Mechanical Systems and Signal Processing 23 (2009) 931–939

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Sensorless speed detection of squirrel-cage induction machines using stator neutral point voltage harmonics

Goran Petrovic, Tomislav Kilic *, Bozo Terzic

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, 21000 Split, Croatia

ARTICLE INFO

Article history:
Received 27 July 2007
Received in revised form
29 May 2008
Accepted 15 June 2008
Available online 18 June 2008

Keywords:
Induction squirrel-cage machines
Rotor slot harmonics
Sensorless speed detection

ABSTRACT

In this paper a sensorless speed detection method of induction squirrel-cage machines is presented. This method is based on frequency determination of the stator neutral point voltage primary slot harmonic, which is dependent on rotor speed. In order to prove method in steady state and dynamic conditions the simulation and experimental study was carried out. For theoretical investigation the mathematical model of squirrel cage induction machines, which takes into consideration actual geometry and windings layout, is used. Speed-related harmonics that arise from rotor slotting are analyzed using digital signal processing and DFT algorithm with Hanning window. The performance of the method is demonstrated over a wide range of load conditions.

1. Introduction

Estimators, observers, and spectral analysis methods are the frequently used techniques for sensorless speed estimation [1]. Sensorless speed estimation can provide robust, field-oriented torque control of an induction machine without a tachometer [2]. Most sensorless control schemes rely on estimation of the back EMF from stator voltages and currents, but the performance of speed estimators depends on the accuracy of the machine model and parameter estimator. Observers for speed estimation have a relatively long delay time that can limit speed detection during a transient.

In order to improve the robustness of sensorless speed estimation, parameter-independent magnetic saliency harmonics can be used to generate an accurate rotor speed signal, which can then be used to tune the parameters of a back-EMF-based observer. Saliency harmonics, which arise from rotor slotting and eccentricity, provide robust speed estimation because they are independent of time-varying motor parameters [3]. Digital signal-processing techniques can effectively extract saliency harmonics from the stator current, but they often require complex filtering techniques. Moreover, prior to digital sampling, an analog notch filter must be applied to reduce the spectral component of the fundamental frequency [2,8].

In this paper, a new method of determining rotor speed from the neutral point voltage of the induction machine is presented. The stator winding must be star connected and must have the neutral point accessible. Voltage is measured between the neutral of the machine and virtual null point realized by means of ideally balanced three resistors. In such way fundamental power supply harmonic is eliminated from measuring voltage signal and the strongest harmonic in that signal is the rotor slot harmonic. As the neutral point voltage has a value of only about 1 V, the voltage transducer is not necessary. Applying digital signal-processing techniques to neutral point voltage signal the frequency of speed-related harmonic is

---

* Corresponding author. Tel.: +385 21 305772.
E-mail addresses: goran.petrovic@fesb.hr (G. Petrovic), tkilic@fesb.hr (T. Kilic), bozo.terzic@fesb.hr (B. Terzic).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2008.06.005

calculated. The proposed method has been demonstrated to work reliably for most standard induction squirrel-cage machines over a full range of load conditions.

2. Mathematical model of machine

A mathematical model of squirrel-cage induction machines with wye-connected stator windings was derived as theoretical background for speed detection using neutral point voltage signal [5–7]. In this model the saturation effects were negligible and uniform air-gap was assumed. Although stator neutral point voltage could be obtained as a sum of three phase voltages in the stator windings' equivalent circuits without a neutral line, in the derived model the neutral point voltage is calculated as voltage drop on the equivalent big resistor, which is set in a neutral line. Neutral point voltage calculation was chosen by reason of numerical stability problems in a simulation procedure. Schematic representation of the stator windings is shown in Fig. 1 where $\ell_{\sigma sg}$ is the leakage inductance, ℓ_{asas}, ℓ_{bsbs}, ℓ_{cscs} are magnetizing inductances of stator windings and ℓ_{asbs}, ℓ_{bscs}, ℓ_{csas} are mutual inductances.

The voltage equation for stator phase *as* can be written as

$$u_{as} - u_z = R_s i_{as} + \frac{d\psi_{as}}{dt} \tag{1}$$

where u_{as} is the stator voltage of phase *as*, u_z is the stator neutral point voltage, i_{as} is the current in phase *as*, R_s is phase resistance and ψ_{as} is the flux linkages of phase *as*. The stator voltage equation in the matrix form can be written as

$$\boldsymbol{u}_s = \boldsymbol{R}_s \boldsymbol{i}_s + \frac{d\psi_s}{dt}, \quad \boldsymbol{\Psi}_s = \boldsymbol{L}_s \boldsymbol{i}_s + \boldsymbol{L}_{sr} \boldsymbol{i}_r \tag{2}$$

where $\boldsymbol{u}_s = [(u_{as} - u_z)\ (u_{bs} - u_z)\ (u_{cs} - u_z)]^T$, $\boldsymbol{i}_s = [i_{as}\ i_{bs}\ i_{cs}]^T$, $\boldsymbol{\Psi}_s = [\psi_{as}\ \psi_{bs}\ \psi_{cs}]^T$, $\boldsymbol{R}_s = diag[R_s\ R_s\ R_s]$, $\boldsymbol{i}_r$ is the subvector of rotor current, $\boldsymbol{L}_{sr}$ is the submatrix of mutual inductance, and $\boldsymbol{L}_s$ is the submatrix of stator inductance.

In general, a mutual inductance function of two windings can be described by means of coil function $z(\gamma_s)$, which describes stator winding along the stator inner surface [7]. The approach based on the winding functions makes no assumption as to the necessity for sinusoidal MMF and therefore include all the space harmonics in the machine. The coil functions of stator phases for the analyzed machine are shown in Fig. 2.

A function of mutual inductance stator windings *as* and *bs* is given by

$$\ell_{asbs} = \frac{\mu_0}{\delta} \frac{d}{2} l_e \int_0^{2\pi} z_{as}(\gamma_s)\, z_{bs}(\gamma_s)\, d(\gamma_s) \tag{3}$$

where μ_0 is the permeability constant, d the average air-gap radius, l_e the length of stator stack, and δ the equivalent air-gap.

The rotor cage can be viewed as Q_r identical and equally spaced rotor bar. For that case, there are $2Q_r$ nodes and $3Q_r$ branches. Therefore, the current distribution can be specified in terms of Q_r+1 independent rotor currents. These currents comprise the Q_r rotor loop currents (i_μ), plus a circulating current in one of the end rings (i_{er}) [7].

Fig. 3 shows the schematic representation of the rotor cage where $\mu = 1, 2, \ldots, Q_r$ is the loop number, r_{rb} the rotor bar resistance, r_{er} the rotor end ring segment resistance, $\ell_{\sigma rb}$ the rotor bar leakage inductance, $\ell_{\sigma er}$ the rotor end ring segment leakage inductance, ℓ_{rr} the magnetizing inductance of rotor loop, and ℓ_{mr} the mutual inductance between two rotor loops.

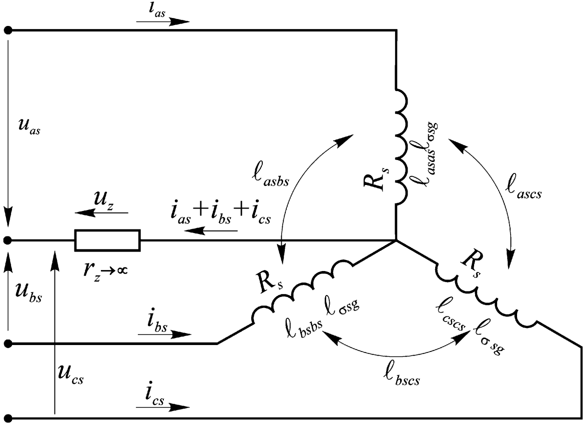

Fig. 1. Schematic representation of the stator windings.