Application on Unloading Transient Electromagnetic Computation of Brushless AC Exciter with Magnet

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Abstract—**To investigate the internal electromagnetic functional principle, dynamic characteristic and faults operational performance of brushless AC synchronous generator with rotating rectifier in Aeronautic AC Power Supply, traditional analytical method is restricted by precondition and cannot improve anymore, while Finite Element Method has been widely used for electromagnetic computation. Since few theses adopt finite element method to analysis AC exciter with armature rotating structure of aeronautic AC power supply, this paper takes it for research object. It states the principle and process of two-dimensional transient field simulation modeling with Magnet software. Furthermore, it also simulates field distribution, electromagnetic and circuit parameters under unloading for AC exciter. With contrast to actual values, the model has been proved available to design and optimize this type of machine. Meanwhile, this method can be extended in other aeronautic AC Power Supply modeling and lays a foundation of optimal design of AC Power Supply system.**

Keywords—**Finite Element Method, two-dimensional transient field, Magnet, brushless AC exciter**

I. INTRODUCTION

When AC generator operates in the transient conditions, the relative motions between stator and rotor windings and magnetic asymmetry from salient rotor have results that the voltage differential equations usually contain variable parameters. Considering the magnetic saturation, inductances are nonlinear and the voltage equations are accordingly nonlinear differential equations [1-2]. On the precondition of constant speed and ignoring magnetic saturation, the voltage equations can be transformed into constant parameters linear differential equations by d-q-0, $\alpha-\beta-0$ and other coordinate transform technology. But the application is restricted by the preconditions, i.e.:

- Suppose the generator model excludes actual high order Harmonic waves.
- Differential equations generated by d-q coordinate model are constant parameters. However, these equations are linear during constant speed and nonlinear during variable speed, which restrict the application area.
- If generator is connected with rectifier, the phase output voltages are affected by harmonic wave current and present non-sinusoidal. Therefore the preconditions of d-q coordinate model are unsatisfied.
- Traditional model is difficult to simulate a certain fault or unbalance state of switch. For example, when rectifier bridge occurs a fault, the system is in the serious asymmetry. Therefore the d-q coordinate model is unfit for application.

Finite Element Method (FEM) was introduced into electromagnetic computation by Peter Silvester and M.V.K. Chari who were the founders of successfully put FEM into electromagnetic computation area in 1970. It makes solution of complex structure, complex boundary and nonlinear medium boundary problems. The basic principle of FEM is to divide the whole area into many small units, make each unit computation simple by choosing proper figure function. With the summation of all these simple computations of the whole units, it gets the solution of the whole area with entire matrixes. In the previous research, most articles adopt FEM to analyze permanent magnetic motors, brushless DC motors [3-7], while until currently the study of armature rotating brushless AC exciter in aeronautic AC power field is relatively scarce. Therefore AC exciter is taken on as the object in this article and its transient characteristic with FEM modeling is analyzed thereof.

II. STATEMENT OF MAGNET IN INFOLYTICA CORPORATION

There is no corresponding model in RMxprt, which is the professional motor design software of Ansoft corporation because AC exciter has a specific structure, while the transient characteristic further affected AC power system. Then Magnet is adopted for FEM modeling and simulation tool.

Infolytica corporation was founded in 1978, who was the first commercial electromagnetic analyzing software corporation. Peter Silvester was working in it. Magnet is specially fit for two-dimension, three-dimension electromagnetic simulation and conveniently used to compute motor transient motion field. It has the following functions:

- Transient motion solver to support multiple motion components.

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- Solution capability to support two-dimension of 1~4 order and three-dimension of 1~3 order.
- The technology of local grid subdivision and adaptive solution order function.
- Make model variable parametric, including geometric size, material, grid, excitation and etc. Able to finish multiple operations simulation in one model.

III. FINITE ELEMENT METHOD SOLUTION PRINCIPLE AND MODELING PROCESS

A. *Solver and Coordinate Choice Principle*

If considering magnetic saturation, rotation of generator rotor makes inductance and the voltage equations nonlinear and grid subdivision is thus different during each simulation step. Because AC exciter is axial symmetry, the vector magnetic force and winding current density only have component of Z coordinate. If the ratio of generator length respect to outer diameter is higher than 0.3, the end magnetic influence can be ignored. Thus two-dimension transient motion solver is chosen to solve this type of problem.

Let us take a certain armature rotating AC exciter in aeronautic constant speed and frequency power supply for example. Primary parameters are listed in list 1 as follows.

TABLE I. BRUSHLESS AC EXCITER PRIMARY PARAMETERS

Name	Value	Name	Value
Rated voltage	30V	Rated current	83.4A
Rated speed	8000rad/min	Rated frequency	800HZ
Power factor	0.9(lag behind)	Stator pairs of poles	6
Phases	3	Rotor slots	45

B. *Geometry Structure Model Design*

Two-dimension and three-dimension model files in AutoCAD, SAT, CATIA, Pro/E, IGES, STEP and Inventor are all compatible in Magnet. Furthermore, there is also editor window in Magnet. Geometry structure figure of laminated AC exciter is established as figure 1.

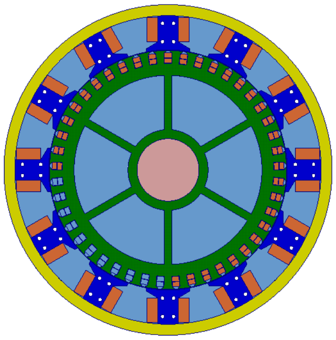

Figure 1. Laminated AC exciter

C. *Material Property*

The material property includes electrical, magnetic and thermal linear and nonlinear property based on temperature and frequency. The type of soft magnetic material does not belong to basic material library. Therefore DC magnetization characteristic data of DW310-35 is defined by WuGang silicon steel sheet plant and "usual material manual of motors". The following are three important materials used in AC exciter.

TABLE II. BRUSHLESS AC EXCITER MATERIAIL PROPERTY

Rotor Armature Lamination	**Stator Pole Lamination**	**Magnetic Yoke**
DW310-35 silicon steel sheet $\delta = 0.35mm$	DT3 pure iron slice $\delta = 0.5mm$	10# hot-rolled steel tube

D. *Boundary Definition*

There have three common boundary conditions, which are Dirichlet boundary condition, Neumanm boundary condition and the combination of the two mentioned before.

Dirichlet boundary condition states the magnetic force in a certain boundary is fixed. In this case, outer diameter of AC exciter is defined zero magnetic force.

Furthermore, Neumanm boundary condition expresses the symmetry of geometry size and excitation. In this case, stator of Ac exciter has six pairs of poles. To decrease the computation time, one sixth structure of magnetic force can be computed accordingly, while the others can be attained by symmetry.

If common function in both Dirichlet boundary condition and Neumanm boundary condition are zero, the boundary can be simplified to homogeneous corresponding ones. In this case, magnetic force and electrical force in any pair of poles can be computed and thus get the whole electromagnetic distribution by symmetry.

E. *Rotor Armature Winding Method Design*

To decrease three and the above odd-degree harmonic waves, double layer, lap taping with 60 degrees phase-belt windings is defined. Thus the angle of slot pitch is 48 degree, the polar distance is 3.75, i.e. each pole and phase occupies $1\frac{1}{4}$ slot. Usually in order to increase winding factor, short pitch winding with pitch 3 is adopts. With the above design method, 45 slots in rotors are divided into three phases, winding A, B, and C. Each winding is two coils paralleled and the parallel branch is 1. The definition of three phases is shown in figure 2.

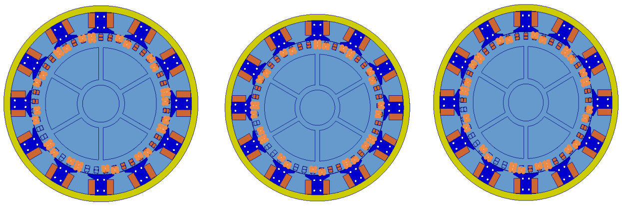

Figure 2. Three phases armature winding method of AC exciter

F. *Adaptive Grid Subdivision*

There are several grid subdivision and set methods, which are grid size set, curvature control, adaptive subdivision and etc. Designer can use the offered tool to further improve the grid precision such as grid subdivision and maximum grid size set and etc. Meanwhile, it also includes P unit and U unit adaptive subdivision, which are based on medium result and automatically confirm the densified grids area during mesh making (called h-adaption) or increase grid polynomial order in the area (called p-adaption). By credible arithmetic it monitors h-adaption and p-adaption until the error meets the tolerance predicted. The number of grids directly influences the precision of computation. The larger number it has, the more space and internal memory it should offer, thus the less convergence and the longer time it has. Some area may occur with the incorrect results caused by too many grids and non-convergence arithmetic. On the contrary, the smaller number it has, the less variable range sensitivity in large radian area it has and the less solved correctness it has. Generally speaking, it is primary for modeling to choose grid subdivision units reasonably.

As is known, stator and rotor are both adopted laminated technology. To decrease the eddy current loss, the laminated factors of both are 0.92 based on the length of pure iron slice and silicon steel sheet. Therefore, the equivalent modeling length equals actual iron length multiples laminated factor. Furthermore, the skin effect is so small both in stator and rotor that it is ignored during modeling. According to air gap, four-layer average subdivision technology is adopted because of the large magnetic force variation. The whole AC exciter grid subdivision and amplified grid subdivision of air gap are shown in figure 3 and 4.

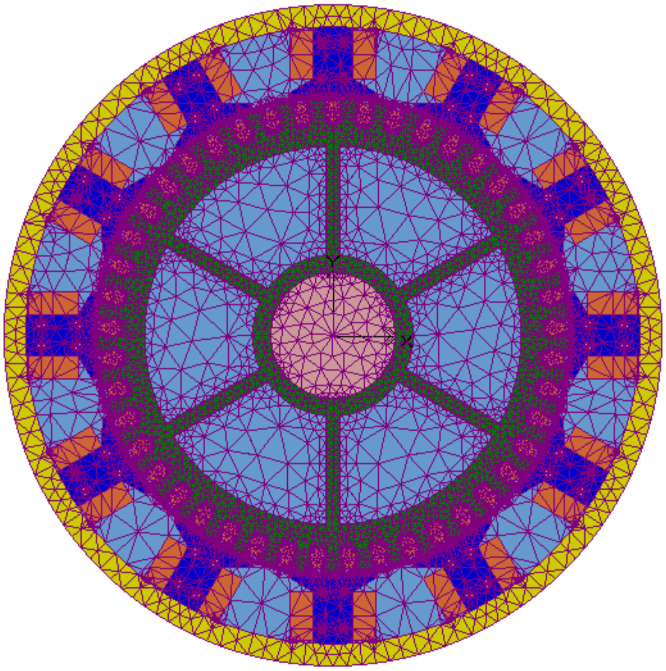

Figure 3. The whole AC exciter grid subdivision

G. *Express Equations*

In the computation process, algebra equations with nodal magnetic force function will be constructed by pre-process physical data, and suitable arithmetic solution method will be computed to get the corresponding values. If choosing the reasonable arithmetic method, computer will finish all the computation process without human-machine interface. Because the whole process will cost large amount of computation and storage, it offers senior speed and memory of the computer itself. Magnet offers two nonlinear equations methods called Newton-Rapson method and simple iterative method. Newton-Rapson method is a very effective arithmetic to search for partial smallest value in multiple variable functions, then spreads out Taylor formula into two-order item and includes first and second order differential items, eventually takes on these differential items as the approximation for the magnetic force function. Its advantage is high convergence. Usually it can be up to square convergence. However, it needs rigorous requirement to primary vectors and can be convergence with adjacent precision value. Furthermore, it also needs partial differential coefficient $f_i(x)$ $(i=1,2,\cdots,n)$. When Newton-Rapson method meets non-convergence, simple iterative method can be adopted then. But its convergence speed is first order.

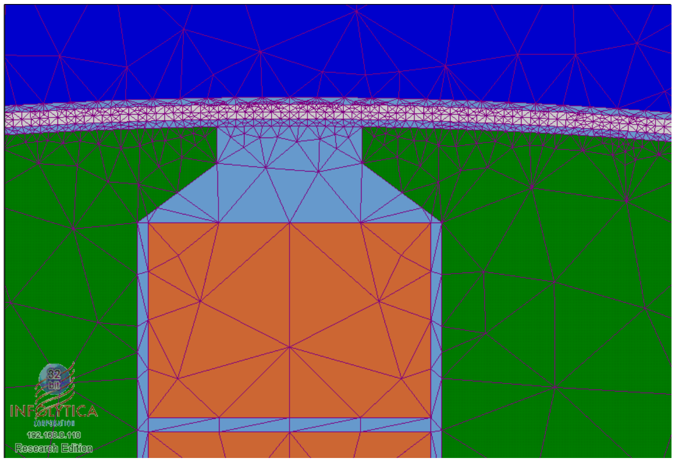

Figure 4. Amplified grid subdivision of AC exciter air gap

In this case, Newton-Rapson method is adopted to solve nonlinear algebra equations for nodal magnetic forces. Here the maximum convergence time is set to 20, error tolerance is 1%, force function is first order approximate polynomial and convergence grads is 10^{-6}%.

IV. ANALYSIS OF ELECTROMAGNETIC PARAMETER SIMULATION RESULTS

Magnet can directly computes magnetic and circuit distribution, including magnetic intensity H, magnetic density B, circuit intensity E, several losses (ohm loss and iron loss), corresponding impedance, force, torque, inductance, energy and etc parameters respect to different frequency. Excitation ban be driven by current or voltage. The circuit can include resistance, capacitance, inductance, switch with position control function and commutator. Therefore the model can simulate any transient operational curves at any time during rotor rotating.

In the instance, simulation time span is set to [0-2.5]ms and simulation step is 0.0125ms because with every 360 electrical degree rotating it costs 1.25ms. The hardware configuration is Intel(R) Xeon(TM) 3.2GHz CPU, 4.00G RAM. Under constant DC excitation and unloading conditions, the model of AC exciter is executed with 7 hours and 43 minutes used.

A. Analysis of Circuit Parameters Curves under Unloading Condition

Figure 5 shows unloading voltage simulation curve of phase A. The effective value is 32V or so, and the actual experimental value is 30V, so the error is 6.67%. The unloading voltages of phase B and C are 120 degree and 240 degree lag behind that of phase A, which are omitted as limited.

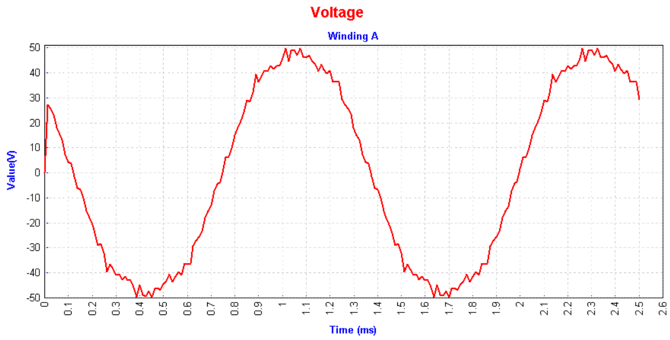

Figure 5. Unloading voltage of phase A in AC exciter

Figure 6 shows the excitation voltage simulation curve of AC exciter under unloading condition. The effective simulation value is 14.5V and the actual experimental value is 16V, so the error tolerance is 9.4%.

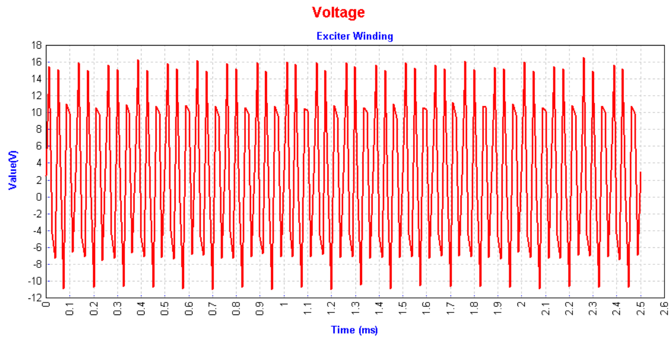

Figure 6. Unloading voltage of excitation winding in AC exciter

Seen from the above circuit curves, two-dimension finite element transient motion model solution values better approach the actual experimental values, which verify the practicability of the established model.

B. Analysis of Magnetic Parameters Curves under Unloading Condition

Under unloading condition, magnetism can only depends on excitation magnetic force caused by excitation winding without influence of armature reaction caused by armature winding. Therefore, magnetic equivalent force line will rotate symmetrically during rotation. The simulation distributions of magnetic equivalent force line at 0ms and 1.1ms are shown as figure 7 and 8.

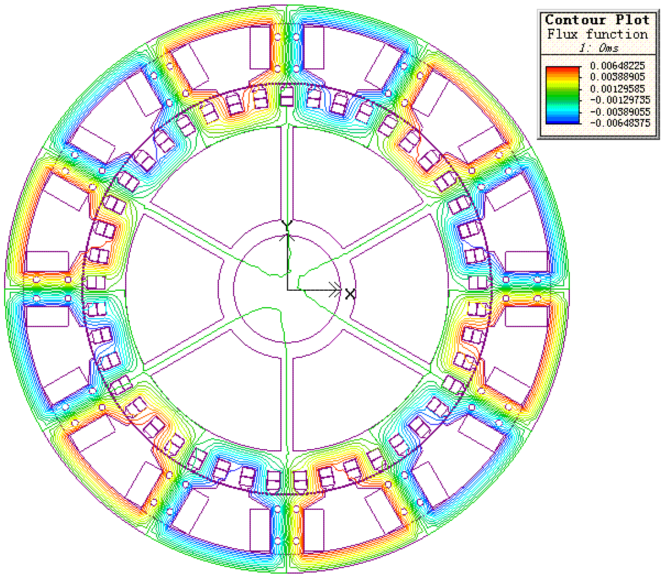

Figure 7. Magnetic equivalent force line distribution at 0ms of AC exciter under unloading condition

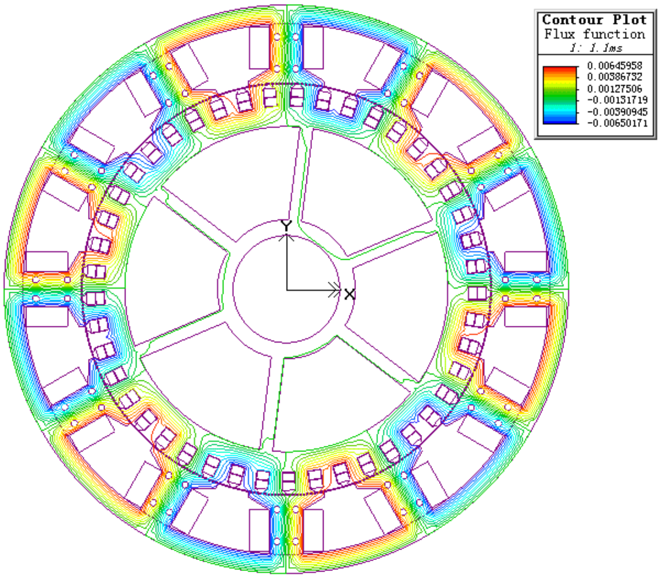

Figure 8. Magnetic equivalent force line distribution at 1.1ms of AC exciter under unloading condition

Since the armature structure of AC exciter, rotor winding currents cannot be measured directly. While through model, these can be simply simulated to get i_a、i_b、i_c and other parameters such as vector magnetic position A, magnetic density B, magnetic chain ψ and magnetic equivalent force line of the whole field space can also be attained. It proves that the finite element model established in this article can truly response the operational principle, transient characteristic inside generator field and circuit. Meanwhile, the model can also be used to investigate the fault operation accordingly.

V. CONCLUSION

As a certain type of brushless AC exciter in constant speed and frequency aeronautic power supply for research, two-dimension transient motion finite element model has been established by Magnet. It solves the transient curves of output phase voltage, excitation voltage and magnetic equivalent force lines, magnetic density vector and other circuit and field curves under unloading condition. By contrast to simulation and actual experimental values, it verifies the precision of model can meet the project design requirement. Computation and variation trend analyse are presented for transient field simulation. This method can be used to design other type of generator, motor, permanent magnetic motor. Meanwhile, the transient circuit and field characteristic research of stable short-circuit, rectifier fault operation can be studied based on it.

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