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FOUR QUADRANT CONTROL OF INDUCTION MOTORS

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ABSTRACT

Induction motors are our nation's workhorse, being the motor of choice in most applications due to their simple rugged construction. It has been estimated that 14 to 27 percent of the country's total electricity use could be saved with adjustable speed drives. Until now though, induction motors have not been well suited for variable speed or servo drives, due to the inherent complexity, size and inefficiency of their variable speed controls. Work at NASA Lewis Research Center on field oriented control of induction motors using a pulse population modulation method holds the promise for the desired drive electronics. The system allows for a variable voltage to frequency ratio which enables the user to operate the motor at maximum efficiency, while having independent control of both the speed and torque of an induction motor in all four quadrants of the speed torque map. Multiple horsepower machine drives have been demonstrated, and work is on-going to develop a 20 hp average, 40 hp peak class of machine. This paper discusses the pulse population technique, results to date, and projections for implementation of this exciting new motor control technology.

BACKGROUND

For aerospace and launch vehicles, electric actuators have fundamental advantages over the more conventional hydraulic actuators. Basically they are more efficient, and require less maintenance. Until recently technical limitations have denied their aerospace application at the required high power levels. Now, however, new technology is available which allows 50 kW class electric powered flight actuators to be built today. At NASA Lewis Research Center electric actuator work for aerospace applications has concentrated on induction motors and associated high frequency link drives, which should have dramatic payoffs in any mechanical process requiring variable operating points.

WHY INDUCTION MOTORS?

The induction motor is, by a wide margin, the most commonly applied motor. It is a mechanically simple, rugged machine capable of providing rapid response and high peak torques. In its simplest conceptual form it is essentially a multiphase transformer with its secondary (rotor) shorted and free to move axially with the rotating magnetic field (stator flux) figure 1.

In such a motor the magnetic flux of the stator varies directly with the source voltage and inversely with the source frequency. The current in the rotor results from the voltage induced by the stator flux and the rotational speed difference between the stator flux field and the rotor (slip frequency). As usually encountered the motor is operated from a fixed voltage, fixed frequency source (e.g., 120/208 V and 60 Hz). When operated under these conditions, a typical induction motor displays the characteristics shown in figure 2. Of particular importance is that under these operating conditions, high torque, efficiency, and power factor are realizable over only a rather limited range of speed.

Of interest also is that these characteristics are symmetrical about the stator (synchronous) speed, and that, for example, if the rotor is driven above synchronous speed (fig. 3) generator

action results. The optimum operating region discussed earlier is expanded in figure 4 with some of the data replotted. The ratio of torque to current is a very interesting parameter. An actuator motor is a current to torque transducer being driven by power electronics with sharply defined current limits. Therefore, in order to fully utilize the electronics capabilities achieving the maximum torque/amp is crucial. Also important in aerospace applications is the minimisation of losses to enhance thermal control. To better illustrate this point under constant voltage and frequency operation refer to figure 2. Full rated torque occurs at about 0.75 power factor and an efficiency of about 0.5. However, maximum torque/amp occurs at about 0.8 power factor and an efficiency of about 0.75. It is to be noted that for this set of data minimum loss is different than maximum efficiency, which is meaningless at stall (blocked rotor) speed.

WHAT TO DO ABOUT IT?

There are several ways to relocate the optimum operating point of an induction motor. If the frequency is held constant and the voltage varied, the characteristics of figure 5 are obtained. This is the approach taken by Frank Nola (ref. 1) to improve the power factor and efficiency of lightly loaded motors. This provides essentially variable torque, constant speed operation. If both the voltage and the frequency are varied with their ratio held constant v/f = c (constant stator flux), the characteristics of figure 6 are obtained. This represents variable speed operation with constant peak torque.

Combining both strategies provides the capability of optimising the motor characteristics at any speed and load including blocked rotor operation in an actuator. The capability of optimising operation at full torque and low speed is a very important advantage. Since v/f control allows full torque at zero shaft speed, the rotor resistance and its associated loss may be reduced. Figure 7 shows how high rotor resistance usually required for high starting torque may be greatly reduced. If v/f control is implemented, the motor peak torque may be obtained at zero speed and rated current. This typically reduces starting currents by a factor of six.

WHAT'S THE PROBLEM?

The approach generally taken to provide a variable frequency source is to create time phased square wave voltages, which when applied line to line form a quasi-sine wave (six-step) (fig. 8). Such an approach, however, has serious limitations. The voltage is not sinusoidal and its harmonic distortion causes additional losses in the motor. Also, the semiconductor switches must turn off the motor current and operate under high stress. Then, to achieve voltage control the voltage steps are pulse width modulated (PWM), which increases both the stress and loss (fig. 9).

Aerospace actuators now in service generally use permanent magnet (PM) motors (brushless dc). No capability exists to optimise either efficiency or power factor. In these motors the resulting high currents, which produce loss but no output, even further stress the switching elements. One approach to these problems requires energy controlling snubbers across the switches. If this snubber energy is recovered, high current spikes are created that add to the already severe electrical noise problem.

Since these problems, in general, involve inductive energy, which varies with the square of the current, they rapidly worsen with increasing power levels. As a result, today's conventional PWM-PM motor technology scales poorly; and, actuators have been limited to relatively low power applications. An attempt to increase power level results in electronic packages many times larger than the associated motor.

WHAT'S NEW?

NASA Lewis, together with its contractors, has developed high power high frequency power distribution systems and components (refs. 2 and 3). Conceptually, such a system delivers energy tailored to the user's actual requirements with the least number of conversions possible (fig. 10). Of particular importance is the fact that in a typical 20 kHz system energy flow is controlled and quantized into 25 μs half sine pulses. In a 10 kW controller each half sine pulse represents only 1 J of energy. Using a high frequency sinusoidal power source, lower frequencies (including dc) may be synthesized. All switching functions are performed at zero voltage, which greatly reduces the circuitry and the electrical loss (fig. 11). The synthesis scheme shown is referred to as pulse population modulation. In this scheme the voltage is controlled by the density of the pulse population and the frequency is controlled by the pulse pattern.

With this modulation scheme voltage and frequency may be independently varied, which in turn allows independent control of the rotor current and the stator current (refs. 5 and 6). Actual bidirectional, four quadrant operation of a 20 hp induction motor is shown (fig. 12). This particular motor controller combination is presently under test at General Dynamic Space Systems as part of the Advanced Launch Development Program (ALDP). This photograph was taken while a large inertia load was being driven bidirectionally under constant torque. The step is the torque command and the ramp is the resulting shaft speed. Of particular note is the instantaneous torque response and the torque control at zero speed. Work has started on a 40 hp electrical actuator using this technology. An advanced induction motor is presently being designed for the actuation system.

WHO CAN USE IT?

The combined benefits of low loss, rapid response, and high power factor, together with electronic switch protection, makes this technology a candidate for many motor driven processes. Immediate applications identified are for thrust vector control on the ALS and other missile systems.

Efforts are now under way at Douglas Aircraft to evaluate the impact of this technology, not only to flight actuators, but also to many other aircraft loads, such as nose wheel steering, braking, and environmental control. This is a renewal of an all electric airplane effort begun at NASA Lewis in the mid-1980's (ref. 7).

CONCLUSIONS

This technology is rapidly approaching full maturity. It has a sound analytical base, is supported by component developments, and is being verified by full scale demonstrations.

REFERENCES

1. Nola, F.J.: Power Factor Control System for AC Induction Motors, U.S. Patent 4266177, May 1981.

2. Hansen, I.G., and Wolff, F.J.: 20 Kilohertz Space Station Power System. NASA TM-88801, 1986.

3. Hansen, I.G.: Status of 20 kHz Space Station Power Distribution Technology. NASA TM-100781, 1988.

4. Sood, P.K.; Lipo, T.A.; and Hansen, I.G.: A Versatile Power Converter for High-Frequency Link Systems. IEEE Trans. Power Electron., vol. 3, no. 4, Oct. 1988, pp. 383-390.

5. Roth, M.E.: Electromechanical Actuation for Thrust Vector Control Applications. NASA TM-102548, 1990.

6. Burrows, L.M.; Zinger, D.S.; and Roth, M.E.: Field Oriented Control of Induction Motors. NASA TM-103154, 1990.

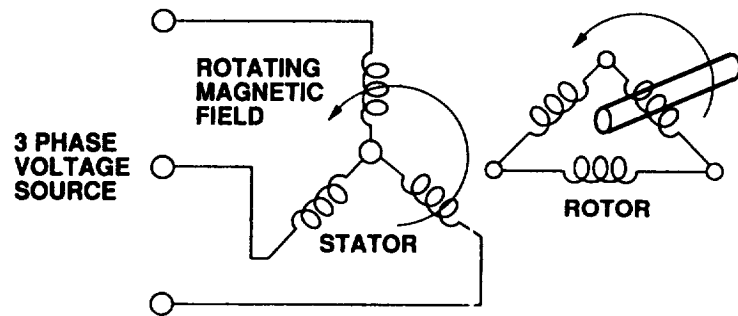7. Hoffman, A.C., et al.: Advanced Secondary Power System for Transport Aircraft. NASA TP-2463, 1985.

FIGURE 1. - INDUCTION MOTOR.
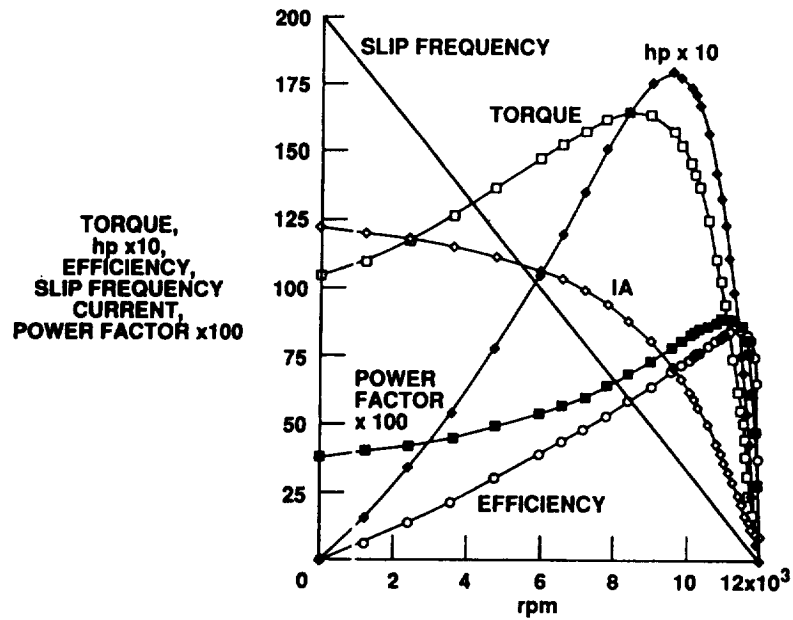
FIGURE 2. - INDUCTION MOTOR CHARACTERISTICS, FIXED VOLTAGE AND FREQUENCY.
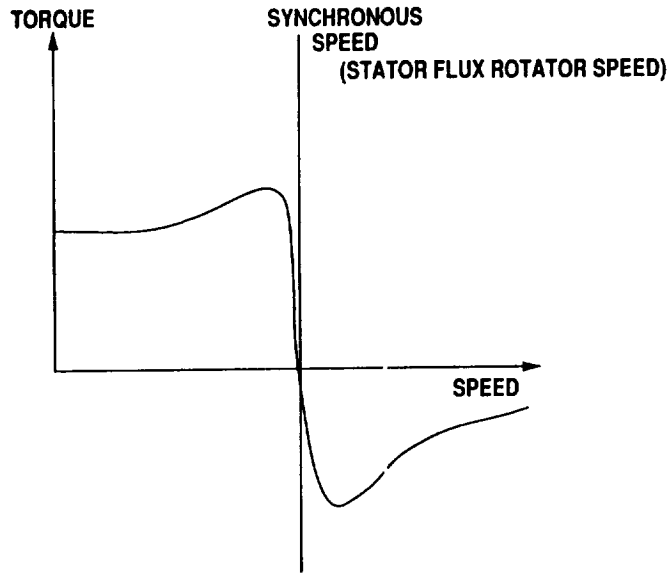
FIGURE 3. - INDUCTION MOTOR/GENERATOR CHARACTERISTICS.
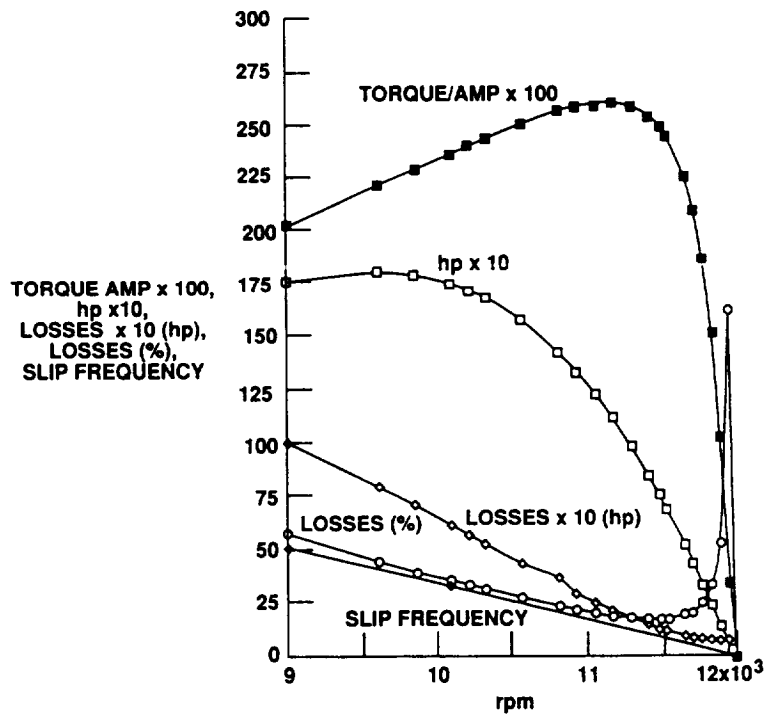
FIGURE 4. - DATA FOR MOTOR 939D228-4.
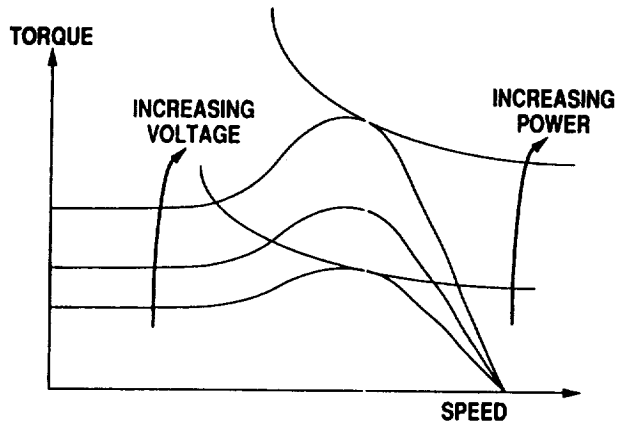
FIGURE 5. - VARIABLE VOLTAGE CHARACTERISTICS.
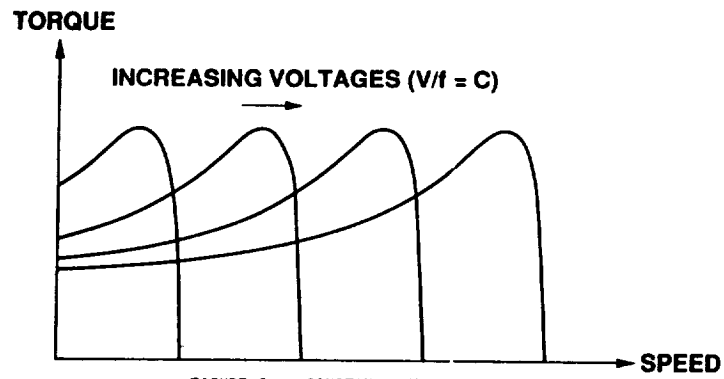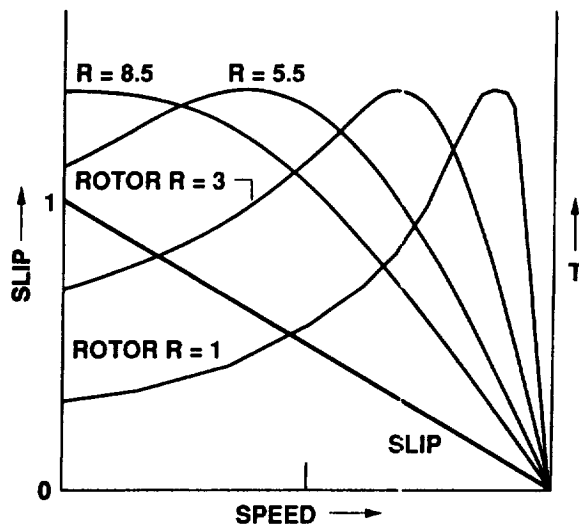

FIGURE 6. - CONSTANT V/f INDUCTION MOTOR.

FIGURE 7. - SPEED TORQUE CHARACTERISTICS OF INDUCTION
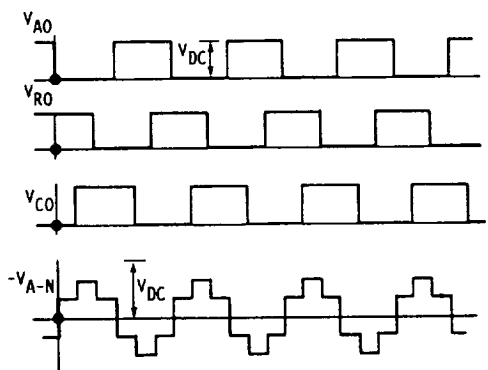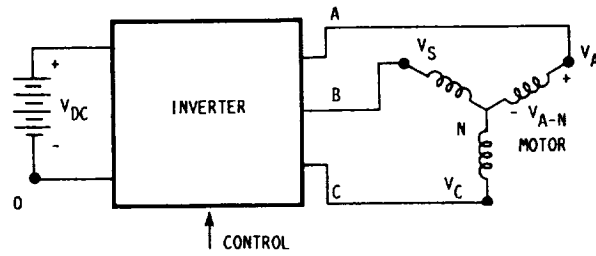MOTOR AS FUNCTION OF ROTOR RESISTANCE.

284

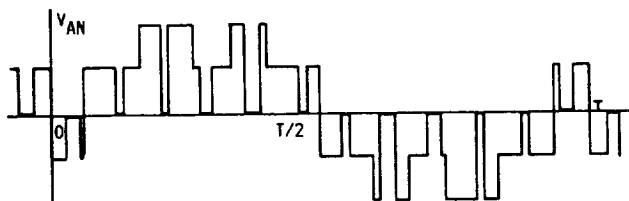FIGURE 8. - GENERATION OF SIX-STEP SQUARE WAVE.

FIGURE 9. - GENERATION OF SINE WAVE PWM.
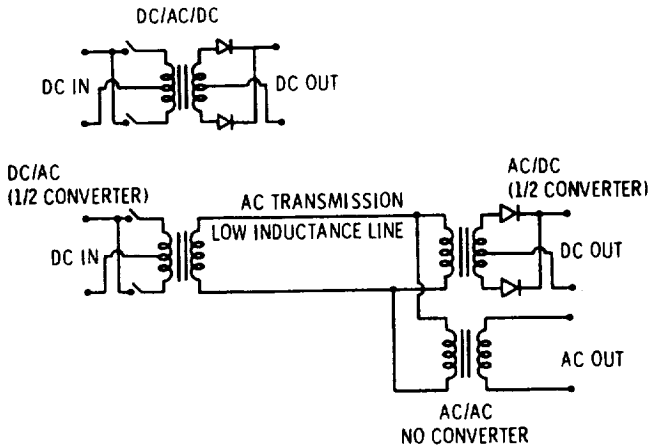
FIGURE 10. - "SPLIT" SYSTEM CONCEPT TO CHANGE DC VOLTAGE LEVELS
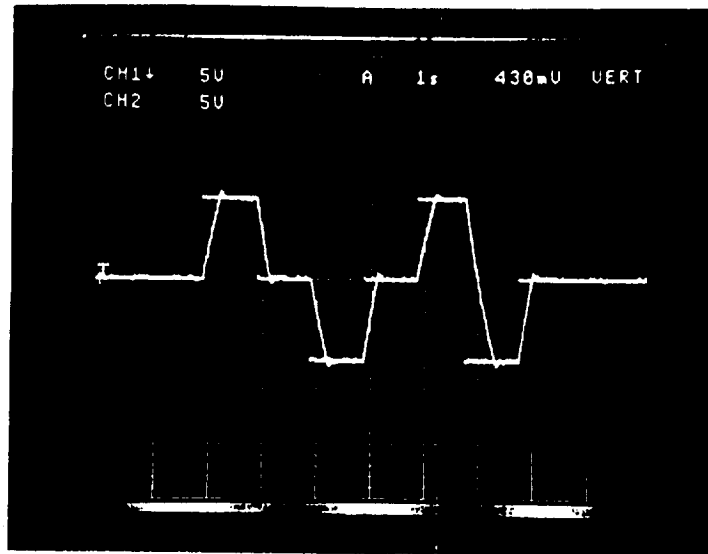(DC/DC CONVERTER).

285

PHASE
VOLTAGE,
v_c(V)
+250
−250

LINE
VOLTAGE,
v_{ab}(V)
+500
−500

←|1 ms|←—

REFERENCE
VOLTAGE,
v_a(V)
+250
−250
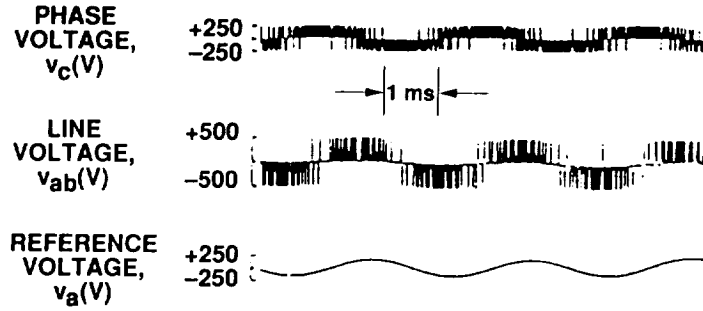
COMPUTER SIMULATION OF LOW FREQUENCY SYNTHESIS
(UNIVERSITY OF WISCONSIN)

FIGURE 11. - PULSE POPULATION MODULATION, PPM.

CH1↓   5U   A   1s   438mU   VERT
CH2   5U

FIGURE 12. - FOUR QUADRANT - CONSTANT TORQUE OPERATION AT 20 HORSEPOWER.

- ADVANCED LAUNCH SYSTEM ACTUATORS

- SHUTTLE ACTUATORS

- AIRCRAFT: POWER BY WIRE
             NOSEWHEEL STEERING
             STARTER GENERATORS
             AUXILIARY POWER UNIT

- SPACE POWER SYSTEMS AND INTERFACES
  WITH BRAYTON AND STIRLING ENGINES

- OTHER APPLICATIONS, ANY MECHANICAL
  PROCESS REQUIRING A VARIABLE THROUGHPUT

FIGURE 13. - ONGOING EFFORTS.

APPLYING HIGH FREQUENCY POWER CONTROL
TECHNIQUES TO INDUCTION MOTOR CONTROL
REPRESENTS ENABLING TECHNOLOGY DISPLAYING THE
ADVANTAGES OF:

- LOW NOISE, BOTH ELECTRICALLY AND ACOUSTICALLY

- LOW WEIGHT

- LOW VOLUME

- HIGH EFFICIENCY

- HIGH POWER LEVEL

FIGURE 14. - CONCLUSIONS.