23} & 0 & 0 \\ 0 & R_{k23} & 0 \\ 0 & 0 & R_{k23} \end{bmatrix};$$

$$X_{k23} = \begin{bmatrix} X_{k23} & 0 & 0 \\ 0 & X_{k23} & 0 \\ 0 & 0 & X_{k23} \end{bmatrix};$$

$$R_1 = \begin{bmatrix} R_{1r} & 0 & 0 \\ 0 & R_{1r} & 0 \\ 0 & 0 & R_{1r} \end{bmatrix};$$

$$X_1 = \begin{bmatrix} X_{1r} & 0 & 0 \\ 0 & X_{1r} & 0 \\ 0 & 0 & X_{1r} \end{bmatrix};$$

$$I_1 = \begin{bmatrix} I_{1A} \\ I_{1B} \\ I_{1C} \end{bmatrix}; \quad I_2 = \begin{bmatrix} I_{2A} \\ I_{2B} \\ I_{2C} \end{bmatrix}; \quad I_3 = \begin{bmatrix} I'_{3A} \\ I'_{3B} \\ I'_{3C} \end{bmatrix};$$

$$X_{1\tau} = (X_{k12} + X_{k13} - X_{k23})/2;$$

$$R_{1\tau} = (R_{k12} + R_{k13} - R_{k23})/2;$$

$\tau = \omega_0 t$; (where R_{k12} , X_{k12} , R_{k13} , X_{k13} , R_{k23} and X_{k23} 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 analysed 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 climbed 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, at necessity, 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 :

$$V_1 = V_{eq1} - Z_{eq1} I_{eq1};$$

$$V_2 = V_{eq2} - Z_{eq2} I_{eq2};$$

$$V_3 = V_{eq3} - Z_{eq3} I_{eq3};$$

$$V_1 - V_2 = -[R_{k12} + X_{k12} \frac{d}{d\tau}] I_2 - [R_1 + X_1 \frac{d}{d\tau}] I_1;$$

$$V_1 - V_3 = -[R_{k13} + X_{k13} \frac{d}{d\tau}] I_3 - [R_1 + X_1 \frac{d}{d\tau}] I_1;$$

$$I_1 = -(I_2 + I_3);$$

$$I_1 = I_{eq1};$$

$$I_2 = I_{eq2};$$

$$I_3 - I_3' = I_{eq3}.$$

(2)

The first three equations of this system indicate the voltages on 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

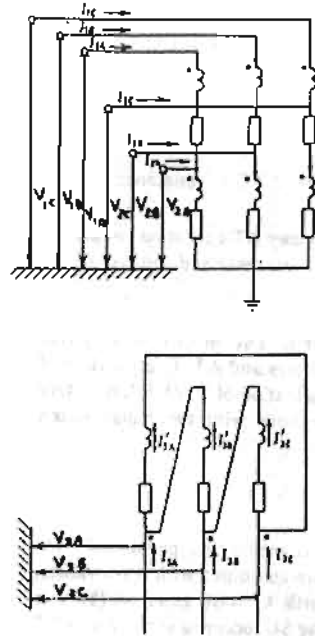


Fig.1. Considered Model of Autotransformer.

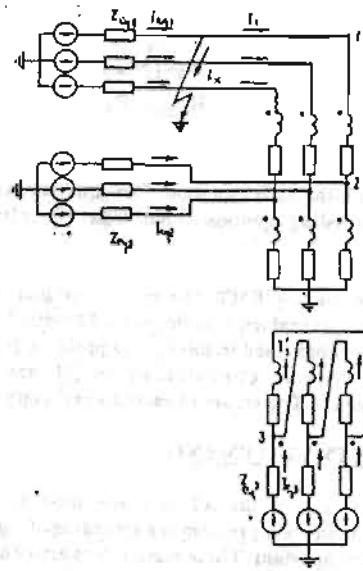


Fig.2. Considered Model for determining Currents and Voltages in AT Circuits.
 Where V_m , Z_m & I_m - equivalent voltage, wave impedance and current in T_1 .
 V_x , I_x - SC voltage and current.

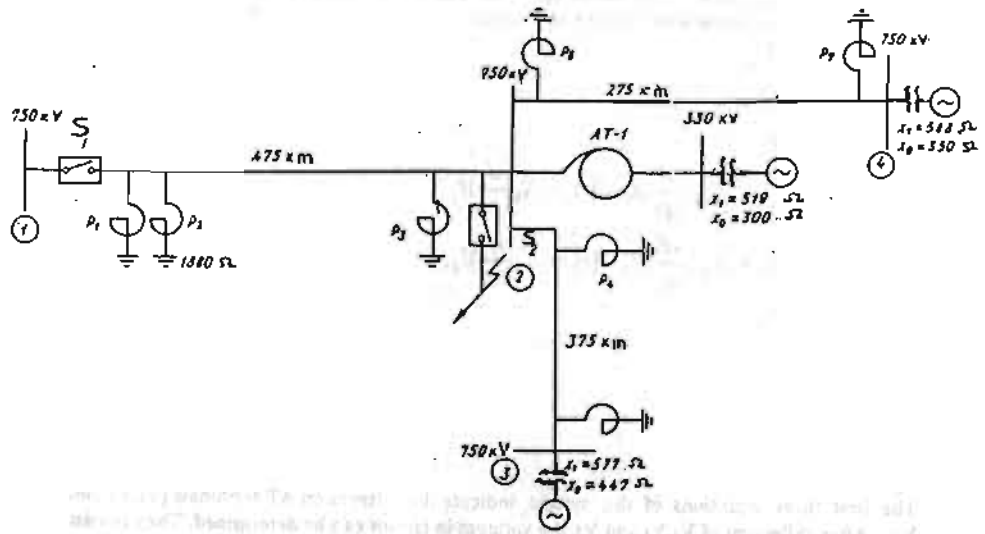


Fig.3. Principle Network of Single Phase SC.

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:

$$V_1 = V_{eq1} - Z_{eq1} I_{eq1} ;$$

$$V_2 = V_{eq2} - Z_{eq2} I_{eq2} ;$$

$$V_1 - V_2 = -[R_{k12} + X_{k12} \frac{d}{d\tau}] I_2 - [R_1 + X_1 \frac{d}{d\tau}] I_3 ;$$

$$V_1 - V_3 = -[R_{k13} + X_{k13} \frac{d}{d\tau}] I_3 - [R_1 + X_1 \frac{d}{d\tau}] I_2 ;$$

$$I_1 = -(I_2 + I_3) ;$$

$$I_1 = I_{eq1} ;$$

$$I_2 = I_{eq2} ;$$

$$I_3 - I_3'' = 0 ;$$

$$V'_{3A} + V'_{3B} + V'_{3C} = 0 ;$$

Where:

$$I_3'' = \begin{bmatrix} I'_{3A} \\ I'_{3B} \\ I'_{3C} \end{bmatrix} \tag{3}$$

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 :

$$\begin{aligned} KV_k &= 0; \\ HI_k &= 0; \end{aligned} \tag{4}$$

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;

$$\begin{aligned} H &= 1 - K \\ 1 &\text{ - Unity matrix} \\ V_k, I_k &\text{ - Column matrices of voltage and current in node 1.} \end{aligned}$$

Substituting by the SC constraints (4) in Eqns. (2) and (3) as follows :

$$K V_{eq1} - K Z_{eq1} I_{eq1} = 0$$

Subtract $H I_k = 0$ from this equation

$$K V_{eq1} - K Z_{eq1} I_{eq1} - H I_k = 0 \quad (5)$$

or substitute by $I_{eq1} = I_k + I_1$ in Eq. (5)

$$K V_{eq1} - K Z_{eq1} I_k - K Z_{eq1} I_1 - H I_k = 0 \quad (6)$$

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

$$I_k = F^{-1} K [V_{eq1} - Z_{eq1} I_1] ; \quad (7)$$

where $F = K Z_{eq1} + H$

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 one. 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_2 is closed, single phase SC occur in time $t = 1.26$ rad. The experimental curves of single phase SC currents, 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 ATs 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 results which constant time of transformer is underrated [8].

In the experiment of switching S_2 on single phase, SC is performed in moment $\tau = 1.26$ rad. For circuit with distributed parameters at indicated phase voltages in SC current, beside suddenly and aperiodical components are observed too periodical components, decrement

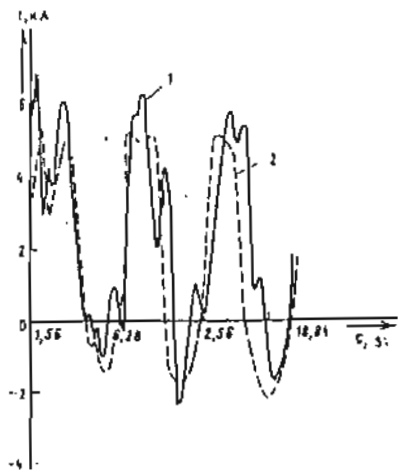


Fig.4. Considered and Experimental Values of Single Phase SC Currents
 1- Considered Curve
 2- Experimental Curve.

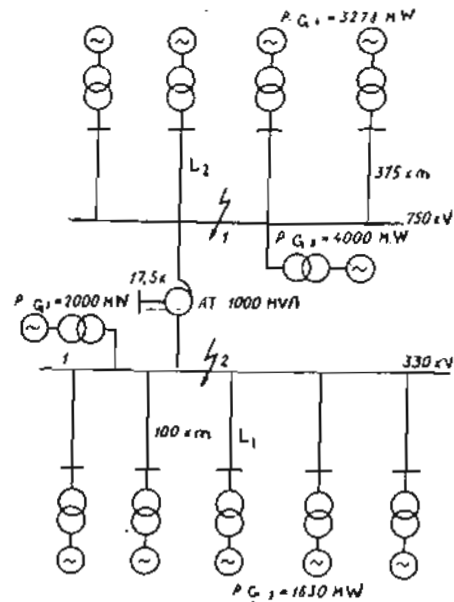


Fig.5. Principle Network of Calculated Sc Currents with AT.

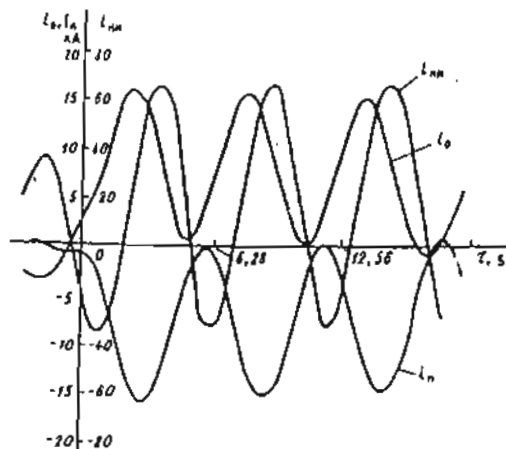


Fig.6. SC Currents Values in AT Windings at 3-Phase SC (High Voltage Side) in the Case of Triple Winding. I_{II} : Current in Series Winding of AT; I_{I} : Current in General Winding of AT & I_{III} : Current in Low Voltage of AT.

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 1

block 300 MW	block 1000 MW	AT 1000 MVA
<u>Generator</u>	<u>Generator</u>	$V_{Tn} = 750 \text{ kV}$
$X_d' = 0.196;$	$X_d' = 0.3;$	$e_{kBH} = 28.2\%$
$V_{Gn} = 20 \text{ kV}$	$V_{Gn} = 24 \text{ kV}$	$e_{kBC} = 10\%$
<u>Transformer</u>	<u>Transformer</u>	$e_{kCH} = 17.1\%$
$S_{Tn} = 400 \text{ MVA}$	$S_{Tn} = 3 \times 417 \text{ MVA}$	$\Delta P_{kBC} = 580 \text{ kW}$
$V_{Tn} = 347 \text{ kV}$	$V_{Tn} = 787 \text{ kV}$	$\Delta P_{kBH} = 255 \text{ kW}$
$e_k = 11\%$	$e_k = 14\%$	$\Delta P_{kCH} = 235 \text{ kW}$

For measurement, three phase SC current which flows through AT winding at SC in node 1. SC losses are written as:

1) Parameters of Generator I:

$$X_G = X_d' V_n \cos \phi_n / P_{Gn} = 312.37 \Omega;$$

$$X_T = e_k V_n / S_{Tn} = 154.7 \Omega; \quad X_G + X_T = 467.07 \Omega;$$

$$X_L = (X_G + X_T) / n = 70.06 \Omega; \quad X_o = X_T / n = 23.2 \Omega;$$

$$\text{Where: } n = P_1 / P_{Gn}; \quad I_1 = \sqrt{2} V_n / (\sqrt{3} X_1) = 8.816 \text{ kA.}$$

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

2) Parameters of generator II:

$$X_1 = 95.7 \Omega; \quad X_o = 28.47 \Omega; \quad I_2 = 6.395 \text{ kA};$$

3) Parameters of generator III:

$$X_1 = 57.9 \Omega; \quad X_o = 15.7 \Omega; \quad I_3 = 10.57 \text{ kA};$$

4) Parameters of generator V:

$$X_1 = 70.68 \Omega; \quad X_o = 19.2 \Omega; \quad I_4 = 8.66 \text{ kA};$$

5) Parameters of AT:

$$X_{kBC} = e_{kBC} V_n^2 / S_{Tn} = 56.25 \Omega; \quad X_{kBH} = 158.6 \Omega;$$

$$X_{kCH} = 96.19 \Omega \quad \text{and} \quad X_{1r} = (X_{kBH} + X_{kBC} - X_{kCH}) / 2 = 59.34 \Omega.$$

Losses:

$$\Delta P_{kBH}' = \Delta P_{kBH} / \alpha^2 = 813.14 \text{ kW};$$

$$\alpha = (V_{TBn} - V_{TCn}) / V_{TBn};$$

$$\Delta P_{kCH}' = \Delta P_{kCH} / \alpha^2 = 749.36 \text{ kW};$$

Active Resistances:

$$R_{kBC} = \Delta P_{kBC} V_{Tn}^2 / (1.6 * S_{Tn}^2) = 0.0204 \Omega;$$

$$R_{kBH} = \Delta P_{kBH} V_{Tn}^2 / (1.6 * S_{Tn}^2) = 0.0286 \Omega;$$

$$R_{kCH} = \Delta P_{kCH} V_{Tn}^2 / (1.6 * S_{Tn}^2) = 0.0263 \Omega;$$

$$R_{It} = (R_{kBC} + R_{kBH} - R_{kCH}) / 2 = 0.0113 \Omega.$$

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

i) TL I(330kV):

$$\text{Wave Impedances : } Z_{c1} = 290 \Omega \text{ and } Z_{c0} = 740 \Omega;$$

$$\text{Conductor resistances: } R_n = 0.054 \Omega \text{ and } C = \tau / Z_{c0};$$

$$C = 34.5 \text{ nF} \quad l_1 = 100 \text{ km};$$

$$= 16.482 \mu\text{F} \quad = 50 \text{ km};$$

$$= 8.2672 \mu\text{F} \quad = 25 \text{ km}.$$

ii) TL II(750 kV)

$$Z_{c1} = 220 \text{ k}\Omega; \quad Z_{c0} = 530 \Omega; \quad \text{and} \quad R_n = 0.0137 \Omega.$$

$$C_1 = 43.2 \mu\text{F}; \quad C_2 = 0.1886 \mu\text{F} \quad l_2 = 200 \text{ km};$$

$$C_1 = 0.249 \mu\text{F}; \quad C_2 = 0.07509 \mu\text{F} \quad l_2 = 100 \text{ km};$$

$$C_1 = 1.305 \mu\text{F} \quad l_2 = 50 \text{ km};$$

$$C_1 = 0.0622 \mu\text{F} \quad l_2 = 25 \text{ km}.$$

Parameters of Sources from low tension side of AT:

$$X' = X_s = 112.5 \Omega;$$

$$I = 5.443 \text{ kA}.$$

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 [1&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 coincide.

Table 2

Program of Computation	SC in Low Voltage Side of AT				SC in High Voltage Side of AT			
	Operation in Triple-Regime				Operation in Triple-Regime			
	3-ph SC	3-ph SC	1-ph SC	1-ph SC	3-ph SC	3-ph SC	1-ph SC	1-ph SC
	i_n	i_0	i_n	i_0	i_n	i_0	i_n	i_0
On base of TWA	8.5	18	9	21	8	7.5	8	7.5
On base of Exp.	7.93	17.03	8.21	17.4	7.3	7.38	7.53	7.861

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 from 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

- 1- L.S. Levin, A.I. Stupel and V.S. Shatine, "Computed of Transient Processes in Electrical systems.", Book, 1968.
- 2- A.I. Stupel, L.S. Levin and U.N. Liv, "Model of High Frequency TL at calculation of transient processes using Traveling Wave", Electrical Journal, No.1, 1972.
- 3- U.R. Chern, V.S. Bogomal and U.N. Liv, "Development of Traveling Wave approach for Computing Electromagnetic Processes in Systems.", Electrical Journal No.7, 1984.
- 4- R.C. Degeneff, "A Method for Constructing Terminal Models for Single Phase Winding Transformers", IEEE PES Summer Meeting, Los Angeles, July 6-21, 1978.
- 5- F. de Leon and A. Semlyer, "Complete Transformer Model for Electromagnetic Transients", IEEE PES winter Meeting, 1993.
- 6- L.V. Bewley, "Traveling waves on Transmission Systems, Second Edition, John Wiley and sons, New York, 1951.
- 7- A.O. Soysal and A. Semlyen, "Practical Transfer Function Estimation and Its Application to Wide Frequency Range Representation of Transformers", IEEE, Sept. 92, Summer Meeting, Paper No. 92.
- 8- P.C. Magnusson, "Traveling Wave on Multi-Conductor Open Wire Lines- A Numerical Survey of the Effects of Frequency Dependence of Modal Composition.", IEEE Trans. on PAS, Vol. 92, pp. 999-1008, 1973.
- 9- Levov. N, Bogomolov V & Chernova R. "Experimental Determination of Short Circuit Parameters of Transformers" VNIA, M. Energy periodical 1984.
- 10- V.A. Venicov "Electromechanical Transient Processes" Book, 1985.
- 11- A. norang and R.H. Briely "Magnetic Model for Steady-State and Transient Studies for Three Phase Core Type Transformers" IEEE Transactions on PAS, Vol. 9, No. 3, Aug. 1994. PP. 1337-1349.
- 12- Y. Baghzovz and X.D. Gong, "Analysis of Three-Phase Transformer No-Load Characteristics", IEEE Transaction on PAS, Vol. 10, No. 1, Feb. 1995, PP. 18-26.