



A Real Adaptive Classification System with DTC Voltage Source Converter for Machine Diagnostics

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ABSTRACT: Energy efficient pulse-width modulation inverters are widely used to control electrical machines accurately for process needs. The pulse-width modulation, however, has also adverse effects and produces additional losses in the motor. These losses increase the motor temperature and result in decrease of the machine power in converter use. A reliable and reasonably accurate loss model of an induction motor drive system is important for the performance prediction of a variable-speed drive. A two-level frequency converter main circuit model is coupled to a finite element method motor model. The drive model is controlled by closed-loop direct torque control. The frequency converter losses are calculated analytically, and the finite-element method motor model provides an analysis of the motor losses. The simulation results are compared with measurement results.

KEYWORDS: AC motors, data driven diagnostics and prognostics, magnetic losses, numerical simulation, power semiconductor switches pulse-width modulation converters, variable-speed drives (VSDs).

I. INTRODUCTION

The additional losses caused by PWM methods have been studied widely in the literature. Several methods have been proposed to calculate the iron losses under non sinusoidal excitation. A model is proposed for accurately estimating the iron losses in rotating electrical machines. The impact that PWM harmonics, amplitude modulation index, and switching frequency have on induction motor iron losses is investigated in with a special test motor with plastic rotor cage.

IEC is developing a new standard: IEC 60034-2-3: Rotating electrical machines—Part 2–3: Specific test methods for determining losses and efficiency of converter-fed ac machines. Converter-fed motors will get their energy efficiency classes. However, there is no generally accepted method to evaluate additional losses caused by PWM in electrical machines. The ac motor power de rating caused by PWM losses varies from 0% to 20%. It is stated that the additional losses in the motor caused by the frequency converter can increase the total motor losses up to 15%–20% compared with the grid operation.

The aim of this paper is to find drive loss estimation methods that could be used without extensive confirming measurements. It is important to assure that the motor temperature at full load does not exceed the thermal limits of the insulation and thus have a negative impact on the motor lifetime. The temperature rise of the machine is the main dimensioning boundary condition for the machine. Direct torque control (DTC) is one type PWM control strategy which can be considered as an alternative for vector control technique. DTC was proposed for ac drives by Depenbrock and Takahashi in the 1980s. The DTC has advantages of high torque response, simple design, and robustness against parameter variations. The variable switching frequency and high torque ripple are drawbacks of the classical DTC.

Numerous improvements in the classical DTC have been proposed for instance. The total losses of frequency converters are not studied widely. In a unified loss model of a converter induction machine system is presented that includes steady state as well as dynamic behavior of both machine and converter. The studies are mainly focused on IGBT bridge losses and the effect of modulation method in inverter losses. This paper provides results on how much the induction motor losses and temperature rise of the motor increase when a PWM supply is used. A 37-kW industrial totally enclosed fan-cooled (TEFC) class 130 (B) temperature rise induction motor is used in the tests. A commercial DTC frequency converter is used as a pulse width modulation (PWM) supply. The sinusoidal voltages are produced by a synchronous generator in the 25 Hz and 40 Hz points; while in the 50 Hz point, normal utility grid voltage is used. The temperature rise tests were carried out with different average switching frequencies of the inverter and with



different rotational speeds of the motor. It should be noted that the cooling conditions with different rotational speed are quite different for a TEFC-motor.

A coupled field-circuit system simulator with a closed-loop control system was used to separate and analyze the drive system losses with the sinusoidal and PWM supply. The data collected from the sensors provide an entry point for the prognostics and health management community and data mining community to perform study and in-depth analysis to obtain insights into a particular process. The readings produced by the sensors provide a wealth of information for knowledge extraction, modeling, analysis, and intelligent prediction as well as decision making. There has been a substantial amount of research conducted in diagnostics and prognostics based on sensor data. These studies, sensors are usually set to sample their readings at a predefined sampling rate. It is important to note that having a constant sampling rate is a prerequisite for most data modeling and analysis methods as it ensures time consistency and similar data distributions in the collected samples.

II. FREQUENCY CONVERTER LOSS MODELS

The losses in the frequency converter are divided into five groups: input inductor, diode rectifier, intermediate circuit, IGBT module, and extra losses. Losses in auxiliary devices such as fans are included.

A. Input Inductor Losses

The input inductors of the frequency converter dissipate power in the core and in the windings. The core losses can be divided into hysteresis losses and eddy current losses. Although the exact calculation of these losses is complicated, they can be estimated using data sheet parameters available from magnetic component suppliers or they can be defined by measurements. The input inductor losses and their frequency dependency can be modeled with the lumped parameters model, Cauer, or Foster equivalent models. In the analysis, only the inductance at nominal point, the dc resistance, and total losses at one load point are known. Therefore, lumped parameters cannot be used, and the losses have to be modeled with a single series resistance-inductance model. The total losses of the input inductor are

$$P_{\text{choke}}(t) = 3i_L(t)ESRL \quad (1)$$

where $i_L(t)$ is the instantaneous inductor line current, and ESRL is the equivalent series resistance. ESRL is calculated by using the measured current and losses of the input inductor.

B. Diode Bridge Losses

The power dissipation of a diode in forward conduction and reverse blocking state can be modeled as a function of forward and reverse leakage currents and voltages. Losses in the blocking state are negligible. Diode switching losses can be considerable but for a line frequency diode bridge rectifier, the switching losses are marginal and only the conduction losses are considered. The parameters needed for calculating the diode bridge losses are the forward voltage drop U_F and the on-state resistance R_F . The instantaneous conduction losses of the diode are

$$P_{\text{diode,on}}(t) = U_F i_{\text{diode}}(t) + R_F i_{\text{diode}}^2(t) \quad (2)$$

The diode bridge losses are six times the single diode losses.

C. Intermediate Circuit Losses

The intermediate circuit of the modeled device does not contain dc link reactors. Therefore, the losses consist of only the losses in the capacitor bank and discharge resistors. The total energy loss in a capacitor bank is a function of dielectric losses attributed to the polarizing mechanisms of the electric field on the molecular structure of the dielectric, and ohmic loss from electrodes and termination metals. Dissipative losses of the capacitor can, again, be represented by equivalent series resistance whose values or a curve of frequency dependency can be found in manufacturers' datasheets.

The number of the series and parallel capacitors in the bank has to be taken into account to calculate the capacitor bank losses correctly. The dc link current consists of a dc component IDC , harmonics produced by the diode rectifier bridge, and the switching harmonics by the IGBT-inverter bridge. The dc voltage produced by a three-phase, full-bridge rectifier carries large amounts of n times sixth-order harmonics. The average capacitor losses P_C can be written

$$P_C = nI_2C(6n)ESRC(6n) \quad (3)$$

where $I_c(n)$ is the RMS value of nth order of the capacitor current and $ESRC(n)$ is the equivalent series resistance of the capacitor for a particular frequency. ESR values for five different harmonic frequencies have been used in the loss model. At 50-Hz line frequency, these harmonic frequencies are 300, 600, 900, 1200, and 3000 Hz. The lower frequency ESR values describes the losses at harmonic currents produced by the rectifier bridge, and the highest frequency ESR value describes the losses in the switching frequency range. The resistive losses in the parallel discharge resistor are

$$P_{\text{discharge}} = U_C^2 R_{\text{discharge}} \quad (4)$$

where U_C is the capacitor RMS voltage. The intermediate circuit conduction losses are neglected in this case. Thus, the total intermediate circuit losses are

$$P_{\text{DC-link}} = P_C + P_{\text{discharge}} \quad (5)$$

D. IGBT Module Losses

The IGBT module losses comprise the conducting and switching losses of a particular device. The same loss models are used for both semiconductor devices—the IGBT and its anti parallel free-wheeling diode. For the IGBTs and diodes, the instantaneous conducting losses are

$$P_{\text{IGBT,cond}} = U_{CE0} i_m(t) + R_{CE0} i_m^2(t) \quad (6)$$

And

$$P_{\text{diode,cond}} = U_{F0} i_m(t) + R_{F0} i_m^2(t) \quad (7)$$

where i_m is motor phase current, U_{CE0} is the IGBT’s threshold voltage, R_{CE0} is the IGBT’s on-state resistance, and U_{F0} and R_{F0} are the corresponding values of the diode. For the switching losses of the IGBTs and diodes, the same linear loss model is used.

The average switching losses for a specific period of time are

$$P_{\text{IGBT,sw}} = U_{DC} U_{\text{rated}} E_{\text{sw,IGBT}} N_{\text{sw}} \quad (8)$$

And

$$P_{\text{fw-diode,sw}} = U_{DC} E_{\text{sw,diode}} N_{\text{sw,change}} \quad (9)$$

where $N_{\text{sw, change}}$ is the number of the switch changes during the specific time period. E_{sw} is the switching loss energy of a particular device given for the reference commutation voltage and current. U_{DC} and I_m are the actual commutation voltage

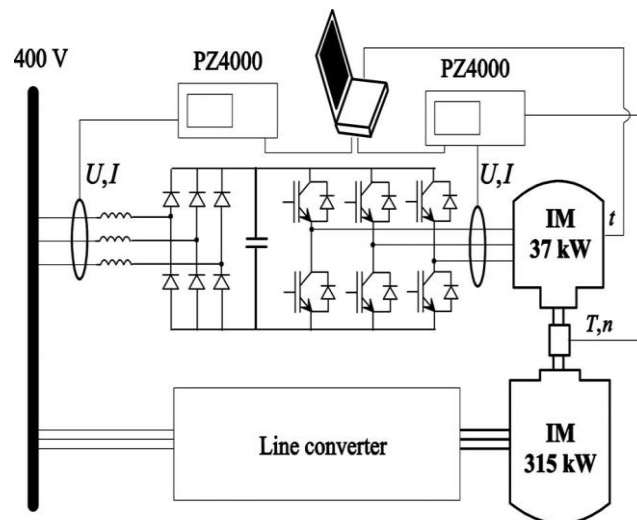


Fig1. Measurement setup



E. Auxiliary Devices Losses

The auxiliary devices losses are comprised of the inverter self-usage, for instance microcontroller, internal power supply, display, keyboard, bus-communication, digital and analog inputs and outputs, and the blower and control system power consumption. In this case, these losses are about constant. The fan speed is not load dependent. Then the system consists of monitoring parameters with the temperature based on ACS system can enhance the classification results, especially when we have relatively less training examples available. For this purpose, we changed the percentages for training and testing in the first two columns. We listed the results of six individual classifiers and our proposed ensemble based method with different machine speeds (fix the medium sampling rate at 1024 Hz in experiments). We observe that our proposed ensemble based method produces consistently better classification results across three machine speeds.

The continuous input and output power of 37-kW voltage source converter supplying 37-kW TEFC induction motor was measured with power analyzers. Rotational speed and torque were measured with a torque transducer. The induction motor temperature was measured with Pt-100 sensors. The frequency converter was set to the frequency control mode with no slip compensation. Thus, the slip of the induction motor depends on the motor load and losses. The input voltage of the frequency converter was accurately set to 400 V RMS value with a transformer. Because of the nature of the DTC, the switching frequencies used in this paper represent average values of 1-s time intervals. Four different average switching frequencies (1, 2, 3, and 3.75 kHz) were used to find out the impact of the switching frequency on the motor losses. As a load, another DTC-controlled induction machine was used.

The nominal point (n = 100%, T = 100%) of the motor always represents an overload for the motor in a normal frequency converter use. This is a result of the additional harmonic components produced by the PWM and, particularly, converter field-weakening operation in the 50-Hz operating point if six-step modulation is not used. The nominal load of the 37-kW induction machine in a 50-Hz sinusoidal 400-V supply is 239 Nm. The load value was set to 220 Nm resulting in 92% of the nominal load. With this load, the RMS value of the stator current of the inverter supplied motor is equal to the nominal RMS current in the 50-Hz operating point.

The rotational speed, torque, and the shaft power (P_{mech} in tables) were recorded by a 500-Nm Magtrol torque transducer. Both the THD and TD values provided are calculated from the measured currents. The THD50 values are calculated from 50 lowest current harmonics. The TD20000 values include all harmonic, inter harmonic, and sub harmonic components from 1 Hz to 20 kHz with 1-Hz resolution. In both values, the fundamental wave RMS value is used as a scaling factor. In the electric power measurement, the averages of 30 × 10 s samples with a 10 μs sample time were used to minimize the errors.

III. EXPERIMENTAL RESULTS

A. 25-Hz Operating Point

In the 25-Hz operating point, a synchronous generator was used to produce the nearly sinusoidal supply to the motor. The results of the discrete Fourier analysis of the voltage show that the most significant harmonic components in the voltage are in the 2nd, 3rd, 5th, and 7th order. This presents the measured DTC voltage spectra in 25-Hz operating point with different average switching frequencies. Even though the voltage waveform is not purely sinusoidal, the harmonic content

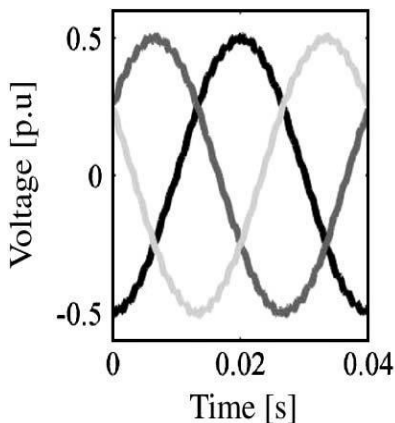


Fig.2

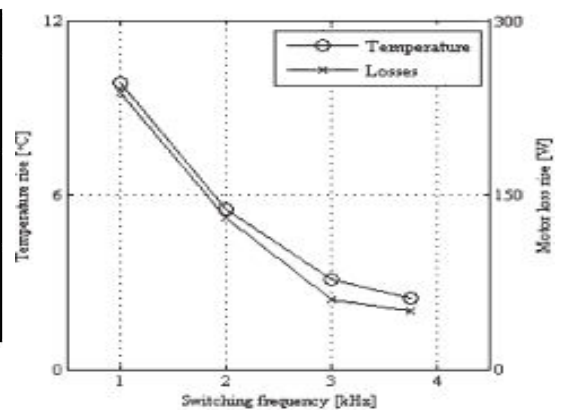
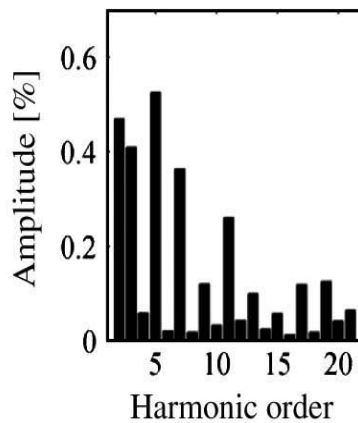


Fig.4



Fig.2. Waveforms of the 25-Hz three-phase voltages produced with a synchronous generator and their harmonic amplitudes given in percents of the fundamental wave amplitude. Fig.4. Temperature rises and changes in losses compared with the 25-Hz sinusoidal supply as a function of switching frequency

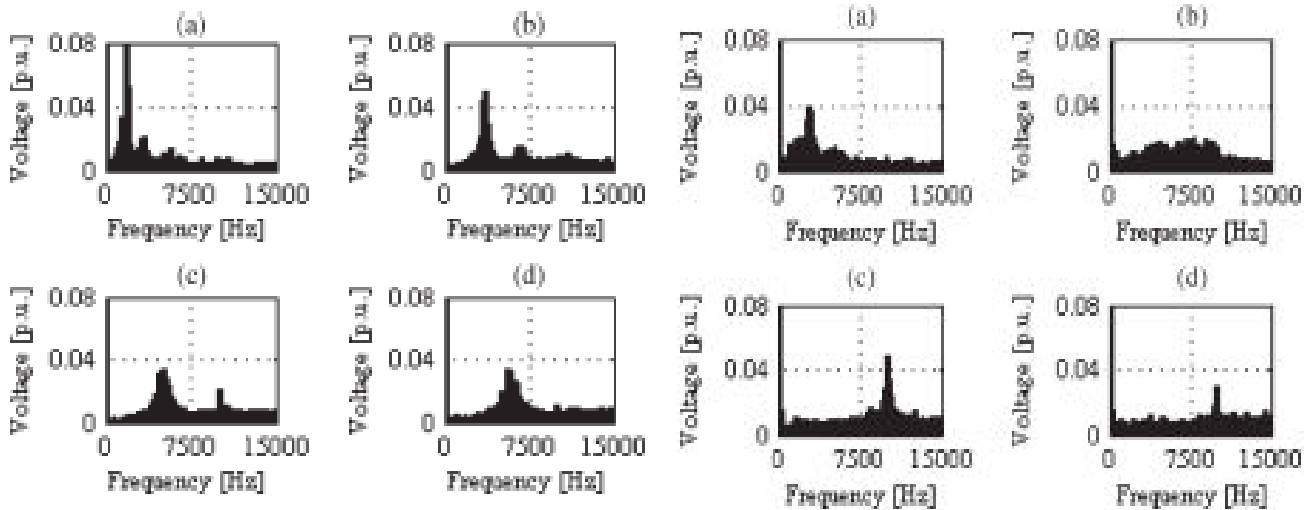


Fig.3

Fig.5

Fig.3. Measured DTC voltage spectra in 25-Hz operating point. The average switching frequencies are (a) 1 kHz, (b) 2 kHz, (c) 3 kHz, and (d) 3.75 kHz Fig.5. Measured DTC voltage spectra in 50-Hz operating point. The average switching frequencies are (a) 1 kHz, (b) 2 kHz, (c) 3 kHz, and (d) 3.75 kHz.

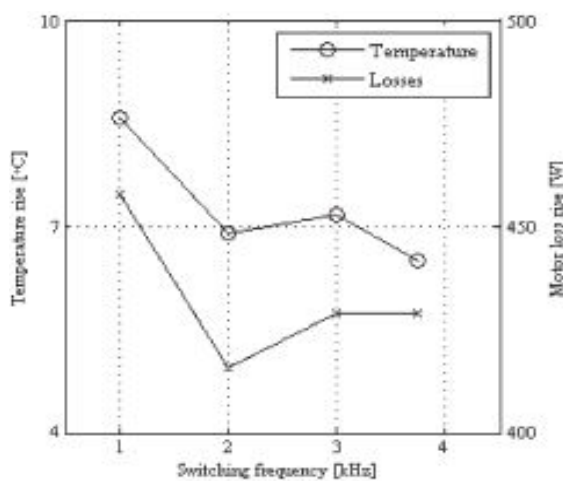


Fig.6

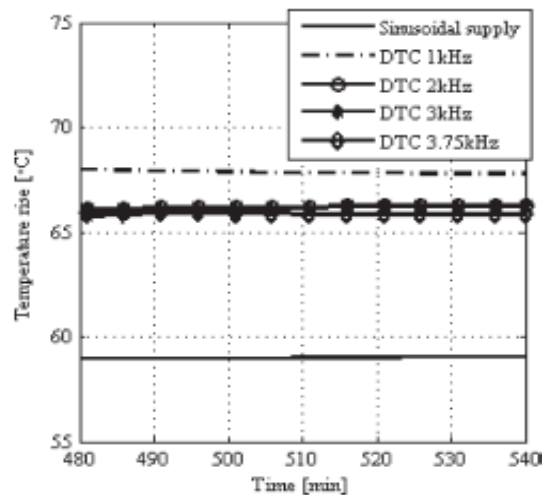


Fig.7

Fig.6. Temperature rise differences and loss changes compared with the 50-Hz sinusoidal supply as a function of average switching frequency in the DTC supply. Fig.7. Temperature rises at the end of the 50-Hz temperature rise test. of the voltage is minimal compared with the voltage produced with PWM. The THD50 value of the voltage is 0.89%. The motor temperature rises during the last 60 test minutes are shown. The difference between the sinusoidal and frequency converter supply in the motor temperature rise and motor losses is shown as a function of the switching frequency.

B. 50-Hz Operating Point

In the 50-Hz operating point, the same load and switching frequencies were used as in the 25-Hz and 40-Hz point. The grid voltage THD50 is 1.24%. It shows the voltage spectra for different average switching frequencies. In frequency converter use, the 50-Hz point is either in the field weakening or over modulation range because of the voltage losses in



the frequency converter input rectifier and filters. In addition to the voltage losses, the converter selects a suitable voltage reserve to be able to control quick load changes. The mechanical power remains almost constant in all measurements when the frequency converter supply is used. The inverter output power decreases as the switching frequency is increased. As shown in the figure in the 50-Hz point, the temperature rise of the machine increases roughly by one degree Celsius against 12 watts of losses. The temperature rises in at 2, 3, and 3.75 kHz switching frequencies are almost constants and so are the measured losses. The increase in the motor losses is 18–20% in the frequency converter supply compared with the sinusoidal supply. The THD values in Tables II–IV show that in the 50-Hz operation point, the currents in the frequency converter supply have a higher harmonic content than in 25-Hz and 40-Hz operating points. In frequency converter supply, this is an outcome that results from the field-weakening operation. The DTC controller leaves a voltage reserve; therefore, the studied converter does not use the full modulation index and hence the field weakening starts at 45 Hz. Another reason of the higher harmonic content is that the inverter can, naturally, with the same switching frequency use only half of the number of switching's per one fundamental wave when compared with the 25-Hz point, therefore, resulting in a more coarse voltage waveform. The motor temperature rise with 3-kHz switching frequency is smaller than with 3.75-kHz switching frequency, although the direct loss measurement gives smaller losses at higher switching frequency.

IV. CONCLUSION

Frequency converter losses are difficult to measure accurately because of the distorted input and output currents and output voltages of the converter. Extra care should be taken at 50-Hz operation with a frequency converter. An accurate efficiency result of the variable-speed drives requires a very constant load and line voltage level as well as good measuring equipment.

The differences between the simulated and measured efficiencies are so small that they cannot be separated from the error originating from measuring setup. The additional losses are a function of rotational speed and switching frequency. In this case, the motor efficiency drop was 0.2%–1.7% units when PWM supply was used compared with the sinusoidal supply depending on the switching frequency and operating point of the motor.

Furthermore, the simple, linear loss models used for frequency converter loss calculation are a source of error and may not give accurate results in every operating point of the converter. For the scope of this paper, to obtain the drive system losses without any measurements, the loss models are well suitable. The coupled circuit simulator used in this study gives encouraging results in the VSD simulation. The ability to estimate drive system efficiencies with a reasonable accuracy without confirming measurements is a powerful resource in scientific and practical work.

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