Modeling and Design of Permanent Magnet Vibration-to-Electrical Power Generator's Induction Coil

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Abstract —The Equivalent Turn Number of Coil (ETNC) which can clarify the relationship among induction coil, magnetic field distribution and vibration is proposed innovatively for optimizing induction coil. Simulation results show that the vibration waveforms have more significant effect at the induction coil's structure than vibration frequency and amplitude. On the basis of ETNC, the optimized coil is composed by two symmetry parts. The effective value of output EMF of optimized coil increases 51.39% than uniform coil's. In the experiment, the optimized and uniform coils are fabricated with 600 turns and comparatively studied in the same vibration-to-electrical power generator. The test results show that the peak-to-peak value and effective value of output EMF of the optimized coil can increase up to 52.59% and 48.76%, respectively, compared with the uniform coil.

I. INTRODUCTION

To solve the power supply restriction problem of distributed miniature sensors and hand-held electric devices, permanent magnet Vibration-to-Electrical Power Generator (VEPG) has caught more and more scholars' eyes. Nowadays, the researchers focus on improving the efficiency of permanent magnet VEPG by optimizing the magnetic field distribution, improving the vibration transmission efficiency, matching electrical and mechanical damping [1-6].

Induction coil as one of the key components of permanent magnet VEPG has not systematic studied and optimized. However, some researchers have noticed the importance of induction coil. C.R. Saha et al. have found that growth rate of power level is 9 times larger at walking condition than slow running condition in the test of VEPG with uniform coil [1]. Dibin Zhu et al. have studied the impact of coil thickness and the magnetic flux through the coil to the induced voltage, and make a tradeoff on the condition of constant gap between coil and magnets [2].

The Equivalent Turn Number of Coil (ETNC) will be proposed innovatively to disclose the relationship among induction coil, magnetic field distribution and vibration.

II. MODELING OF EQUIVALENT TURN NUMBER OF COIL

A typical permanent magnet VEPG sketch is axial symmetric structure, so the VEPG is mathematically studied in cylindrical coordinate system. Let the center position of permanent magnet oscillator as the reference coordinate system origin. If the initial axial position of any single-turn coil i is z_{0i}, the displacement and velocity vectors of coil i can be respectively expressed as $\vec{z}(t)=\left[z_{0i}+z(t)\right]\vec{e}_z$ and $\vec{v}(t)=v(t)\vec{e}_z=\frac{dz(t)}{dt}\vec{e}_z$. $B_{ri}(t), B_{\phi i}(t), B_{zi}(t)$ are radial, tangential and axial components of magnetic flux density, respectively. The output EMF model has been built in [7], and the average value of output EMF of the single-turn coil i can be calculated as follow:

$$E_i=\frac{\pi r_i}{T}\int_0^T\left|v(t)\left(2B_{ri}(t)-\frac{\partial\overline{B}_{zi}(t)}{\partial z}r_i\right)\right|dt \quad (2)$$

Here, T is the EMF period, and every turn of coil always has the same vibration period.

The ETNC of single-turn coil i is defined to reveal every single-turn coil's contribution to the total output EMF. A single-turn coil i_{max} can generate the maximum average value E_{imax} of output EMF among all the single-turn coils of the induction coil. The single-turn coil's ETNC is the ratio of E_i and E_{imax}.

$$n_i=\frac{E_i}{E_{i\max}}=\frac{r_i\int_0^T\left|v(t)\left(2B_{ri}(t)-\frac{\partial\overline{B}_{zi}(t)}{\partial z}r_i\right)\right|dt}{r_{i\max}\int_0^T\left|v(t)\left(2B_{ri\max}(t)-\frac{\partial\overline{B}_{zi\max}(t)}{\partial z}r_{i\max}\right)\right|dt} \quad (2)$$

Here, $n_i\in[0,1]$.

The cross-sectional area of coil can be calculated as: $S=N/N_S$. Here, N is the turn number of coil, and N_S is the turn number of per unit area.

Furthermore, the minimum ETNC n_{imin} can be determined by coil cross-sectional area S. The position of coil i can be explicit specified according to corresponding ETNC. Then, the optimized coil structure can be determined.

III. DESIGN OF INDUCTION COIL

A. Calculation and analysis of ETNC

The transient magnetic flux density of the permanent magnet VEPG is calculated by FEM. To further simulation analysis, the parameters of oscillator are given as follow: The permanent magnet rod with length 10 mm and 20 mm in diameter is used as oscillator. Permanent magnet oscillator is axial magnetization cylinder Nd-Fe-B magnet, and its remanence and coercive force are 1.245 T and 900853.7 A/m respectively.

The ETNC distribution can be calculated by substituting axial and radial components of magnetic flux density and position information into (2). If the permanent magnet oscillator is motivated by sinusoidal vibration with frequency 25 Hz and amplitude 1 mm, the corresponding ETNC is shown in Fig.1. The ETNC in this simulation is almost symmetric along axial direction, and at the 13 mm position of radial direction the ETNC is about one-tenth of the largest one.

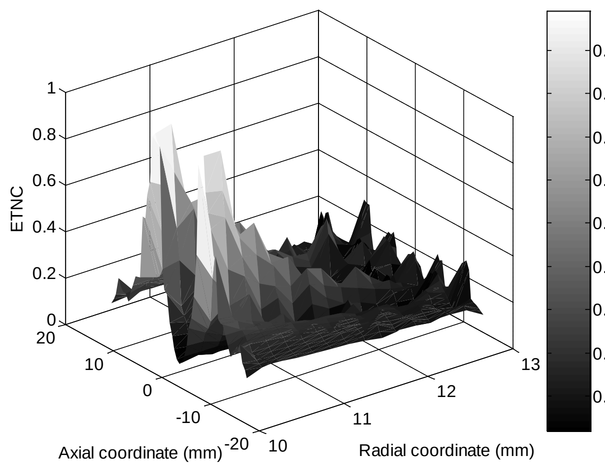

Fig.1 The ETNC distribution along the axial and radial coordinate on the condition of sinusoidal vibration

And the calculated results show that the ETNC distribution changes little with the amplitude and frequency.

Furthermore, the ETNC distributions of other vibration sources have been simulated. And the simulation results show that the waveform of the vibration source has significant effect on the ETNC distribution. So it is necessary to design differently induction coils according to the vibration source as well as magnetic filed distribution.

B. *Output EMF simulation of optimized and uniform coils*

For sinusoidal waveform is more general than other waveforms, the following simulation is based on sinusoidal vibration with frequency 25 Hz and amplitude 1 mm. An optimized coil can be designed by the ETNC shown in Fig .1.

The optimized coil contains two longitudinally symmetrical parts which can be worked in series or parallel. Here, the range of ETNC is set as [0.22, 0.50].

The two parts of induction coil are series connection in the simulation analysis. A comparative study is made between optimized coil and uniform coil. The output EMF values of the same permanent magnet VEPG with two kinds of coils are shown in Table I.

The simulation results show that the peak-to-peak voltage, effective value of voltage and average value of voltage of the optimized coil increase up to 63.21%, 51.39% and 47.47%, respectively, compared with the uniform coil. So it is meaningful to optimize the induction coil structure according to the ETNC.

TABLE I
OUTPUT EMF VALUES OF UNIFORM AND OPTIMIZED COIL

	peak-to-peak voltage (V)	effective value (V)	average value (V)
Uniform coil	1.9046	0.6461	0.5775
Optimized coil	3.1086	0.9781	0.8516

IV. EXPERIMENTAL STUDY

A permanent magnet VEPG prototype has been fabricate with an axial magnetization cylinder Nd-Fe-B magnet. The diameter, length, remanence and coercive force of the permanent magnet are 20 mm, 9 mm, 1.41 T and 876000 A/m, respectively. And the VEPG is motivated by sinusoidal vibration with frequency 25 Hz and amplitude 1 mm.

In the experiment, the coil is made of enameled wire with nominal diameter and the turn number of per unit area 0.11 mm and 5476×10^4 turns/m^2. The total number turns of uniform coil and optimized coil are both 600.

The permanent magnet VEPG has been tested with uniform and optimized induction coils. Here, the uniform coil has the same length with the permanent magnet oscillator.

The experimental results show that output peak-to-peak value and effective value of EMFs of the optimized coil increase 52.59% and 48.76%, respectively. The experimental results show that the induction coil optimized on the basis of ETNC can significantly improve the efficiency of permanent magnet VEPG.

V. REFERENCES

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