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# Behavior of three-phase induction motors with variable stator coil winding pitch

R. Deshmukh,<sup>a)</sup> A. J. Moses, and F. Anayi

Wolfson Centre for Magnetics Technology, Cardiff University, P.O. Box 925, Newport Road, Cardiff CF24 0YF, United Kingdom

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A pulse-width modulation (PWM) inverter and sinusoidal output voltage supplies feeding four different chorded three-phase induction motors were tested for low-order odd voltage harmonic components and efficiency at different loads. The total harmonic distortion due to the third, fifth, and ninth harmonics was lowest in a motor with 160° coil pitch energized by both sinusoidal and PWM voltages. The efficiencies of the motor with the short-chorded winding were as much as 5% and 16% higher than that of the full-pitched motor under sinusoidal and PWM excitation, respectively, due to harmonic cancellation. © 2006 American Institute of Physics. [DOI: 10.1063/1.2170062]

## I. INTRODUCTION

Three-phase induction motors are widely used in industry with sinusoidal and pulse-width modulation (PWM) supplies for variable speed drives. Unfortunately, losses in inverter-fed machines are always greater than in those operating under sinusoidal voltage supplies. In some cases this requires derating of the motor.<sup>1</sup> Rotating machines are considered as a source of harmonics<sup>2,3</sup> because the winding is embedded in slots and the magneto-motive force (mmf) can never be considered sinusoidal. Low-order voltage harmonics have a larger impact on three-phase induction motors than that of high-order harmonics.<sup>4</sup> One method of reducing the low-order harmonics is to adopt chording (fractional pitch) of the stator winding. The chording factor (pitch factor)  $K_p$  is the amount by which short pitching each coil of a lap winding would reduce the back emf, assuming flux that the per pole is unchanged.  $K_p = \sin(\beta/2)$ , where  $\beta$  is the actual coil span in electrical degrees.

This paper compares the effect of chording on three-phase squirrel-cage induction motors fed from a three-phase sinusoidal supply with that when fed from a PWM voltage supply.

## II. CONFIGURATION OF THE EXPERIMENTAL SYSTEM

A three-phase, 746 W, four-pole squirrel-cage induction motor was connected to either a three-phase sinusoidal of 240 V, 50 Hz rms supply or to a PWM inverter with the same output at a switching frequency of 4 kHz. A digital power analyzer was used to measure the stator voltage harmonics, stator voltage, stator current, and input power. Four commercial motors were tested, each was mounted in turn on a drive bed and loaded by an eddy current brake. The applied torque was measured using an inbuilt torque sensor on the drive bed.

The stator windings of four motors were rewound with different coil pitches. The coil pitches of motors designated

as M180, M160, M140, and M120 were 180° (full pitch), 160°, 140°, and 120°, respectively. All the windings were simple lap configurations. Figure 1 shows the configuration of the three-phase double-layer windings embedded in the slots. The letters ( $x$ ,  $y$ , and  $z$ ) indicate conductors corresponding with the phases  $X$ ,  $Y$ , and  $Z$  and their vertical positions designate conductors in the same slot. The direction of the stator current is indicated by  $x$ ,  $x'$ , etc. The pole pitch is nine slots with three conductor slots per pole per phase. The slot pitch is 20° so for a full pitch winding the coil pitch is 180°. If the coil pitch is shortened by  $1/n$  of the pole pitch, where  $n$  is an integer, then the  $n$ th voltage harmonic will be suppressed or the harmonics near to  $n$  will be lower because of the harmonic cancellation at that coil pitch.<sup>5</sup>

The motors were loaded with an applied torque from 1.0 to 6.5 N m (full load torque was 5.5 N m). The power and harmonic analyzer that employs the fast fourier transformation to obtain the voltage harmonic components with sinusoidal and PWM supplies was used. The repeatability of torque measurements was found to be  $\pm 0.75\%$  over the full measurement range.

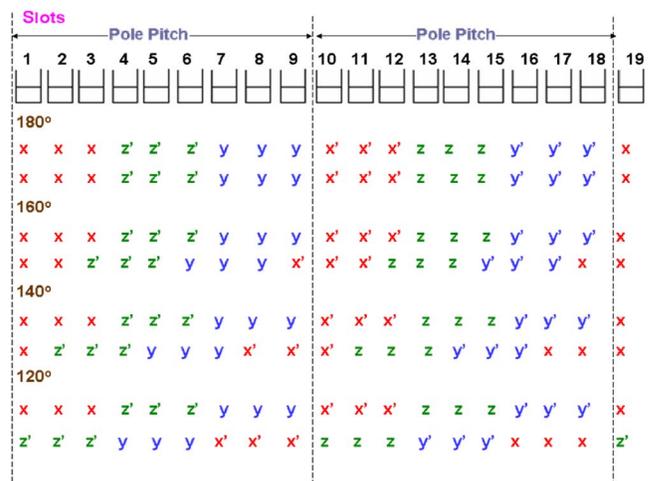


FIG. 1. (Color online) Three-phase double-layer winding configuration in stator slots.

<sup>a)</sup>Electronic mail: deshmukhr@cf.ac.uk

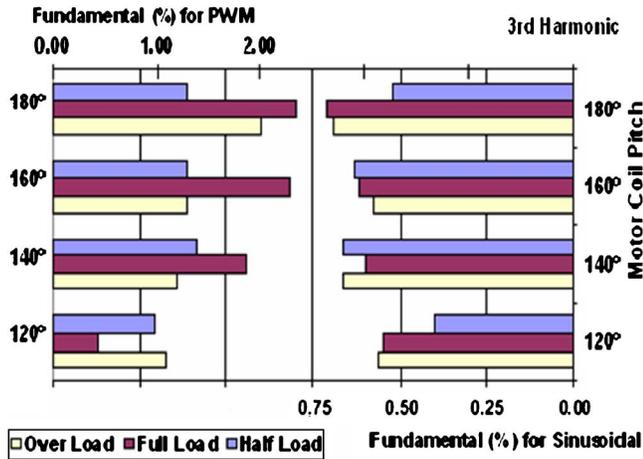


FIG. 2. (Color online) Third-harmonic voltage at different loads under sinusoidal and PWM voltage supplies.

III. RESULTS

As the full pole pitch is 180° and for motor M120 the coil pitch is reduced by 60° (1/3 pitch), the third voltage harmonic should be reduced compared to other motors with different coil pitches under both sinusoidal and PWM voltage supplies at half load (375 W), full load (746 W), and overload (880 W), as shown in Fig. 2. If we consider the motor M140, the coil pitch is reduced by 40° (1/4.5 pitch), so the fifth-order voltage harmonic is reduced with the PWM supply but with the sinusoidal supply the motor M160 has a lower fifth voltage harmonic, as seen in Fig. 3. In motor M160 the coil pitch is reduced by 20° (1/9 pitch), the ninth harmonic is less than in the other motors, and this reduction of the ninth voltage harmonic is more with the sinusoidal supply, than with the PWM supply as shown in Fig. 4. This is because the significant number of pulses with the PWM supply increases the amplitude of the lower-order harmonics<sup>6</sup> and thus the amplitude of the ninth harmonic is higher with the PWM supply.

If we consider motor M180, the upper and lower coils in each slot have the same phase and direction of currents, as shown in Fig. 2. But for motor M160 slot numbers 3, 6, and

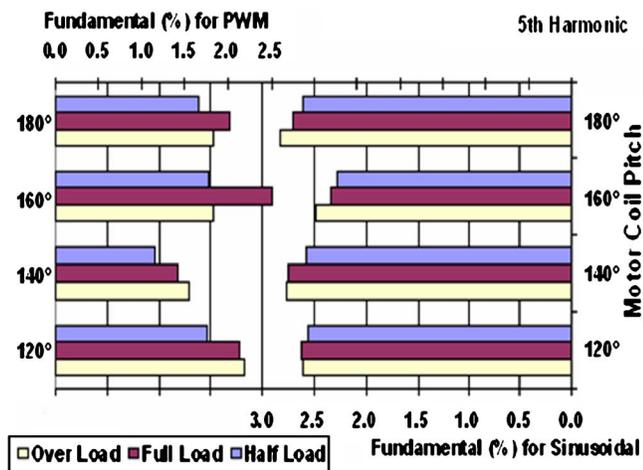


FIG. 3. (Color online) Fifth-harmonic voltage at different loads under sinusoidal and PWM voltage supplies.

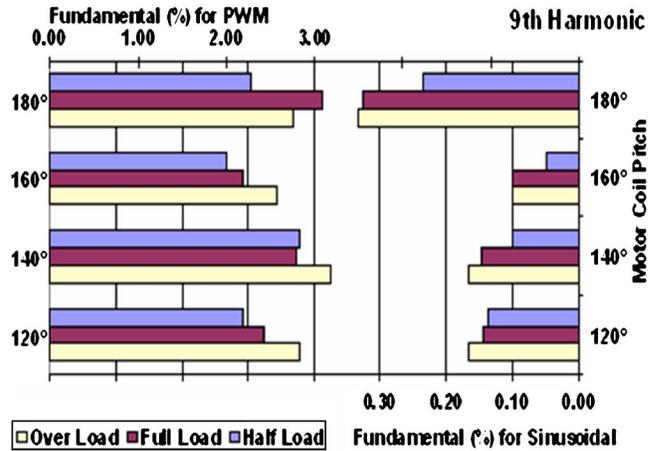


FIG. 4. (Color online) Ninth-harmonic voltage at different loads under sinusoidal and PWM voltage supplies.

9 have different phase conductors with opposite currents, thus the overlapping between adjacent phase bands benefits their air gap flux pattern by canceling the harmonics.<sup>7</sup> This overlapping is higher in motor M140 and higher again in motor M120. Hence, there are greater possibilities of harmonic cancellation in motors M140 and M120. However, if we note the total harmonic distortion (THD) due to the third, fifth, and ninth harmonics of the four motors at the three different loads, motor M160 has lower harmonics than the other motors under both sinusoidal and PWM voltages, as shown in Fig. 5. This is due to the aiding of the low-order odd harmonics (third, fifth, and ninth) due to the overlapping of the mmf wave caused by short chording the coils. For example, the aiding of the fifth and ninth harmonics is more than the suppression of the third harmonics in motor M120 under both sinusoidal and PWM supplies due to the amplitude of the harmonic voltage.

Motor M160 has the highest efficiency of all the motors under sinusoidal supply, for example, 5% higher than that of the full pitch motor, as seen in Fig. 6. This is because under sinusoidal supply, the THD for the lower-order harmonics was less for motor M160. In the case of PWM supply, motor M120 has the highest efficiency of all the motors, for ex-

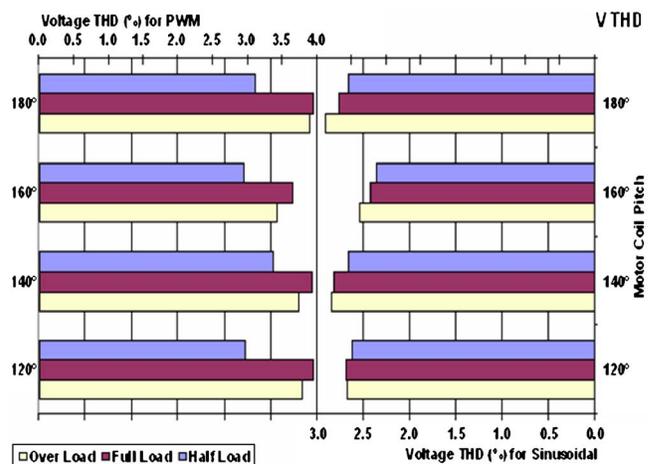


FIG. 5. (Color online) Voltage THD under sinusoidal and PWM voltage supplies.

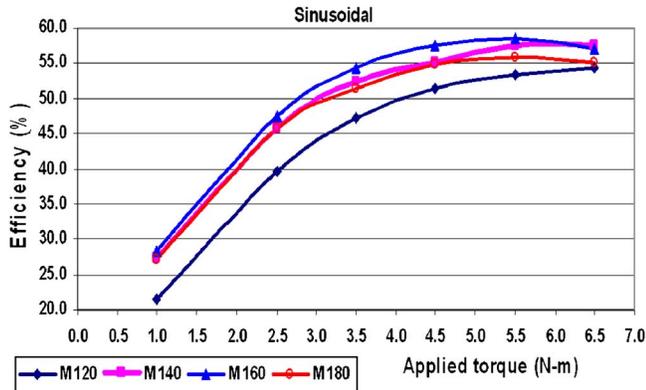


FIG. 6. (Color online) Efficiency of all motors at different loads with sinusoidal voltage supply.

ample, 16% higher than that of the full pitch motor shown in Fig. 7. This is due to the presence of lower- and higher-order harmonics in the PWM supply which increases the harmonic cancellation due to the overlapping of the adjacent phase bands.

#### IV. CONCLUSIONS

The low-order harmonics in the stator voltage of the three-phase induction motors fed by a PWM voltage source can be reduced by short chording the stator winding in the same way as for the sinusoidal excitation. The phenomenon of chording by  $1/n$ th of pole pitch to suppress the  $n$ th harmonic was particularly followed by motors with coil pitches of  $120^\circ$  and  $160^\circ$ . The motor with a coil pitch of  $160^\circ$  is considered efficient under the sinusoidal voltage supply and the motor with a coil pitch of  $120^\circ$  is found more efficient

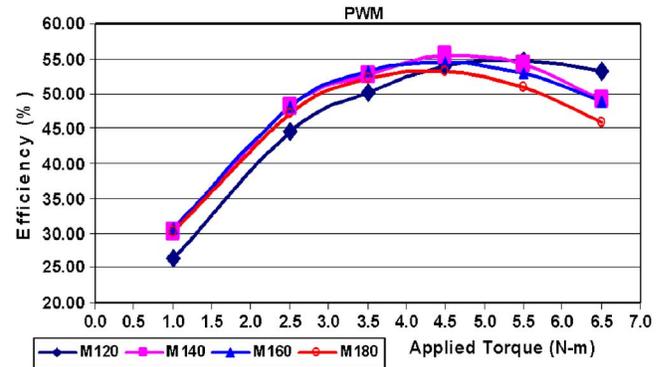


FIG. 7. (Color online) Efficiency of all motors at different loads with PWM voltage supply.

when energized with the PWM voltage supply and the increases are 5% and 16%, respectively, when compared to that of a full pitch motor. There is a significant chording effect at full load and overload under PWM as well as sinusoidal supplies for a three-phase induction motor.

<sup>1</sup>A. J. Moses, J. Leicht, and F. Anayi, Seventh International Workshop on One and Two-Dimensional Magnetic Measurement and Testing (Physikalisch-Technische Bundesanstalt Braunschweig, Berlin 2002), 81, p. 37.

<sup>2</sup>Harmonics Working Group and IEEE PES T and D Committee, IEEE Transactions on Power Delivery, 19(4), October 2004, p. 1802.

<sup>3</sup>IEEE Report No. 84 EHO 221-2-PWR (Power System Harmonics Tutorial, Power Engineering Society, New York, 1984).

<sup>4</sup>C. Y. Lee and W. J. Lee, IEEE Transactions on Energy Conversion, 14(2), June 1999, p. 193.

<sup>5</sup>M. G. Say, *Alternating Current Machines*, 5th ed., (Longmans, London, 1983), p. 95.

<sup>6</sup>S. Ekram and B. Sarkar, J. Inst. Eng. (India), Part EL-1 85, p.1 (2004).

<sup>7</sup>*AEMT Good Practice Guide* (Association of Electrical and Mechanical Trades, St. Louis, Missouri, 1998), p. 30.