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# 基于横向磁通电机的派生能量收集研究

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**摘要：**为了监测汽车电机的工作情况需要应用各类传感器，其中的挑战之一是为在旋转部件上布置的传感器提供电能。通过使用能量收集器，可以将电机中的寄生能量如电磁能和动能收集、转化为电能并储存，存储的电能可用来操作传感器。因此，本文以电机转子为重点，对一台横向磁通机进行研究，其中能量收集器用于收集足够的能量，并为一个温度传感器以及低功耗蓝牙非接触数据传输供电。为此，本文计算了当能量收集器被放置在横向磁通电机转子上时，在运行和生产过程中可望收集到的能量值。

**关键词：**自供能传感器；能量收集；电动机

**中图分类号：** U463.23　　**文献标志码：** A

# Analysis of a Transverse Flux Machine with Regard to Operation of Energy Harvesting

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**Abstract：** Electric machines are replacing increasingly combustion engines as traction machine in modern vehicles. To monitor the behavior of the electric machines，sensors are needed. A major challenge is the electrical powering of the sensors on rotating parts of the machine. By using an energy harvester，parasitic energy from the electric machine，such as electromagnetic and kinetic，can be collected. The collected energy gets transformed into electric energy and used to power sensors. Additionally，a storage device can be integrated. To realize an energy harvester，a transverse flux machine has been investigated，focusing on the rotor of the machine. The goal for the energy harvester is to collect enough energy to power a temperature sensor with contactless data transfers via Bluetooth Low Energy. Therefore，the amount of energy that can be expected to be collected during operation and production when positioning the energy harvester on the rotor of the transverse flux machine is calculated.

**Key words：** energy harvesting； self-sufficient sensors； electrical machines

## 1 Introduction

The automotive industry has experienced increasing electrification in the past few years. At the beginning of the 20th century this was still predominantly limited to the implementation of electrical functions via the integration of sensors and electrical actuators. Nowadays electrification is increasingly focusing on the powertrain. The number of newly registered vehicles with purely electric drive is increasing every year and a further rise is expected in the coming years. The drive concept with electric machine as traction machine is，in terms of the automotive industry，still a new drive concept compared to the conventional drive variant with combustion engine. Therefore，great potentials are to be expected in the field of electric machines for traction applications. In addition，as the number of electric machines rises，manufacturers are becoming increasingly interested in the efficiency of the machines and their quality. This is necessary in order to be able to reduce the costs of the individual machine. Sensor data are essential for the development of traction machines. For new drive concepts，it is also essential to collect data at the

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earliest point possible in the product's life in order to feed it back into the development process, since there is no or only limited access to empirical values. With regard to an electric machine, measured variables on the rotating components of the machine are particularly important[1-2]. The rotor not only serves to transmit power, as it is the case for combustion engine, but also has a decisive influence on the magnetic field required to generate the machine torque. Thus, rotor variables are mandatory. One way of determining the required rotor variables is to calculate them using a simulation model. However, each simulation model is subject to assumptions that must be made, resulting in deviations from reality. Also, each simulation model must be validated with measurement data. In combination with the increasing demand for efficiency of the electric traction machine, there is a need to be able to measure rotor variables directly. The challenge of direct measurement of rotor variables lies in the energy supply. Here, energy harvesting offers a possibility to provide the energy supply for sensors on the rotor.

## 2 Energy harvesting

Energy harvesting describes the process of collecting energy from the environment of the harvester, converting it into electrical energy and storing it. In technical applications, the forms of energy used for energy harvesting are usually thermal-, kinetic- and electromagnetic energy. For energy harvesting in the context of a technical system, the parasitic energies generated by the technical system itself are suitable. Thus, the negative influence of the energy harvester on the system is significantly lower. Since the parasitic forms of energy remain unused without a harvester in the form of lost energy at the system, an increase in the efficiency of the system is achievable through the use of a harvester. A harvester is a self-sufficient system. Thus, a system with an energy harvester has the advantage over a purely battery-powered system of not requiring maintenance in the form of battery replacement.

On moving components, especially rotating ones, on which a system must to be supplied with electrical energy, there are no slip rings for the transmission of electrical energy needed, which suffer from wear. In the automotive industry, an energy harvester is ideal for supplying power to sensors. This allows to place sensors in positions in the vehicle that are difficult to access. Due to the small amount of electrical energy required to supply a sensor, it is also referred as micro energy harvesters[3]. The forms of energy that lend themselves to the operation of an energy harvester in the vehicle are kinetic energy in the form of vibrations and thermal energy in the form of waste heat, especially in the drivetrain. For the design of an energy harvester system, a precise knowledge of the energy forms prevailing at the point of use of the energy harvester is necessary. In addition, the targeted sensor system to be operated must already be defined, since this determines the target value of the electrical energy required.

Fig. 1 shows a schematic illustration of an energy harvester. This consists of the Micro Power Generator, which converts ambient energy into electrical energy. The energy harvesting circuit is used for the electrical control of the energy harvester. The AC/DC converter is not necessary in every application. The battery provides the intermediate circuit. Especially in micro energy harvesters, where the output power of the micro power generator is less than the required sensor power.

In this case, the sensor is only operated if sufficient energy is stored in the battery. In addition to the measuring system, a data transmission system is also integrated in the sensor itself. Here, a contactless data transmission system is ideal so that the energy harvester remains self-sufficient.

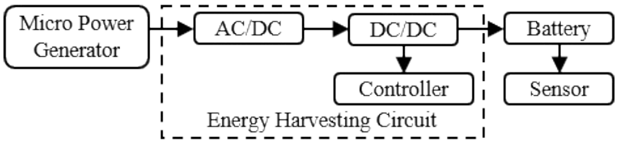

**Fig.1 Schematic illustration of an energy harvester based on Ref. [4]**

## 3 Boundary conditions of analysis

As previously explained, the design of an energy harvester requires a precise definition of the boundary conditions. The transverse flux machine investigated is an external rotor machine being developed at the Institute of Electrical Energy Conversion in the University of Stuttgart as part of the ICM (InnovationsCampus Mobilität der Zukunft)[5-6]. The machine has a targeted power output of $P_{\mathrm{TFM}}=3\,\mathrm{kW}$ and maximum rotating speed of $n_{\max}=2\,400\ 1/\mathrm{min}$. The targeted geometric dimensions are the outer diameter of $d=120$ mm and the length of $l=70$ mm of the rotor. As a reference of the power necessary to be collected by the energy harvesting, a temperature sensor with data transmission via BLE is used[7]. This has a power consumption of $P_{\mathrm{sen}}=250$ mW and a resistance of $r_{\mathrm{sen}}=100\,\Omega$. If the energy collected by the energy harvester does not reach the required 250 mW, the sensor must be switched off temporarily, so that the energy harvester can charge the battery. A measuring cycle including data transmission requires 5 s. This requires an energy of $W_{\mathrm{sen}}=1.25$ J in the battery.

## 4 Analysis of a transverse flux machine

After the boundary conditions have been defined, the transverse flux machine is analyzed with regard to the potential use of an energy harvester. The peculiarity of the analysis is the early stage of development in which the transverse flux machine is in. An energy harvester based on kinetic and thermal energy is analyzed. Fig. 2 illustrates an energy harvester for electric machines. Kinetic energy, as parasitic energy in electric machines, occurs in the form of vibrations. Focusing on the rotor of such a machine, one main source of vibration is the imbalance of the rotor. The force, caused by the imbalanced rotor, is directly related with the rotating speed of the rotor. Thus, the frequency of the vibration is equal to the rotating speed. For harvesting this kinetic energy, piezo elements attached to the rotor are investigated. A piezo element generates a voltage under the influence of a force according to the piezoelectric effect.

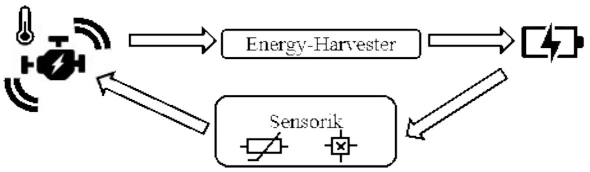

**Fig.2　Energy harvesting in electric machines**

Piezo elements can be divided into two common operating modes as shown in Fig. 3. The modes distinguish the direction in which applied stress and the generated voltage are related[4]. For the application in the context of energy harvesting, the use of the $\mathrm{d}_{33}$ mode is commend. Around the year 2000, NASA developed the so-called MFCs (macro fiber composites). The MFC combines piezo elements in layers of adhesive, electrodes and polyimide film. An MFC builds a ready-to-use-package. Mathematically, the piezoelectric effect can be described with the Van Dyke matrix[8].

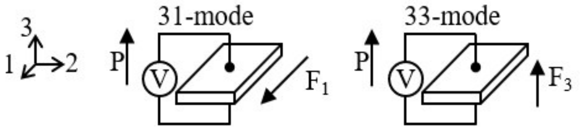

**Fig.3　Operation modes of piezo element based on Ref. [4]**

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \times T^V + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \times \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{1}$$

For use as an energy harvester, a seismic mass is applied to the MFC. Due to the acceleration of the rotor in direction 3, the seismic mass exerts an alternating compressive/tensile load in direction 3. This results in the following equation from the Van Dyke matrix:

$$D_3 = d_{33} T_3 + \varepsilon_{33} E_3 \tag{2}$$

If this is expanded and rearranged with the following relationships:

$$D = E \times \varepsilon;\ E = \frac{U}{t};\ T = \frac{F}{A};\ C = \frac{\varepsilon A}{t}; \tag{3}$$

the resulting voltage generated by the MFC is

$$U(t)=\frac{d_{33}F(t)}{C} \tag{4}$$

$F(t)$ results from acceleration of the seismic mass in direction 3 of the MFC. The acceleration, which the seismic mass experiences, results as a combination of a constant part caused by the imbalance and the alternating part due to the gravity. Because the observed machine is still in the design process, there are no data available about the imbalance. Thus, Ref. [9] regulates the maximum allowed peak-to-peak displacement for electric machines.

$$s_{P-P}=13\,200/\sqrt{n_{\max}}\ \ \mu\text{m} \tag{5}$$

This results in an acceleration of

$$a_{P-P}=2.699\times 10^{-4}\,\omega^2\ \text{m/s}^2 \tag{6}$$

Adding the gravity

$$a=a_{P-P}+9.81\times m_s\sin(\omega t) \tag{7}$$

With the given equation of the acceleration and a seismic mass set to $m_s=5\,g$, the load on the MFC is defined. For the next step, an MFC from the company Smart Material GmbH, with the properties $C=5.07\,\text{nF}$, $d_{33}=400\frac{pC}{N}$, length$=67$ mm, and width$=37$ mm is chosen[10]. With this MFC, a voltage output of $U=0.0072\,\text{V}$ at maximum rotating speed is calculated. This leads to a power output of $P_{\text{Piezo}}=5.23\,\text{mW}$ in regard to the resistance $r_{\text{sen}}$ of the temperature sensor. The outer surface of the rotor offers space for a total of 10 MFCs. Thus, a total power of $P_{\text{Piezo,max}}=52.3\,\text{mW}$ could be achieved. Therefor a continuous powering of the sensor is not possible. With this setup every 23.9 s the temperature could be measured in regard to $W_{\text{sen}}$. If the rotor is penetrated by the magnetic field of the stator, losses occur in the rotor. One form of loss is thermal energy. To make this usable for energy harvesting, a thermogenerator is used. These use the Seebeck effect to convert thermal energy into electrical energy. In this process, an electrical voltage is generated between two points on a conductor when these points are at different temperatures[11]. Semiconductors are often used in the thermogenerator. Here, a semiconductor is connected in n- and p-doped form. If k pairs are connected in series, an electrical voltage result according to:

$$U_{\text{th}}=(\alpha_n+\alpha_p)\times k\times\Delta T \tag{8}$$

The Seebeck coefficient α depends not only on the material but also on the temperature. Thus, the output voltage and the output power depend not only on the relative temperature difference but also on the absolute temperature at which the thermogenerator is operated. In this investigation, a thermogenerator from the company Adaptive is used. The maximum temperature that the rotor can reach is limited by the magnets installed, otherwise they will demagnetize. This temperature is $T_{\max}=120\,℃$. Thus, the maximum temperature of the hot side is $T_{\text{H}}=120\,℃$. The temperature of the cold side results from the ambient temperature. **Fig.** 4 shows the power output for the given temperatures of the cold side[8]. For $T_{\text{C}}=30\,℃$ the needed power output of 200 mW is reached at a rotor temperature of of $T_{\text{H}}=94.5\,℃$. $T_{\text{C}}=50\,℃$ is the maximum temperature of the cold side where it is possible to power the temperature sensor continuously, in regard to $T_{\max}$.

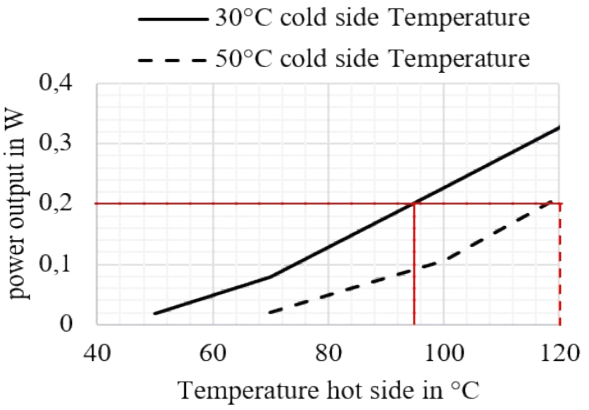

**Fig.4 Power output of thermogenerator[12]**

## 5 Conclusion

This paper shows the analysis of a transverse flux machine, which is still in the design process, in the context of energy harvesting. As energy, which is collected by the energy harvester, exclusively parasitic energy forms of the machine were considered. The goal was to operate a temperature sensor with data transmission via BLE. It has been shown that kinetic energy in form of vibrations only allows a limited operation of the sensor system. Waste heat as thermal energy shows a sufficiently large amount of energy, but it turns out that the ambient temperature is the limiting factor. From the procedure shown here, a method can be derived with which an evaluation of a machine with regard to energy harvesting is possible at an early stage of the development process. In order to be able to make a more precise statement about the results, the machine is to be analysed in different conditions, as well as the calculated values are to be validated by e. g. simulations.

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