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Simulation and Analysis Package Development of Short-Circuit Electrodynamic Force of Power Transformer Windings

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Abstract: This study presents the calculation method for short-circuit electrodynamic force of power transformer winding and development of electrodynamic force analysis software package. Finite element method is used to achieve the leakage magnetic field of transformer winding under short circuit operation. Electromagnetic force is calculated by using Lorentz force formula. Based on mechanical properties of kraft-manila paper and press-board, which are used as insulation and reinforcement materials, considering the elastic force and friction of the various insulating materials, the equivalent mass spring model of winding is established and axial dynamic force and displacement is calculated. Using client/server mode, short-circuit electrodynamic force analysis software for power transformer winding is developed, which consists of several sub-system, such as parameter input and calculation and result analysis. The client/server structure facilitates the expansion of the software features. This software package has been applied in the power transformer manufacture enterprise.

Keywords: Electrodynamic force, electromagnetic force, finite element method, leakage magnetic field, power transformer, software package

INTRODUCTION

With the development of power grid level, the capacity of power grid gets higher and makes a claim for higher performance transformer. Thus the grid needs better ability for undergoing short-circuit fault for transformer. When short-circuit occurs, the amplitude of the maximum short-circuit current will be several times that of the rated current amplitude and hundreds of times of the electromagnetic force of steady-state operation suffered by the short-circuit winding. The short-circuit electromagnetic force generates quickly and the circuit breaker is difficult to turn off the circuit in a short time. Under such a large electromagnetic force, the transformer windings will vibrate up and down, leading to the deformation, distortion and dielectric breakdown of windings. It even can cause winding collapse. Transformer short circuit test is destructive and needs a huge cost and long time, so simulation of electrodynamic force of transformer winding under short-circuit fault plays an important role in practical transformer design and operation. Therefore, development a software package to study electrodynamic force of transformer winding under short-circuit fault has higher theoretical significance and practical value.

Beginning in 1973, the calculation of the leakage magnetic field of transformer has been paid more and more attention. The analysis methods range from two-dimensional axisymmetric static magnetic field to three-dimensional transient magnetic field. The anisotropy of core and the eddy current can be considered (Anderson, 1973; Augusto and Roberto, 1983; Liang, 2001). The some scholars have done a lot of research on transformer short-circuit strength (Lang-Qi, 1974). Analysis of dynamic force and dynamic displacement of the transformer winding causes more and more attention due to the elasticity of the kraft-manila paper and press-board. The kinetic equation of transformer winding has been derived (Zhen-Mao and Jian-Xue, 1990). The dynamic force, dynamic displacement and circumferential and radial stresses of windings in and out of the transformer window can be calculated. Tamaki *et al.* (1999) considered the damping force generated by the transformer oil. The dynamic force of the transformer windings when sudden short-circuit fault occurs and short-circuit dynamic force analysis software for large transformer has been developed (Li, 1995; Liu, 2007).

This study presents the calculation method for short-circuit electrodynamic force of power transformer winding and development of electrodynamic force analysis software package. Finite element method is used to achieve the leakage magnetic field of transformer winding under short circuit operation. Electromagnetic force is calculated by using Lorentz force formula. Based on mechanical properties of kraft-manila paper and press-board, which are used as

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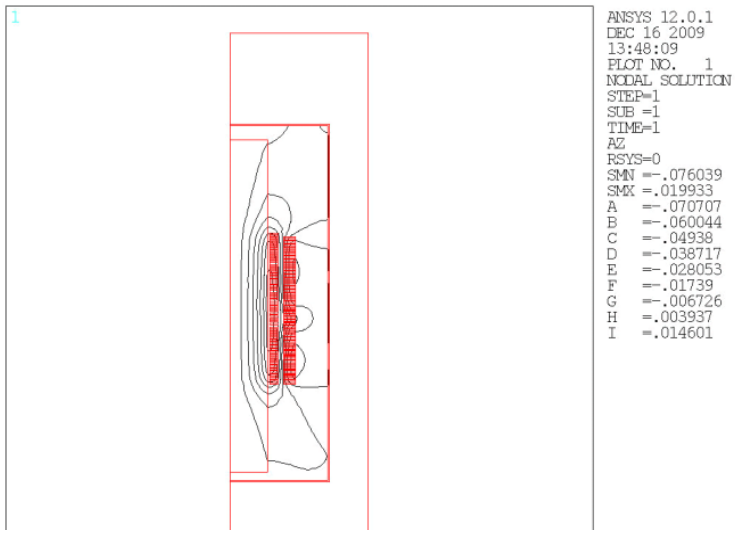


Fig. 1: Leakage magnetic field distribution

insulation and reinforcement materials, considering the elastic force and friction of the various insulating materials, the equivalent mass spring model of winding is established and axial dynamic force and displacement is calculated. Using client/server mode, short-circuit electrodynamic force analysis software for power transformer winding is developed, which consists of several sub-system, such as parameter input and calculation and result analysis. The client/server structure facilitates the expansion of the software features. This software package has been applied in the power transformer manufacture enterprise.

METHODOLOGY

Finite element calculation of transformer leakage magnetic field: It is hard to calculate the winding force for each segment because three-dimensional electromagnetic field calculation is time consuming work. The Finite Element Analysis (FEA) for two-dimensional axisymmetric magnetic field is used to calculate the leakage magnetic field of the winding in this paper. The model consists of core, high, medium and low-voltage windings and the tank (Yan-Qin, 2009). On short-circuit conditions, the magnetic vector potential A_θ is used to analyze the two-dimensional magnetic field model. The boundary value problem of magnetic field is expressed as (1):

$$\begin{cases} \Omega: \frac{\partial}{\partial z}\left(\frac{1}{\mu r}\frac{\partial(rA_\theta)}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{\mu r}\frac{\partial(rA_\theta)}{\partial r}\right)=-J_\theta \\ A_\theta\big|_\Omega = 0 \end{cases} \quad (1)$$

where,
μ : Permeability of material
J_θ : Current density
Ω : The solving domain

In this study, a commercial FEA package, ANSYS is used to calculate the transformer leakage magnetic field. Figure 1 shows leakage magnetic field distribution in transformer windings.

Dynamic force calculation of transformer windings: When a short-circuit fault occurs, the current flowing through the high, medium and low voltage windings of the transformer is related to the state transformer locates. Steady value of the short-circuit current is related to the impedance of the transformer and power lines. To meet engineering requirements, the three-phase short circuit steady-state current is:

$$I_k = \frac{u_\Phi}{Z_1} \quad (2)$$

where,
u_Φ : The phase voltage
Z_1 : The positive sequence short-circuit impedance

Maximum amplitude of the transient short-circuit current often appears in the first cycle. The maximum value of transformer short-circuit current, which is known as the inrush current, can be expressed as (3) (Shuo *et al*., 2011):

$$i_{Km} = \sqrt{2}I_K[e^{-\frac{r_k}{L_k}\frac{\pi}{\omega}} - \cos\pi] = K\sqrt{2}I_K \quad (3)$$

where,
$K = 1 + e^{\frac{r_k}{L_k}\pi}$: The impact factor of the short-circuit current (K is 2.67 in this paper)
L_K : Reactance of the transformer
r_k : Resistance of the transformer
l_k : RMS of the periodic component of the steady-state short-circuit current

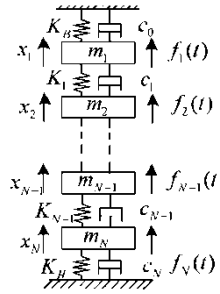


Fig. 2: Axial vibration model of a single winding

According to the principle of Lorentz force, the axial and radial electromagnetic force of each segment of winding can be calculated by the radial and axial component of leakage magnetic field and winding current. Then circumferential stress and radial pressure of winding segment can be calculated.

When calculating the axial dynamic force and the dynamic displacement of winding segment, each segment is equivalent to a rigid body. The press-board and insulated kraft-manila paper immersed in oil are regarded as an elastic element. The elastic force and deformation relationship is as follows:

$$F = \bar{a}\delta + \bar{b}\delta^3 \tag{4}$$

$$C = 0.00025\bar{a} \tag{5}$$

where,

$\bar{a}$ & $\bar{b}$: Elastic coefficient related to the area and thickness
F : The elastic force
C : The damping coefficient

The axial vibration model of a single winding is shown as Fig. 2 (Scheubert *et al*., 1999).

The axial electromagnetic force is regarded as the excitation. According to the mass-spring system of transformer winding, considering the pre-compressing force, the winding kinetic equation is written as:

$$\begin{cases} m_1\frac{d^2x_1}{dt^2} + c_1(\frac{dx_1}{dt} - \frac{dx_2}{dt}) + K_B x_1 + \bar{a}_1(x_1 - x_2 - \delta_1) + \bar{b}_1(x_1 - x_2 - \delta_1)^3 = f_1(t) \\ m_2\frac{d^2x_1}{dt^2} + c_1(\frac{dx_2}{dt} - \frac{dx_1}{dt}) + c_2(\frac{dx_2}{dt} - \frac{dx_3}{dt}) + \bar{a}_1(x_2 - x_1 - \delta_1) + \bar{b}_1(x_2 - x_1 - \delta_1)^3 \\ +\bar{a}_2(x_2 - x_3 - \delta_2) + \bar{b}_2(x_2 - x_3 - \delta_2)^3 = f_2(t) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ m_i\frac{d^2x_i}{dt^2} + c_{i-1}(\frac{dx_i}{dt} - \frac{dx_{i-1}}{dt}) + c_i(\frac{dx_i}{dt} - \frac{dx_{i+1}}{dt}) + \bar{a}_{i-1}(x_i - x_{i-1} + \delta_{i-1}) + \bar{b}_{i-1}(x_i - x_{i-1} \\ +\delta_{i-1})^3 + \bar{a}_i(x_i - x_{i+1} - \delta_i) + \bar{b}_i(x_i - x_{i+1} - \delta_i)^3 = f_i(t) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ m_N\frac{d^2x_N}{dt^2} + c_{N-1}(\frac{d^2x_N}{dt^2} - \frac{d^2x_{N-1}}{dt^2}) + K_H x_N + \bar{a}_{N-1}(x_N - x_{N-1} + \delta_{N-1}) + \bar{b}_{N-1}(x_N \\ -x_{N-1} + \delta_{N-1})^3 = f_N(t) \end{cases} \tag{6}$$

where,

m_i (i = 1~N) : Mass of the winding unit, i.e., segment
K_B & K_H : Elasticity coefficient of press-boards
x_i : The displacement of the ith winding segment with respect to its starting position
c_i : The damping coefficient of the kraft-manila paper in the ith oil passage
$m_i\frac{d^2x_i}{dt_2}$: Inertial force of the ith winding segment
$C_{i-1}\left(\frac{dx_i}{dt} - \frac{dx_{i-1}}{dt}\right) + C_i\left(\frac{dx_i}{dt} - \frac{dx_{i+1}}{dt}\right)$: The damping force of the ith winding segment
$\bar{a}_{i-1}(x_i - x_{i-1} + \delta_{i-1}) + \bar{b}_{i-1}(x_i - x_{i-1} + \delta_{i-1})^3 + \bar{a}_i(x_i - x_{i+1} - \delta_i) + \bar{b}_i(x_i - x_{i+1} - \delta_i)^3$: The elastic force of the ith winding segment

The first segment is connected to the upper press-board and the last segment is connected to the bottom press-board. Friction force of press-board is ignored. f_i (t) is the axial electromagnetic force acting on the ith winding segment. The weight of each segment is about 1% of the size of the electromagnetic force and therefore can be ignored.

According to the initial conditions $x|_{t=0} = 0$ and $\frac{dx}{dt}|_{t=0} = 0$, variable step size fourth order Runge-Kutta method is used to solve this differential equations and the winding displacement changing over time can be obtained. Then, the elastic force, i.e., dynamic force, acting on the each segment and transient deformation process can be calculated by mechanical FEA (Dughiero and Forzan, 2002).

The transient Electromagnetic force under short-circuit occasion is written as:

$$f_i(t) = \frac{1}{4} f_{im}(e^{-2\alpha t} + \frac{1}{2} + \frac{1}{2}\cos 2\omega t - 2e^{-\alpha t}\cos\omega t) \tag{7}$$

where,

f_{im} : The maximum short-circuit electromagnetic force
α : Time constant related to transformer reactance and resistance

DEVELOPMENT OF ANALYSIS PACKAGE OF SHORT-CIRCUIT ELECTRODYNAMIC FORCE FOR TRANSFORMER WINDING

Client/Server mode is used to design the software package of short-circuit electrodynamic force analysis of transformer windings in this paper. This package is easy to be integrated with design and optimization package of transformer. The software structure is shown in Fig. 3.

In Fig. 3, the client includes the input module of material and structure parameter of transformer. The module of short-circuit electrodynamic force analysis, which will send the message to call ANSYS and receive the calculated results and module of result output. The Server includes ANSYS, which may receive the requirement from client to calculate the leakage electromagnetic field, winding short-circuit electromagnetic force, circumferential and radial stresses and deformation of winding, the axial vibration analysis based on MATLAB and system database

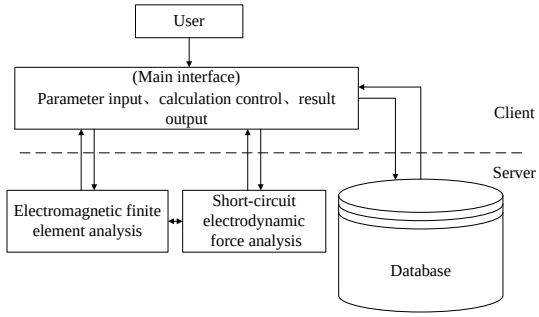


Fig. 3: Structure of analysis package of short-circuit electrodynamic force of transformer winding

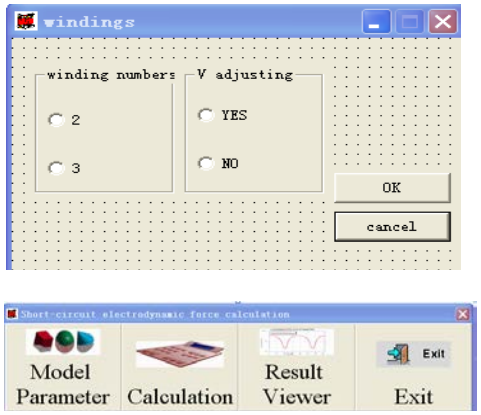


Fig. 4: Main interface

which stores the transformer parameters and results. The system can be run in personal computer, but also easy to upgrade to the use of the network hardware environment.

The function of each module is briefly described as follows.

Figure 4 is the main user interface. Transformer winding numbers can be chosen and the client function module can be called.

Parameter input module includes transformer rated capacity, short-circuit capacity, rated voltage and other requirement and constraint information. It also includes parameters input of high, medium and low voltage windings, high-tuned, medium tuned winding, balance winding and height of the oil duct, number of kraft-manila papers, turns of different partition of windings, etc. Figure 5 is a parameter input interface of a no-load transformer with the high and low voltage windings. The input parameters can be stored in the prescribed format database and can be used by each system module.

In the result viewer interface, the axial dynamic force distribution, the axial strength of each partition of winding, allowed displacement of each partition of winding, etc., may be viewed in the windows with MATLAB type.

Fig. 6 is the axial electromagnetic force of high-voltage winding with maximum, nominal and minimum taps, respectively. The Axial collapsing load of high voltage winding is shown in Fig. 7.

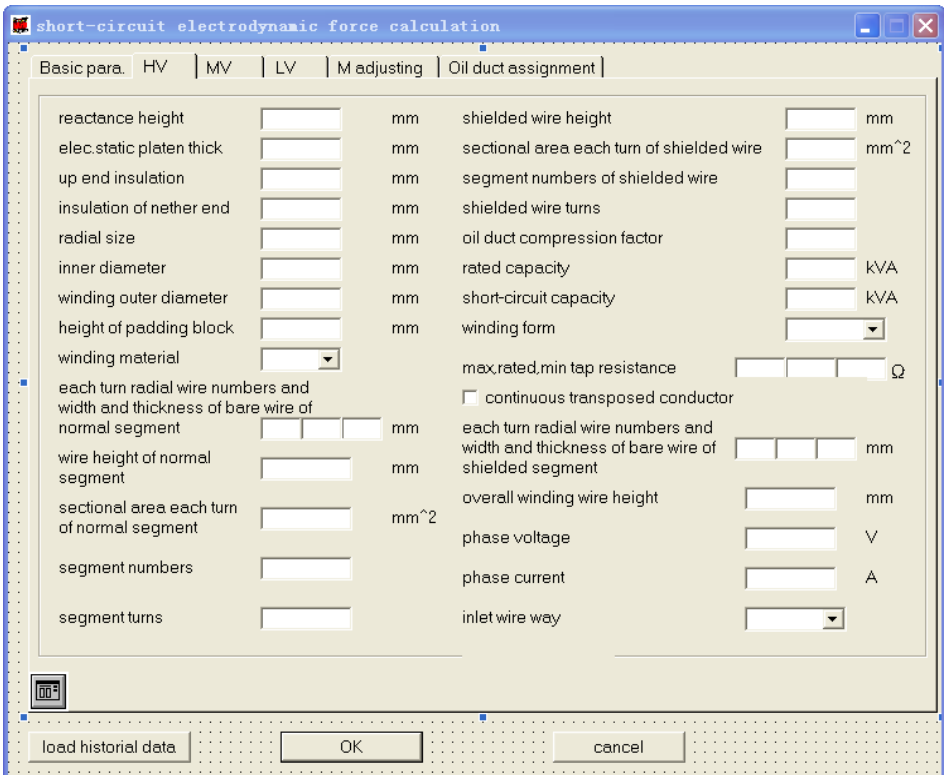


Fig. 5: Parameter input interface of a no-load transformer with high and low voltage windings

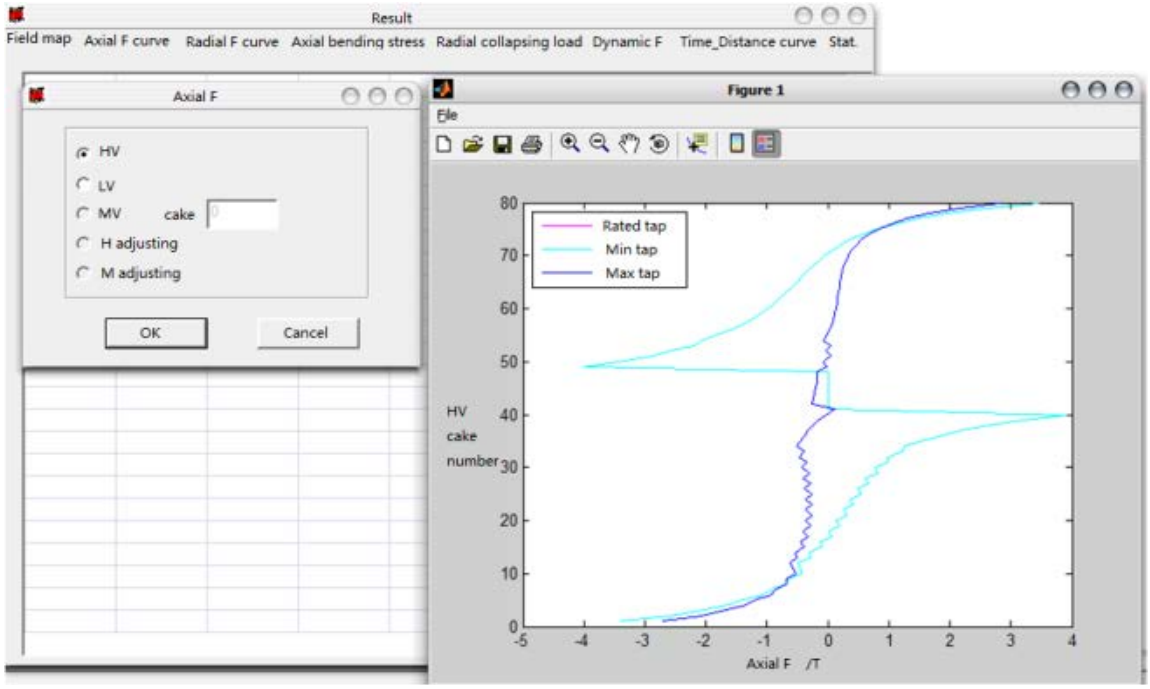


Fig. 6: Axial electromagnetic force of high-voltage winding on maximum, nominal and minimum taps, respectively

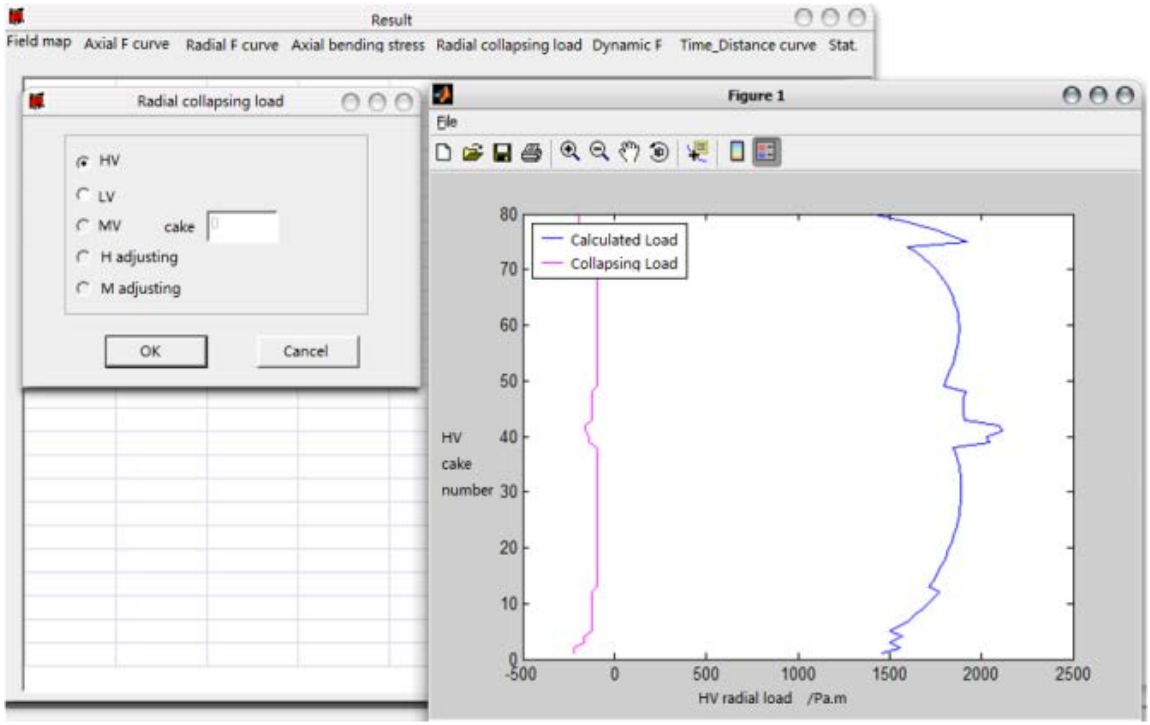


Fig. 7: Axial collapsing load

In Fig. 7, the collapsing load is little than axial electromagnetic force of the high voltage winding. Therefore, axial instability will not occur. Figure 8 and 9 show the axial dynamic force and displacement of the second segment of low voltage winding, respectively.

Figure 10 illustrates an interface, in which the axial stability of a high voltage winding is evaluated. For each partition of winding, the axial dynamic force and displacement, the thresholds of axial mechanic strength and displacement, the safety factor of force and

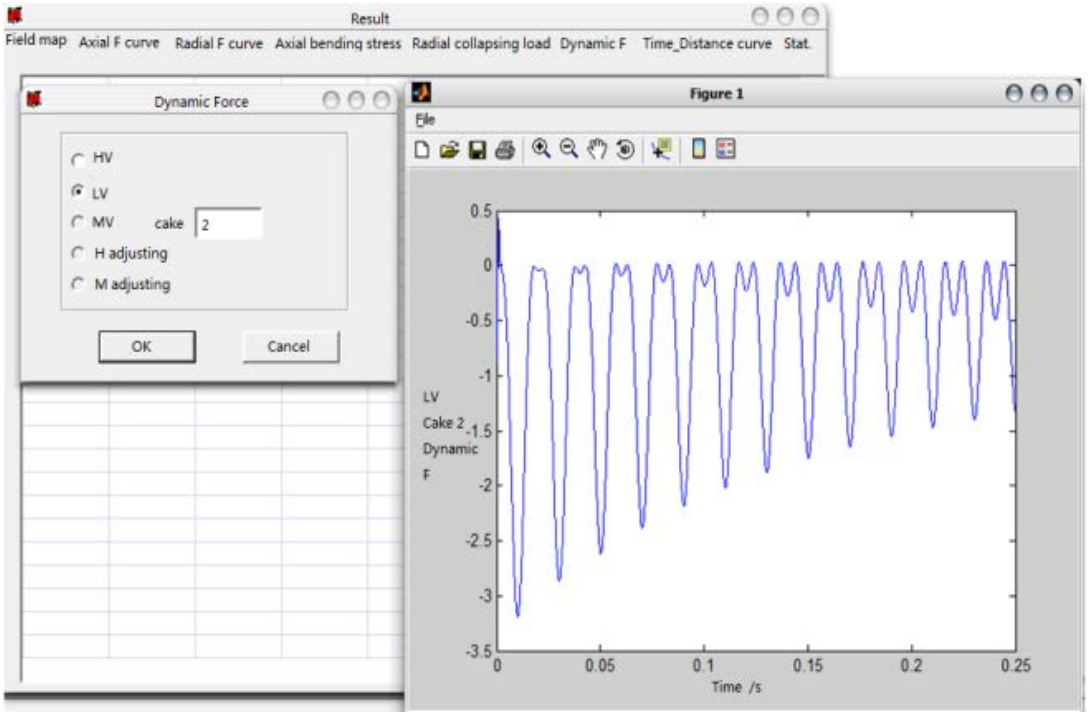


Fig. 8: Dynamic force of the second segment of low voltage winding

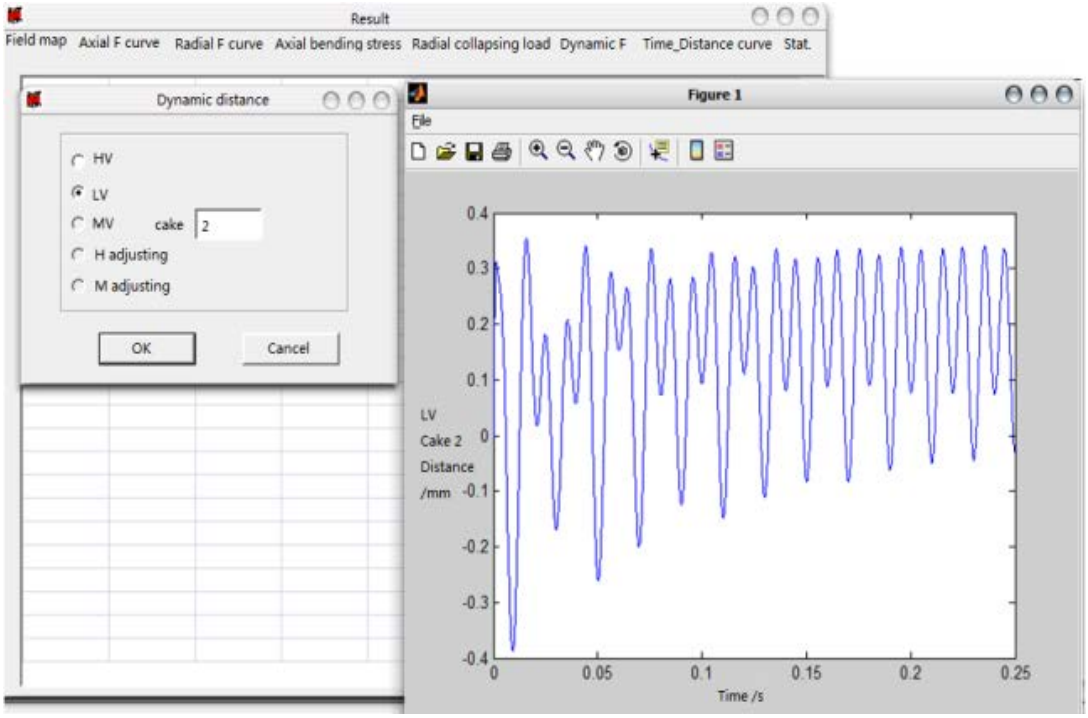
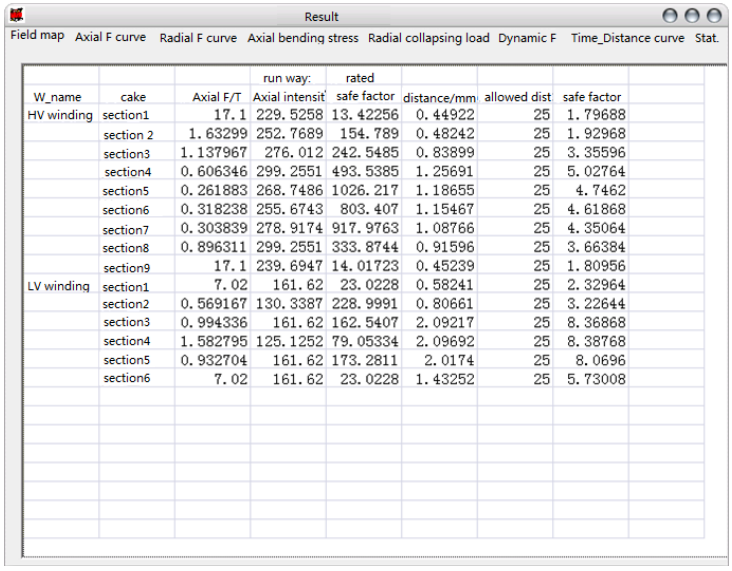


Fig. 9: Dynamic displacement of the second segment of low voltage winding

displacement can be concluded in this interface to provide the assistance on evaluation of the winding mechanic properties.

The software can calculate the axial, radial electromagnetic force, radial stress and hoop stress, axial bending stress axisdynamic force, the dynamic displacement, allowed axial strength and *et al* when three windings transformer works on every state. This package provides a favorable basis for transformer design.



Result

Field map | Axial F curve | Radial F curve | Axial bending stress | Radial collapsing load | Dynamic F | Time_Distance curve | Stat.

			run way:	rated			
W_name	cake	Axial F/T	Axial intensit	safe factor	distance/mm	allowed dist	safe factor
HV winding	section1	17.1	229.5258	13.42256	0.44922	25	1.79688
	section 2	1.63299	252.7689	154.789	0.48242	25	1.92968
	section3	1.137967	276.012	242.5485	0.83899	25	3.35596
	section4	0.606346	299.2551	493.5385	1.25691	25	5.02764
	section5	0.261883	268.7486	1026.217	1.18655	25	4.7462
	section6	0.318238	255.6743	803.407	1.15467	25	4.61868
	section7	0.303839	278.9174	917.9763	1.08766	25	4.35064
	section8	0.896311	299.2551	333.8744	0.91596	25	3.66384
	section9	17.1	239.6947	14.01723	0.45239	25	1.80956
LV winding	section1	7.02	161.62	23.0228	0.58241	25	2.32964
	section2	0.569167	130.3387	228.9991	0.80661	25	3.22644
	section3	0.994336	161.62	162.5407	2.09217	25	8.36868
	section4	1.582795	125.1252	79.05334	2.09692	25	8.38768
	section5	0.932704	161.62	173.2811	2.0174	25	8.0696
	section6	7.02	161.62	23.0228	1.43252	25	5.73008

Fig. 10: Axial dynamic mechanic properties evaluation

CONCLUSION

This study discusses the simulation and software package development of short-circuit electrodynamic force for power transformer winding on arbitrary working conditions. The finite element method is applied to calculate the leakage magnetic field of windings. By using the Lorentz force calculation, short-circuit electromagnetic force of winding is achieved. The circumferential, radial stresses and radial deformation of each winding are analyzed. By using mass-spring system analysis, the dynamic forces, dynamic displacement can be obtained. Various strength requirements also are evaluated. The software package is developed by using the client/server model, which has friendly user interface and diverse result displaying interfaces. This package is easy to upgrade to the network version. As the part of the design, simulation and optimization software package of power transformer, it can provide detailed mechanic property analysis for the transformer design.

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