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Induction Motor Dynamic Control

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***Abstract*—Induction motors consume over half of the electric energy produced. Much of it is wasted because efficiency drops when induction motors are not fully loaded. Typically, motors are oversized to meet peak load demands and are inefficient for lesser loads. This paper describes a system for dynamically matching the motor to the load by increasing stator turns for light loads. This decreases stator current and power absorbed from the power line. Stator turns are adjusted in half cycle increments. This results in a wide range of possible average adjustments and quick response. Dynamic power control increases efficiency and improves power factor.**

***Keywords* — Induction motor, stator winding, energy saving, motor efficiency, smart motors, power factor, dynamic matching, variable-load motors, electric motor, energy economics, energy engineering, electric drives**

I. INTRODUCTION

In 2008 20×10^{12} kilowatt-hours of electricity were consumed worldwide [1]. Assuming a cost of $0.10 per kilowatt-hour results in $2 trillion spent on electricity worldwide in 2008. More than half of all electrical energy is consumed by induction motors [2]. Much is wasted. Induction motors are inefficient when they are not sufficiently loaded. Typically, motors are oversized. This is due to the fact that motors are sold in fixed frame sizes. Designers, out of caution prescribe larger motors than are necessary. Motors are designed so that they will operate at low line voltages and are oversized for normal or higher line voltages. On average, the motors operate at 60% of their rated load [2]. Lightly loaded motors have poor power factors. The low power factor of motors, poorly matched to their loads, causes power factor problems for industries running many motors. When a motor is loaded, input power is transmitted to the load. In spite of winding and core losses, efficiency is high. When the output load power is reduced, winding and core losses remain. This results in lower efficiency for lighter loads.

Dynamic power control of induction motors [3] provides promising methods that modify the motor, matching it to the load. This allows motors to operate close to full load at all times. A microcontroller responding to user inputs and/or feedback from the motor, controls switching to determine motor power, as shown in Fig. 1.

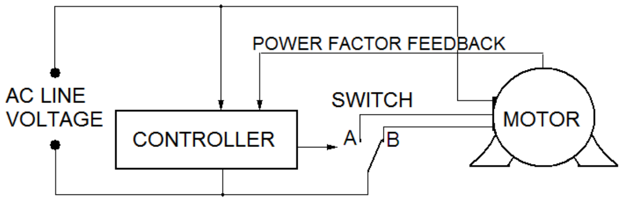

Fig. 1 A microcontroller determines the proportional switching times for accurate power control

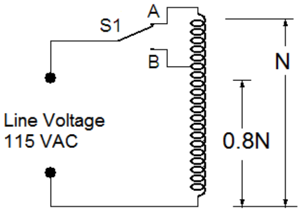

Fig. 2 The stator winding is configured as an autotransformer. The switch, S1, is shown in the "A" position where 100% of the coils are energized. When the switch is in position "B" 80% of the coils are energized. The current drawn from the power line and therefore the power is greater when the switch is in position "B".

A unique aspect of the approach is the dynamic switching. Power is adjusted in half-cycle increments. This permits a variety of average powers with just two stator taps. A drawback is that the stator has to be wound with taps.

Efficiency improvements will yield significant savings. This paper describes simple models and experimental data that predict power savings.

The motor is modified. Motor modifications are updated every half cycle. This differs from techniques that modify the power source driving the motor such as power inverters that convert the AC line voltage to DC and then regenerate an AC voltage from the DC [4]. With inverter driven motors, the motor is driven by the AC voltage output of the inverter. This power source can be any desired voltage and frequency [4]. Motor operating parameters such as efficiency, speed and torque are sensitive to power source voltage and frequency. Sinusoidal inverter output can be achieved by pulse width modulation of a KHz carrier. The carrier is filtered out leaving a sinusoid of the desired frequency and amplitude. The switches used to rectify the power line and the switches used to regenerate the desired AC voltage produce electromagnetic interference (EMI). Lowpass filters are required at the inverter's input to prevent noise from propagating on the AC power line. Techniques have been proposed to generate drive voltages and frequencies that produce maximum efficiency [6][7]. The dynamic power control described in this paper modifies the motor to improve its operation. Fernando et. al. [6] investigated a motor modifying approach. They found that three phase induction motors operating under varying loads are more efficient when the stator winding is switched from a delta to a star configuration when loads are light. Others have found that increasing the number of stator turns for light loads improves efficiency and power factor [9][10][11].

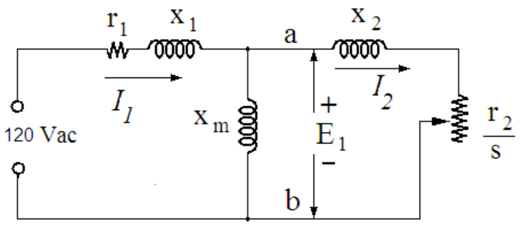

Fig. 3 Induction motor circuit model is shown. Power delivered to the load is incorporated into the resistance r2/s.

II. MOTOR MODEL

Prediction of dynamic control is obtained using a simple motor model. The interaction of the stator and the rotor windings is similar to that of the primary and secondary windings of a transformer. The rotor windings act like the secondary. The speed of the rotor relative to the rotating magnetic field is $n_1 - n$. If the rotor were rotating at synchronous speed, n_1, it would see a constant magnetic field (zero frequency). There would be no voltage induced in the rotor and no rotor currents. The frequency of the magnetic field seen by the rotor is a fraction, s, of the frequency seen by the stator. The voltage induced in the rotor windings is proportional to the slip, s.

Impedances attached to the secondary are referred to the primary. Rotor resistance r_2 and reactance x_2 are referred values from the rotor to the stator. Power delivered to the load is incorporated into the power dissipated in r_2.

An equivalent circuit for the motor is shown in Fig. 3. x_1 is the stator leakage reactance. r_1 is the stator resistance. x_m is the magnetization reactance. It accounts for the current needed to set up the magnetic field. Once the magnetic field is set up, additional stator current is offset by rotor currents that act, by Lenz's law, to minimize changes in the magnetic field. The motor equivalent circuit is essentially the same as that of a transformer with the rotor impedance, seen by the stator, varying as the square of the number of stator turns. Impedance matching is achieved by varying the number of stator turns

III. POWER CONTROL

A. *Quasi Static Control*

Power control is achieved by switching between stator taps to change the number of stator turns. For quasi static control stator changes are infrequent. In a situation where the motor is idling the number of stator turns would be increased during the time the motor is lightly loaded. A simplified model predicts power savings.

Configuring the stator as an autotransformer as shown in Fig. 2, allows the power to be controlled. The back emf induced in the stator is,

$$E_1 = N\frac{d\lambda}{dt} \tag{1}$$

where λ is the air gap magnetic flux and N is the number of stator turns. If we ignore the small voltage produced by leakage flux, the back emf, given by Equation 4, equals the applied line voltage. Since the line voltage is constant, the magnetic field varies inversely with the number of turns, N. The voltages and currents induced in the rotor are proportional to the magnetic field and also vary inversely with the number of turns. The force on the rotor and the torque are proportional to the product of the rotor currents and the magnetic field. Thus, torque is inversely proportional to the square of the number of turns. Power is torque multiplied by angular velocity. At a given speed, the power delivered is inversely proportional to the square of the number of stator turns. This is illustrated in Fig. 5.

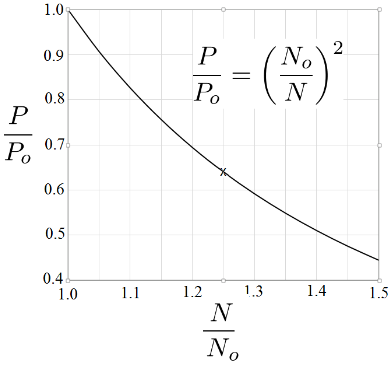

Fig. 4. Power varies inversely as the square of the number of stator turns. In the design discussed here, the number of turns is increased by 25% to 1.25 N_o. Power decreases to 0.64 P_o, a decrease of 36%.

$$\frac{P}{P_o} = \left(\frac{N_o}{N}\right)^2 \tag{2}$$

where N_o is the reference number of stator turns, N is a different number of turns, and P_o is the input power when the number of stator turns is the reference number. When $N/N_o = 1.25$, $P = 0.64\ P_o$.

B. Dynamic Control

With dynamic power control, stator turns are adjusted in response to performance parameters such as power factor. The stator configuration is updated every half cycle. Stator switches connect when the voltage is zero and disconnect when the stator current is zero. Current flow is not interrupted. This prevents troublesome voltage spikes and radio frequency interference (RFI).

For example, consider a stator with a connection at 80% of the turns and a connection at 100% of the turns. Taking 80% as the reference number of turns, when the stator is switched to 100%, power decreases by a factor of 0.64, as shown above. For dynamic power control this change lasts for half cycle multiples of the power line frequency.

Consider a design where the stator turns are increased for n cycles in every 8 cycles of the AC line. Since current varies inversely as the square of the stator turns, during the time the stator turns are increased by 25% to 1.25 times the reference number, the current will decrease to 64% of the reference current. Since the line voltage is constant, power will decrease to 64% of the reference power. If the power losses are attributed to stator current, the power loss will decrease by 36%. Power loss is inversely proportional to the square of the number of stator turns.

$$\frac{P_L}{P_{Lo}} = \left(\frac{N_o}{N}\right)^2 \qquad (3)$$

where P_L is the power loss and P_{Lo} is the power loss when the number of stator turns is the reference number, N_o

Consider dynamic switching where the power is reduced for n cycles out of 8. For $N_o / N = 1/1.25$, $P_L / P_{Lo} = 0.64$. The power saved is $P_{Lo} - P_{Lo} = 0.36\ P_{Lo}$ The power averaged over 8 cycles is

$$P_{ave} = \left[1 - 0.36\left(\frac{n}{8}\right)\right] P_o \qquad (4)$$

where n is the number of cycles out of 8 that the stator turns are increased.

If n is 8 the average power is decreased by 36%.

The percent power saved is the decrease in power divided by P_o. For this example, the power saved is,

$$P_{saved} = \frac{P_o - Pave}{P_o} = 0.36\left(\frac{n}{8}\right) \qquad (5)$$

where P_o is the power with 80% of the stator turns energized. Fig. 10 shows that measured data is in agreement with (5).

C. Power Factor Feedback

The Dynamic Power Controller determines the motor load by measuring the power factor. The power factor parameter is used to control the tapped stator winding switch. The power factor is measured by determining the time between the supply voltage signal zero crossing and the corresponding motor current signal zero crossing. This time represents the phase delay of the current relative to the voltage. It is used in a lookup table to calculate the corresponding cosine of the angle which is the power factor.

The highest power factor is near full load. Increasing the number of stator turns weakens the motor resulting in a lower full load power. The closed loop feedback of the controller, using power factor measurement, seeks to operate the motor at high power factor.

D. Porportional Switching

Possible proportional switching sequences are shown in Fig. 6.

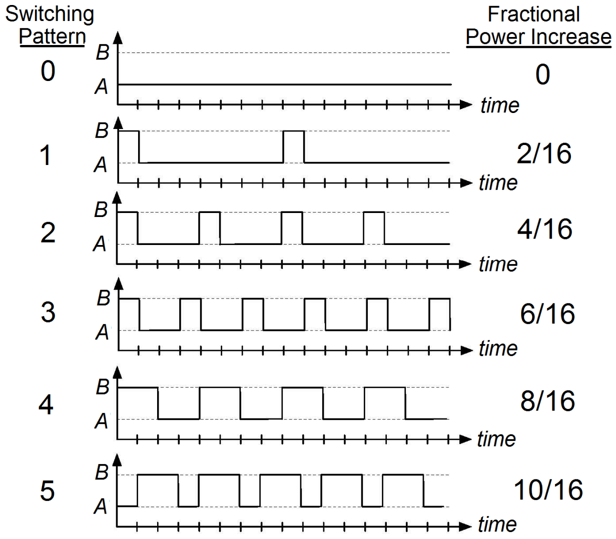

Fig. 5 Proportional Control of one out of eight cycles using half cycle switching is shown. Thus, the controller can produce eight discrete power levels from 64% to 100% rated full power. A and B refer to the switch positions shown in Fig. 2.

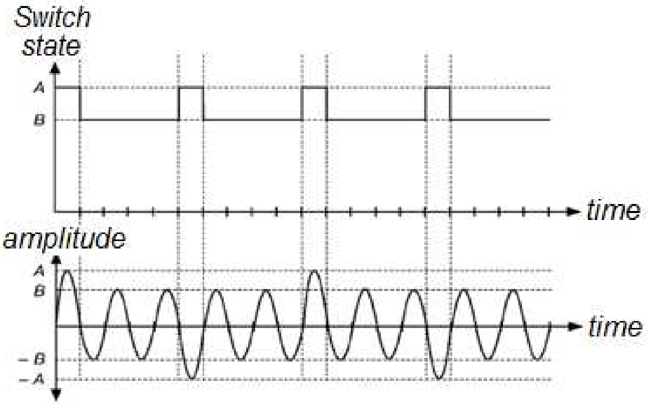

Fig. 6 Proportion Control Diagram illustrates how we can proportionally shift from maximum to minimum power. The software program can select 8 RMS power increments between minimum and maximum power. The large peaks provide 100% of the power and the smaller peaks 64% of the power. By proportional switching we can obtain eight steps from 64% to 100%.

IV. EXPERIMENT

Measurements were taken. A diagram of the experiment is shown in Figure 7. Figure 8 is a photograph of the set up. A microcontroller determined the stator configuration. A rewound 4-pole Baldor L1200 motor with a tap on each pole at 80% of the turns was used. N_o represents 80% of the turns. $1.25N_o$ represents 100% of the turns. A Fisher-Price 00968-9002 12VDC motor with a multiple 10 ohm resistive load was used to load the induction motor. The current, voltage and power into the motor were monitored. The current, voltage and power output to the resistive load were also monitored. Eight different stator configurations were studied. Stator turns were switched from N_o turns to 1.25 N_o turns in eight different time sequences. Switching was done in full cycle increments. The microcontroller dynamically switched the number of stator turns from N_o to 1.25 N_o for n out of 8 cycles.

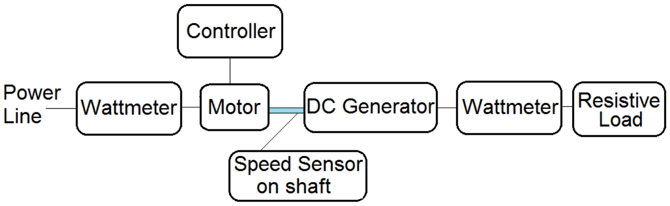

Fig. 7 A block diagram of the experiment is shown.

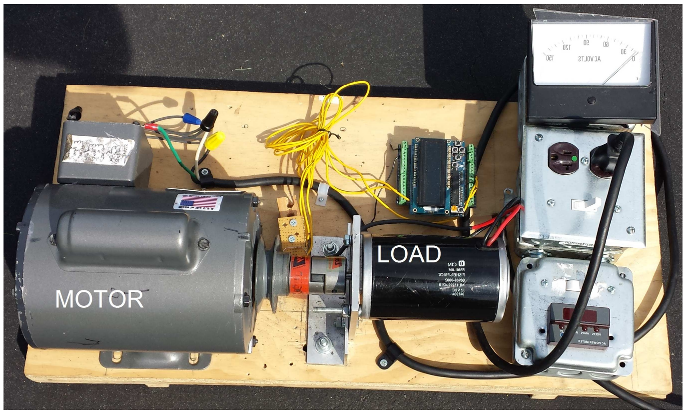

Fig. 8 The test set up is shown.

Fig. 9 shows the power consumed by the motor as a function of load for three different dynamic stator configurations. A is the standard number of stator turns, N_o. The motor is over designed and consumes more power than necessary. In configuration B the number of turns is increased by 25%. Power consumed drops significantly. Configuration C represents dynamic switching from configuration A to configuration B for 4 cycles out of 8. Savings occur at low loads. The curves tend to converge for higher loads where there is less opportunity for increased efficiency. Fig. 10 shows measured power saved when the number of stator turns are increased for n cycles out of 8. The percent power saved is greater when the motor load is lighter and the motor is less efficient. The percent power saved is proportional to the time spent at the larger number of stator turns. For light loads, increasing stator turns by 25% results in approximately a 36% increase in power saved as shown in (5) and Fig. 10.

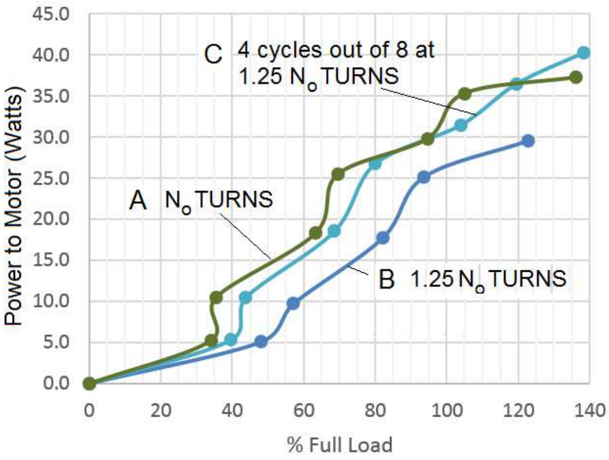

Fig. 9 A plot of measured power delivered to the motor for 3 different stator configurations is shown. The data in curve C describes dynamic switching between No turns and 1.25 No turns.

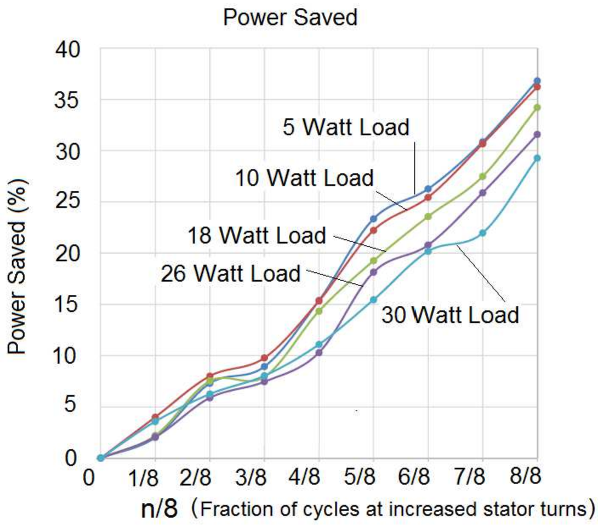

Fig. 10 Measured power saved as a function of the dynamic switching between two stator configurations is shown.

V. SUMMARY

Induction motors consume over half of the electric power produced. Much is wasted because motors are not matched to their loads. Motors are chosen for operation under worst case conditions of low line voltage and maximum load. This results in most motors being oversized. They are lightly loaded under normal operating loads and voltages. The efficiency of lightly loaded induction motors is improved by increasing the number of stator coil turns. Dynamic Power Control adjusts the number of stator coils to match the motor to its load. Matching to a variety of loads, constant and varying, is possible. An intelligent controller determines the stator configuration based on feedback, such as power factor feedback. The stator is dynamically updated in multiples of half cycles. Windings are switched out when their current is zero and switched back in when the voltage is zero, using for example, triacs. Current is not abruptly interrupted. This switching technique eliminates voltage spikes and radio frequency interference. Power factor improves when efficiency improves. Significant power is saved by dynamically increasing stator turns for light loads. Bursts of torque can be achieved by dynamically decreasing stator turns.

The Dynamic Power Controller delivers the minimum necessary power to safely drive a load regardless of load or line variations.

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