# Determination of Rotor Slot Number of an Induction Motor Using an External Search Coil

## Ozan Keysan and H. Bülent Ertan

**Abstract:** This paper describes determination of the number rotor slots of an induction motor from the induced emf in an external search coil. This information is needed in prediction of motor speed from the external search coil induced voltage. The approach is based on identifying saliency harmonics and rotor slot harmonics, via FFT analysis of the external search coil emf. The proposed approach is tested on an induction motor driven by the mains supply. The experiments are repeated with a PWM supply. It is shown that the method works well in both cases and the number of rotor slots of the test machine is accurately predicted.

**Keywords:** Induction motor, drive, parameter prediction.

## 1 Introduction

THIS paper reports some results of a research, which aims to investigate the external search coil, placed on the frame of an induction motor, as a sensor for detecting useful information on the motor. In the literature, it can be observed that research on utilizing an external search coil is rather rare. Existing studies concentrate on trying to capture harmonics caused by machine faults such as broken rotor bars, worn bearings, etc. by axial or radial leakage flux sensors and often the data is analyzed offline. But none of them try to estimate the rotor speed, position and number of rotor slots by an external sensor. However, it is very desirable to be able to predict these parameters for vector control purposes. In this paper the study is on identifying the rotor slot number from the induced voltage in an external search coil.

Consider Fig. 1, which is a sketch of the magnetic circuit of a typical motor. It is clear that some of the mutual flux leak out of the magnetic circuit. Note that this flux

is revolving at the synchronous speed. Therefore, it may be argued that if a search coil is placed outside the frame; an induced voltage containing the information available in the mutual flux will be obtained. It may be possible to process this signal, to obtain the rotor speed and rotor slot number or any other information available in the mutual flux. In the study here a U-shaped coil placed on the motor frame as shown in Fig. 2, is used for recording the induced voltage.
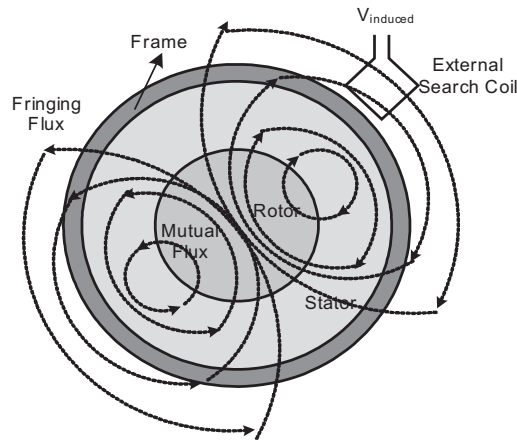


Fig. 1. Mutual flux linking the external search coil.

Induced voltage on the coil is measured in various axial and radial positions. It is found that the radial position of the coil is not critical. However, correctly placing the coil in the axial direction is very important.
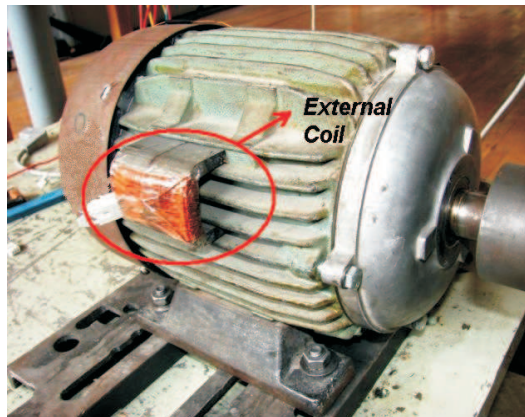


Fig. 2. "U shaped" external search coli on the frame of an induction motor.

## 2 Information Content of the Search Coil Voltage

It is well known that, for a $P$ pole pair, induction motor with $Z$ number of rotor slots, rotating at a mechanical frequency $f_r$; the harmonic frequency of the flux observed on the stator reference frame is $f_{rsh}$ and is given by (1) [1].

$$f_{rsh} = \frac{Z}{P}(f_r \pm f_s) \tag{1}$$

The rotor slot harmonics naturally induce voltage on the stator coils and therefore appear also in the currents flowing through the windings. This fact has been used for the detection of motor shaft speed and for diagnostic purposes in the literature. The external search coil also links the mutual flux leaking out of the core. Therefore it is reasonable to expect that the rotor slot harmonics will also be observable in the voltage induced in the external search coil. However, it is clear that there will be difficulties in separating these harmonics from those stemming from the power supply and other internal or external sources. Especially, when the motor is driven by a PWM voltage source there will be many other harmonics stemming from the pulsed power supply. It is known that the harmonics observable in the mutual flux in this case are given by;

$$f_{rsh} = \frac{Z}{P}f_r \pm \alpha f_s, \qquad \alpha = 1,2,3,\dots \tag{2}$$

where $\alpha$ is the time harmonic order [1].

It is shown in a recent study [2] that it is possible to identify the rotor slot harmonics, by analyzing the external search coil voltage, even if the motor is driven by a PWM inverter. Therefore, speed of the induction motor can be deduced from this information.

The frequency of rotor slot harmonics ($f_{rsh}$) is given by (1). Since the supply frequency $f_s$ is known, from (1), $f_r$ can be extracted as;

$$f_r = \frac{P}{Z}(f_{rsh} \pm f_s) \tag{3}$$

In an induction motor the rotor speed in revolution per-minute (rpm) is given in (6)

$$N_r = 60\frac{f_r}{P} \text{ rpm} \tag{4}$$

Using (3) and (4) the rotor speed in revolutions per minute ($N_r$) can be expressed as in (7).

$$N_r = \frac{60}{Z}(f_{rsh} \pm f_s) \text{ rpm} \tag{5}$$

So it is obvious that if the rotor slot side band harmonics $(f_{rsh} \pm f_s)$ can be determined via some means, the rotor speed can be calculated from (5). But, notice that, the number of rotor slots should be known for this process. The number of slots on the rotor may be obtained from the manufacturer's data. If it is not available, as in most cases, the number of rotor slots must be estimated. If one can measure the rotor shaft speed the number of rotor slots can be identified from (5), [3]. This however is not always possible. So some other means of determining $Z$ is desirable.

## 2.1  Saliency Harmonics

It is well known that even a healthy machine has some type of rotor saliency [4]. The rotor saliency introduces harmonics independent of the rotor slotting. The frequency of these harmonic is only related to rotor speed.

$$f_{saliency} = f_s \pm k\frac{f_r}{P} \tag{6}$$

where $f_s$ is the supply frequency, $k$ is the harmonic order, $f_r$ rotor frequency and $P$ is the number of pole pairs. It must be noted that the frequency of the saliency harmonic is much lower than the harmonics due to rotor slotting.
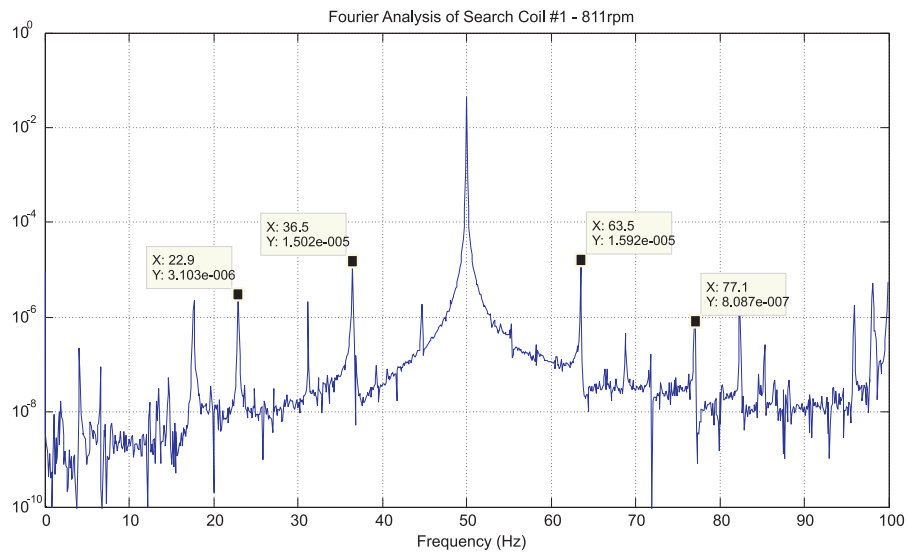


Fig. 3. FFT analysis of external search coil voltage data at 811 rpm with $f_s = 50$Hz.

Suppose that the external search coil voltage is recorded and FFT analysis of the captured waveform is carried out (Fig. 3). One can eliminate the stator frequency
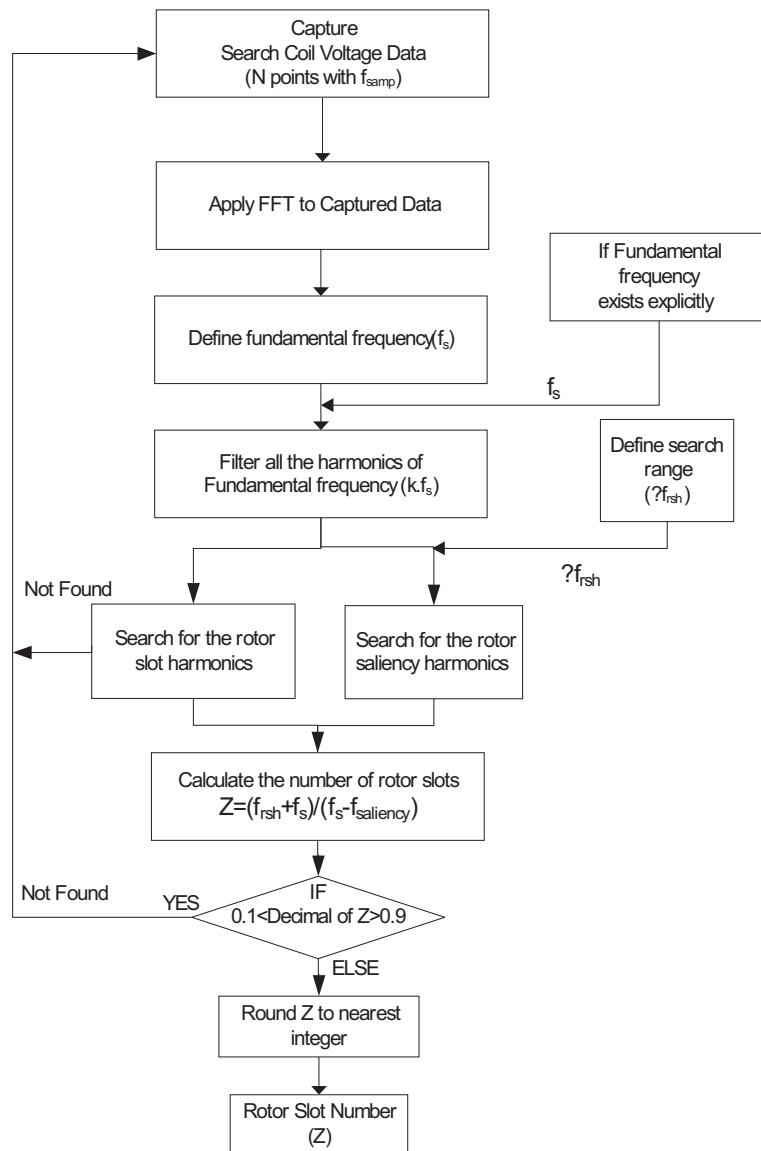
Fig. 4. Block diagram of number of rotor slots.

harmonics and its multiples, relatively easily, as $f_s$ is known. The remaining dominant harmonics in the spectrum are the rotor saliency harmonics ($50\pm13.5$ Hz in Fig. 3) and the rotor slot harmonics given by (1). The saliency harmonics and rotor slot harmonics ($f_{rsh}$) can be identified from the FFT analysis result. Saliency

harmonics occur at a frequency range considerably lower than rotor slot harmonics and they occur in pairs. Therefore they are easy to identify. From (6), $f_r$ can be determined. Now (3) can be solved for $Z$, and hence the rotor slot number can be obtained.

The flowchart of the algorithm used for this purpose is given in Fig. 4. Naturally, the number of rotor slots is an integer number. However, the predicted number almost always is not an integer. In the algorithm to avoid faulty predictions, the decimal in the predicted number of slots is required to be either less than 0.1 or greater than 0.9. If this condition is not satisfied a new set of data is recorded and the prediction process is repeated.

Note that it is sufficient to run this algorithm only once during commissioning. Once this is done, it is possible to determine the speed of any induction motor accurately using the external search coil voltage as described in [2].

## 2.2   Test results

To test the proposed algorithm for determination of the rotor slot number of an induction motor, experiments have been done on several induction motors. The tests have been made first with the sinusoidal mains voltage at 50 Hz. They are repeated with a PWM inverter to determine whether the algorithm is affected due to the presence of various harmonics in the supply voltage. Results obtained on one of the test motors will be presented here. Information on the test motor used for obtaining the test results presented is given in Table 1.

Table 1. Test motor data

| Motor 1 | 3-phase, 380V, | Y-connected | 6-pole | 26 rotor slots |
|---------|----------------|-------------|--------|----------------|

In sinusoidal supply voltage tests the slip at which the motor is operating is changed by loading the motor. Figure 3 displays the FFT analysis result of one of the recordings of the external search coil voltage, placed on test motor 1. On the figure the saliency harmonics as defined by (6) are marked. Note that it is relatively easy to identify the saliency harmonics which occur in pairs.

Table 2 summarizes the sinusoidal supply voltage test results performed on test motor 1. From this table it can be observed that the done on this motor correctly predict the rotor slot number of the motor. During the tests it is observed that with the sinusoidal supply voltage, the slot number of the motor could be predicted correctly in one iteration. Tests done on other motors also confirmed this finding.

Table  2. Test motor 1 $Z_{actual} = 26$

| Slip | $Z_{estimated}$ |
|------|------------------|
| 0.20 | 25.97 → 26 |
| 0.15 | 25.92 → 26 |
| 0.10 | 26.08 → 26 |
| 0.05 | 26.09 → 26 |

## 2.3   Tests with a PWM voltage source

The algorithm proposed in this paper for the prediction of the number of rotor slots of an induction motor, is also tested while the motor is fed by a PWM. The experiments are again performed on test motor 1, at 20 Hz, 40 Hz and 50 Hz fundamental frequency. The FFT analysis result of the search coil voltage at 50 Hz is shown in Fig. 4. On the figure, both the identified saliency harmonics and the rotor slot har-
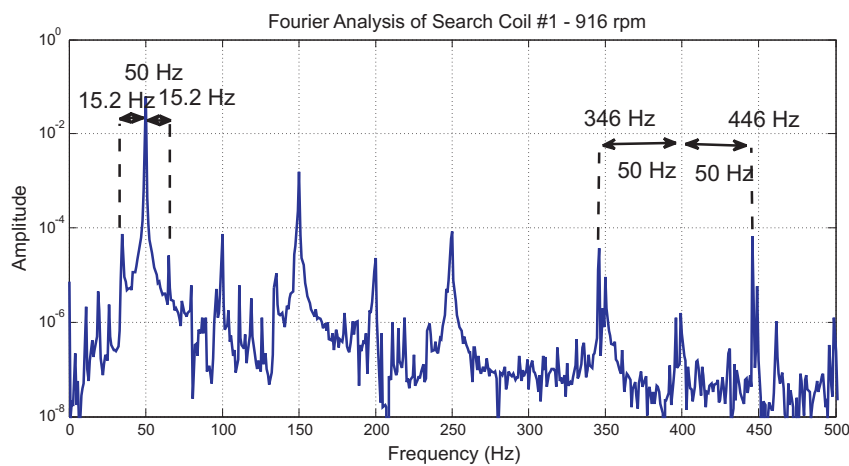


Fig. 5. FFT analysis of the external search coli voltage on test motor 1 driven by PWM supply.

monics are marked. It can be observed from this figure that many other harmonic frequencies appear in the spectrum due to the PWM modulation, as compared to sinusoidal excitation case. However, the study with PWM supply revealed that the rotor slot number still could be correctly predicted. In this case though, it is observed that more than one iteration may be necessary, especially as the fundamental frequency gets smaller.

**2.4    Conclusions**

In this paper a method for the prediction of the number of slots of an induction motor is proposed. The approach is based on FFT analysis of the induced voltage in an external search coil. It is shown that the method works well irrespective of whether the motor is driven by the mains voltage or via a PWM modulated inverter.

The study here also illustrates that the voltage induced in an external search coil, bears the information contained in the mutual flux, such as saliency harmonics or rotor slot harmonics. As shown here this information can be extracted from the induced voltage and can be used for the prediction of the rotor slot number of an induction motor. It is also possible to use this data for the prediction of motor speed. The proposed approach is simple, it can be used in a laboratory for predicting the slot number of an induction motor. Alternatively, it can be integrated to the commissioning process of an induction motor driven by an inverter.

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