Autocycle Motor

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January 2, 2015

The Autocycle Motor is a system for controlling motor power. A microcontroller responding to user inputs and/or feedback from the motor, controls a switch to determine motor power, as shown in Figure 1.

This concept uses the windings of the motor to simulate an autotransformer. Two coils are in series. One with 90% of the coils and the other with 10% of the coils. This configuration is similar to an autotransformer. The line voltage can be switched between the 90% and the 100% coil. Please note: that maximum power is applied when the line voltage is across the 90% coil.

We can use the cycle saver concept to provide greater accuracy of control, by switching the 110 Vac between turns at computed accuracies. This is illustrated in Figure 2. By switching the switch, S1, we can transfer the line voltage from 90% of the coils to 100% of the coils. By controlling the duration of the time that the switch, S1, is at point "A" and at point "B", we can control the rms energy that is delivered to the motor to a finer degree.

The controller is similar to the cycle saver. It adjusts the timing and the switching rate, correcting for line voltage. It connects at zero voltage and interrupts at zero current.

Reducing the number of stator turns increases the current and power absorbed from the AC line. The torque developed by the motor also increases.

The cycle saver principle is used to control the switch. The switch conducts for short periods of approximately one half cycle of the AC line. When the switch conducts, stator current flows through it. The switch opens when the stator current is zero. This prevents troublesome voltage spikes and radio frequency interference (RFI). The average motor power is varied by controlling the number of half cycles per second that the switch is conducting.

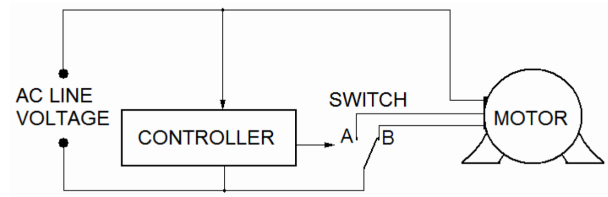

Figure 1 A microcontroller determines the timing of the autocycle switch.

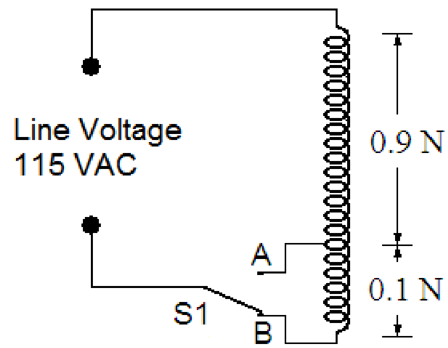

Figure 2 The stator winding is configured as an autotransformer. The switch, S1, is shown in the "B" position where 100% of the coils are energized. When the switch is in position "A" 90% of the coils are energized.

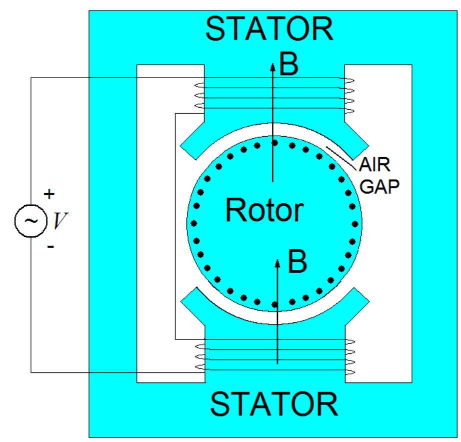

Figure 3 Simplified representation of a single phase induction motor

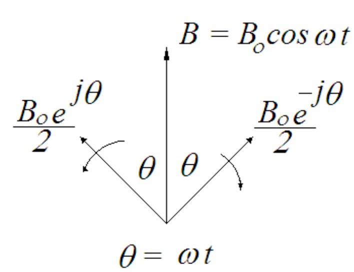

Figure 4 The air gap magnetic field is composed of two components, one rotating clockwise and the other rotating counterclockwise.

Induction Motor

A representation of a single phase induction motor is shown in Figure 3. The line voltage ***V*** causes a current to flow in the stator winding. This current creates a magnetic field, *B*. The magnetic flux flows through the stator, rotor and the air gap.

Figure 4 shows a representation of the sinusoidally varying magnetic field, $B_o cos(\omega t)$. The magnetic field is in the vertical direction. It consists of two components, one rotating clockwise and the other rotating counterclockwise. Motor operation requires a rotating magnetic field. Rotor currents interacting with the rotating magnetic field generate the motor torque.

The physical mechanism that generates rotor torque is depicted in Figure 5. The clockwise rotating component of the magnetic field, B is shown. The rotor also rotates clockwise but at a slower rate. The relative motion of the rotor coil and the magnetic field causes a force on charges in the coil that results in coil current. The force on charges that causes coil current is,

$$\vec{F}_q = q\vec{v} \times \vec{B} \qquad (1)$$

where V , the velocity of the coil relative to the magnetic field, is to the left. The force on charges in the rotor is perpendicular to both the B field and the velocity, V . This force results in the current, I , into the paper as shown in Figure 5.

The rotor current flowing in the magnetic field experiences a second force given by,

$$\vec{F} = I\vec{L} \times \vec{B} \qquad (2)$$

where I , is the rotor current. and L is the length of the wire segment. This force is to the right in Figure 4. It is responsible for the rotor torque. This force causes the rotor to move in the direction of the passing rotating magnetic field. Both forces, F and F_q , are Lorentz forces that result from motion of charge relative to a magnetic field. F and F_q are perpendicular to each other.

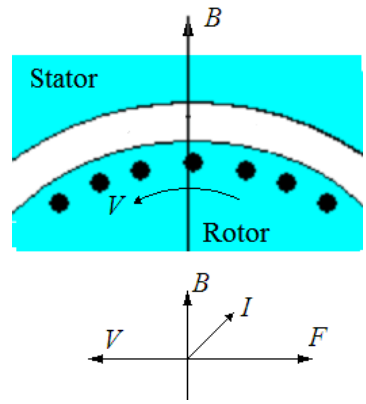

Figure 5 Motion of the rotor relative to the magnetic field induces a force on the rotor in the direction of the motion of the field. V Is the velocity of the rotor relative to the magnetic field. I is the current induced in the rotor and F is the force on the rotor.

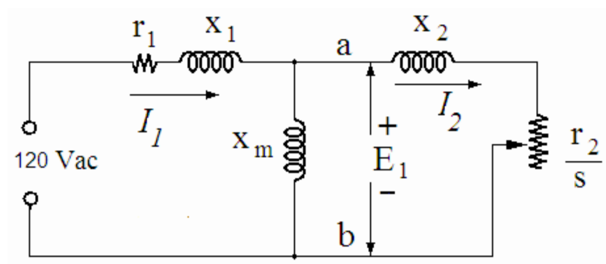

Figure 6 The motor equivalent circuit is shown. *s* is the slip. If the rotor is rotating at synchronous speed, *s* is zero. If the rotor is blocked and not rotating, *s* = 1.

Starting

When the magnetic field is not rotating, there is no torque generated. The magnetic field shown in Figure 4 is stationary. True, it has two rotating components, but their sum is stationary. An additional coil, the starting coil, is necessary. A starting stator winding is employed to produce a rotating magnetic field. The starter winding is perpendicular to the main stator winding. If the current in the starter winding were 90^o out of phase with the main winding and if it produced a magnetic field of the same magnitude, the magnetic field in the, say x, direction would be $B\ cos(\omega\ t)$ and the magnetic field in the y direction would be $B\ sin(\omega\ t)$. The result would be a rotating magnetic field. Typically the starter winding has a more resistive impedance than the main winding. The current in the starter winding is out of phase with the current in the main winding. This results in a rotating stator field that causes the motor to start. Once the rotor is rotating, it will interact with one of the rotating components of the magnetic field, shown in Figure 4, to produce torque. Typically the starter winding is switched out once the motor comes up to speed.

Slip

The rotating components of the magnetic field, shown in Figure 4, rotate at synchronous speed. Synchronous speed for the single pole motor shown in Figure 3 is 60 Hz or 3600 rpm. The rotor rotates at a speed less than the synchronous speed. The rotor sees a changing magnetic field that results in voltages and currents that produce torque. If the rotor is rotating at n rpm in the forward direction and the synchronous speed is n_1, then the rotor is traveling at a speed $n_1 - n$ in the backward direction relative to the magnetic field. The slip of the rotor is $n_1 - n$ rpm. The slip is usually expressed as a fraction of the synchronous speed,

$$s = \frac{n_1 - n}{n_1} \qquad (3)$$

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.

The motor is like a transformer where impedances attached to the secondary can be 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.

Since the induced voltage in the rotor is proportional to the frequency seen by the rotor, the rotor voltage referred to the stator is divided by the slip, s. $E_1 = E_2 / s$, where E_1 is the back emf induced in the stator by the changing magnetic field and E_2 is the equivalent emf induced in the rotor referred back to the stator. If the rotor were blocked, s would be one and the equivalent rotor voltage, referred to the stator, would equal the stator back emf, E_1.

The impedance of the rotor is

$$\frac{E_2}{I_2} = r_2 + jsx_2 \qquad (4)$$

where the reactance, x_2, is multiplied by the slip fraction, s, to reflect the lower frequency seen by the rotor.

Since the rotor voltage is also less by a factor of s,

$$\frac{E_2}{I_2} = s\frac{E_1}{I_2} = r_2 + jsx_2 \qquad (5)$$

Solving for the rotor impedance referred back to the stator.

$$\frac{E_1}{I_2} = \frac{r_2}{s} + jx_2 \qquad (6)$$

If the rotor is rotating at synchronous speed, s = 0. Then there is no slip and the rotor looks like an open circuit. If the rotor is blocked, s = 1. The equivalent rotor resistance is a minimum. Power delivered to the rotor is a maximum.

An equivalent circuit for the motor is shown in Figure 5. 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.

Autocycle Control

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

$$E_1 = N\frac{d\lambda}{dt} \qquad (7)$$

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 7, equals the applied line voltage. Since this 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, therefore, the torque is proportional to the product of the rotor currents and the magentic field. Torque varies inversely as the square of the number of turns. Power is torque multiplied by angular velocity. At a given speed, the power delivered will vary inversely as the square of the number of stator turns. This is illustrated in Figure 7.

Consider a design where the stator turns are decreased for k half cycles in every k_o half cycles of the AC line. During the time the stator turns are reduced, the power increases by 23.5%. This results in an increased average power given by,

$$P_{ave} = \left[1 + 0.235\,\frac{k}{k_0}\right] P_0 \qquad (8)$$

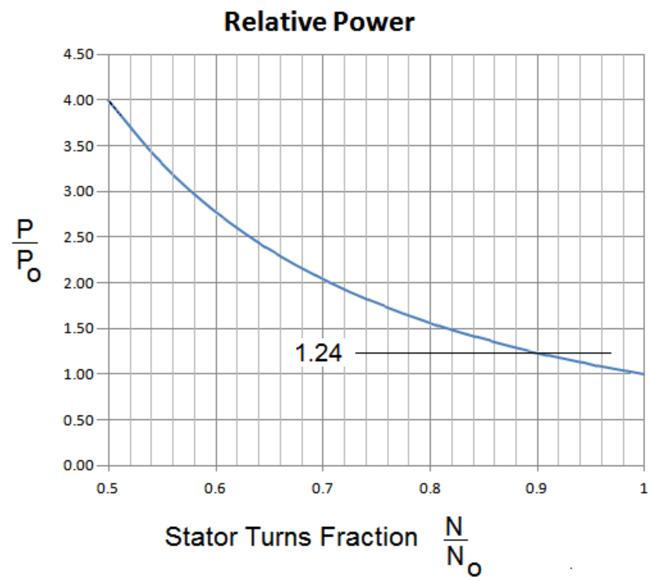

Figure 7 Power varies inversely as the square of the number of stator turns. In the design discussed here, the number of turns is reduced by 10% to 90% of N_o. Power increases by 1.235, nearly 25%.

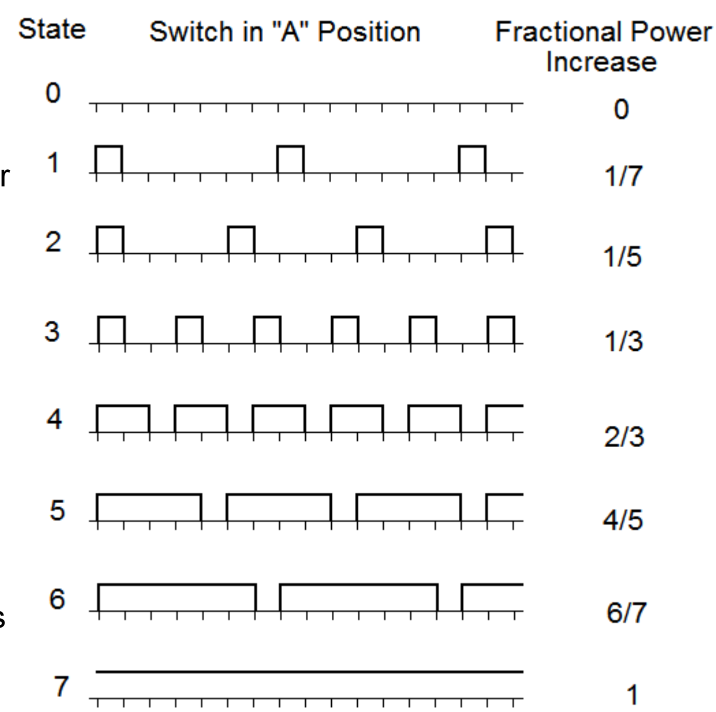

Figure 8 Switching states are shown. For state "0". the switch is never in position "A". Power is not increased. For state "7", the switch is always in position "A", reducing the number of turns by 10%, resulting in a 23.5% power increase.

where k is the number of half cycles per second switched out. k_o is the number of half cycles per second. (120 for a 60 Hz line voltage)

Half cycle increments permit a fine tuning of the power. Figure 8 shows eight switching states. Each results in a different power. For state "0" there is no switching. Power is the base minimum. For state "1" power is increased for 1/7 of the time. Power is increased by 1/7 of the maximum increase of 23.5%. For state "7" the switch is in position "A" all the time and the maximum increase of 23.5% is realized.

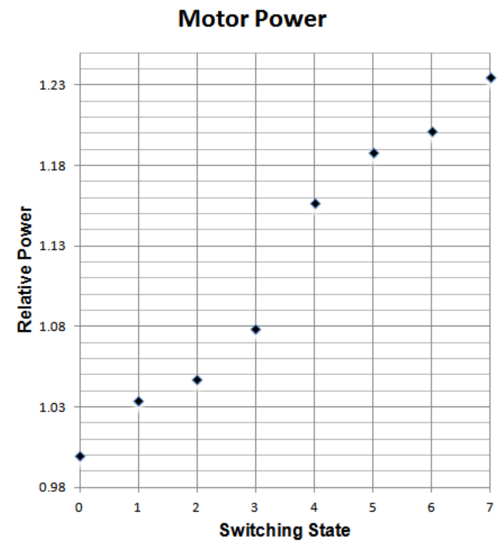

Figure 9 Motor power that results from the switching states shown in Figure 8 is shown.

The microcontroller determines the zero crossings of the line voltage and, based on inputs, turns on the triac switch at the proper time. The triac turns itself off when its current goes to zero. Flowing current is not interrupted. The switching sequences shown in Figure 8 are chosen to produce a zero DC component to the current.

Circuit Implementation

An automotor circuit is shown in Figure 10. Two triac switches control how many stator coils are energized. When triac A conducts, 90% of the coils are energized. When triac B, conducts 100% of the coils are energized. When one triac conducts the other is off. The switches are controlled by a 16F690 microcontroller. The microcontroller receives input information from (1) the AC line voltage, (2) an 8 position rotary switch, (3) a motor speed sensor, and (4) a mode control switch.

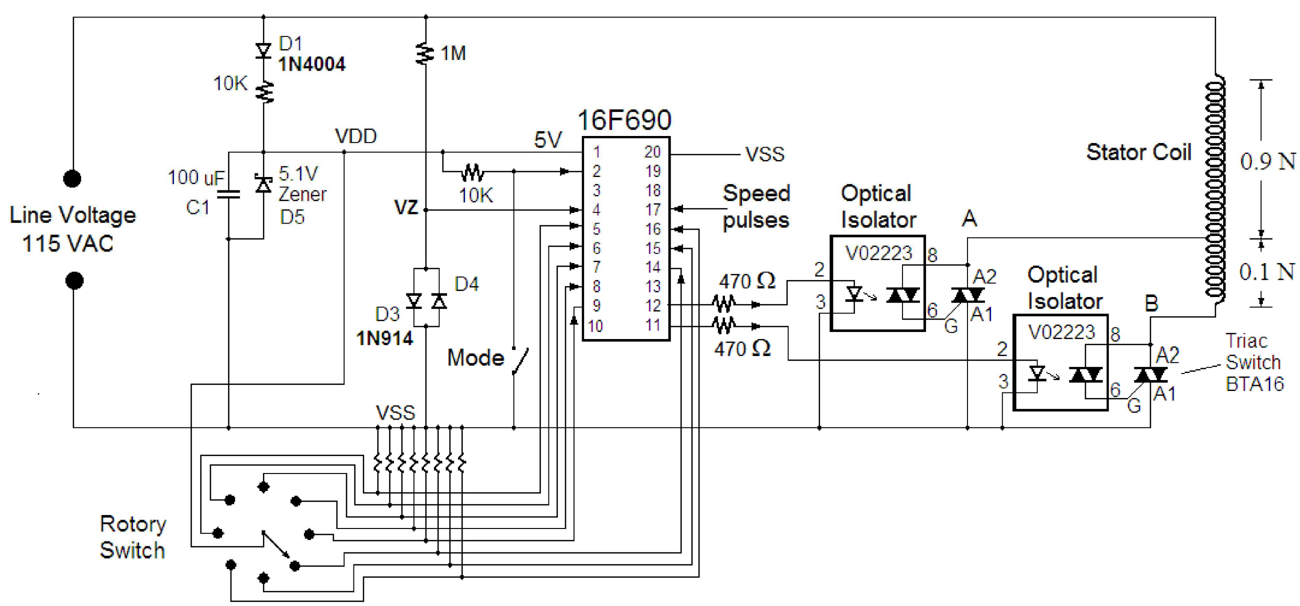

Figure 10 The 16F690 microcontroller pins 11 and 12 control the switches. When triac A conducts, 90% of the coils are energized. When triac B, conducts 100% of the coils are energized. The signal VZ is a square wave synchronized with the line voltage. The microcontroller reads pin 4 to determine the line voltage zero crossings. The system has two modes of operation. The voltage on Pin 2 is controlled by a switch and determines the mode. The microcontroller knows the position of the rotary switch. It used this information to determine the switching state. Pulses on pin 17 are used to determine the motor speed.

Operating Modes

A user selects the mode of operation by setting the mode switch.

Mode 1 In mode #1, the microcontroller selects one of 8 switching states based on the position of the rotary switch.

Mode 2 In mode #2, motor speed is sensed and the power level is adjusted to achieve one of the 8 speeds set on the rotary switch.

Summary

The Autocycle Motor is capable of producing a wide variety of power levels. Power is controlled by reducing the number of stator coil windings. Following the cycle saver principle, windings are switched out when their voltage is zero and switched back in when the stator current is zero. That is, the triac switches begin to conduct when the voltage is zero and end conduction when their current is zero. Current is not abruptly interrupted. This switching technique eliminates voltage spikes and radio frequency interference. A triac naturally opens when its current is zero.