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Title: A STATIC FREQUENCY CONVERTER SPEED CONTROL SYSTEM

FOR THE THREE-PHASE SQUIRREL-CAGE INDUCTION MOTOR

Abstract approved: __________________________ (Signature)

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The three-phase squirrel-cage induction motor is rugged, compact, inexpensive, can be totally enclosed and requires little maintenance. Its use as a variable speed drive has been limited, however, by the state-of-the art of control components.

The advent and continuing development of the silicon controlled rectifier and associated solid-state components has provided the technology for conceiving a static frequency converter to allow continuous motor speed adjustment over a wide range. The static frequency converter system adjusts the motor input frequency and voltage so the motor can match a given load speed-torque requirement.

The high cost and low thermal overload capabilities of the solid-state components required for a prototype dictate the use of modeling and simulation techniques for analysis of complex systems such as the static frequency converter motor speed control system.
A Static Frequency Converter Speed Control System for the Three-Phase Squirrel-Cage Induction Motor

by

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I. INTRODUCTION

The three-phase squirrel-cage induction motor (SCIM) is the most popular fixed-speed drive in use today. It is more rugged, more compact, and the initial cost and operating costs are less than for either the a-c wound-rotor induction motor or the d-c motor. In the past, however, the SCIM was not considered practical for variable-speed drive applications because of control hardware limitations. Previously, variable-frequency speed control systems used the mercury-arc rectifier as the basic switching element. The mercury-arc rectifier had long turn-on and turn-off times, arc-back problems and required water cooling, all of which were undesirable characteristics for a motor speed control system.

Invention of the silicon controlled rectifier (SCR) by the General Electric Co. and improvements to other solid-state devices permitted conception of the static frequency converter (SFC) circuitry for speed control of the SCIM. The development of analog and digital computer systems and the use of modeling and simulation techniques can provide economical analysis of complex, power-handling systems, such as the SFC.

The objectives of this Thesis are as follows:

1. Determine the parameters of the three-phase squirrel-cage induction motor that allow for, or are affected by, adjusting speed.

2. Present a solid-state speed control system capable of varying the required motor input parameters.

3. Describe a technique for analyzing the speed control system which provides the basis for work beyond the scope of this project.
and includes: constructing a quantitative model for the system; simulating the model to obtain desired system goals; and constructing a prototype model for field testing.
II. SPEED CONTROL PRINCIPLES OF THE MOTOR

The conception of a speed control system for the three-phase squirrel-cage induction motor (SCIM) requires investigation of the parameters which cause speed change or are directly affected by speed change.

**Motor Speed**

The speed of the rotating magnetic field in the stator of a poly-phase induction motor is termed "synchronous speed" and is given by:

\[ n_s = 120 \frac{f}{p} \text{ rpm} \]  

for a p-pole machine supplied with a frequency \( f \) (5, p. 127)(18).

Slip is usually expressed as a per-unit (dimensionless) quantity relating the difference between synchronous speed \( n_s \) and rotor speed \( n_r \) to the synchronous speed (5, p. 130).

\[ s = \frac{n_s - n_r}{n_s} \]  

An equation is found for the rotor speed by solving Equation 2 for \( n_s \), and substituting into Equation 1.

\[ n_r = 120 \frac{f}{p} (1 - s) \text{ rpm} \]  

Equation 3 indicates that the rotor speed \( n_r \) can be varied by changing the slip \( s \), the number of poles \( p \), or the frequency \( f \). Changing the slip is practical only if the speed must be varied over
a small interval. Changing the number of poles produces discrete speed changes and cannot be used where continuous variation is required. Changing the frequency produces continuous speed adjustment over a large interval and is the technique that will be used.

**Motor Characteristics with Variable Frequency**

Utilizing frequency change to effect speed control as indicated by Equation 3 has restrictions, because other motor parameters vary with the supply frequency. The flux density, total flux per unit area, varies with frequency, but the allowable flux density of the magnetic materials in the motor is fixed (5, p. 121). A theoretical relationship of the maximum flux $\Phi_m$ to frequency $f$ is needed to allow establishing a control technique.

The maximum value of the induced voltage $E_m$ in a distributed winding of $N$ series turns is, according to Faraday's Law,

$$E_m = 2\pi f \Phi_m k N$$  \[4\]

where $k$ is the winding distribution factor, $\Phi_m$ is the total flux per pole of the inducing wave, and $f$ is the supply frequency (5, p. 123). Assuming that the voltage drop due to winding resistance is negligible, the flux must vary to induce an EMF $E_m$ equal to the voltage $V_T$ applied to the winding. Rearranging Equation 4 and substituting $V_T$ for $E_m$ yields

$$\Phi_m = \frac{V_T}{2\pi f k N}.$$  \[5\]
Magnetic saturation can be avoided by maintaining flux $\Phi_m$ constant. Equation 5 indicates that the supply voltage $V_T$ must be varied in a linear relationship with supply frequency $f$, in order to maintain $\Phi_m$ constant. Therefore, the pertinent speed control parameters for the SCIM are frequency and voltage.

**Motor Performance with Variable Voltage and Frequency**

The speed-torque curves on Figure 1 indicate the performance of a small, 60-hertz, NEMA Design B SCIM with the supply voltage varied directly with frequency. Evaluation of the curves indicates the following:

1. No-load speed reduces directly proportional to the frequency.

2. Slip at 60 Hz is about 0.03 per unit, based on synchronous speed. Slip at 20 Hz is about 0.05 per unit, based on 60 Hz synchronous speed. (0.15 per unit based on 20 Hz synchronous speed.) Therefore, full-load speed only differs slightly from a direct relationship with frequency.

3. The changing shape of the speed-torque curves with reduced frequency (i.e. reduced torque output) shows that Equation 5 is only approximately correct. If controlling voltage directly with frequency maintained flux $\Phi_m$ constant, the maximum torque would be the same for all curves.

**Motor Performance with Nonsinusoidal Supply**

An idealized six-step approximation of a sinusoidal voltage waveform has harmonic content as indicated in Table 1, page 24.
FIGURE 1  TYPICAL SPEED-TORQUE CURVE FOR DISCRETE FREQUENCIES (32)
Motor performance depends on both the motor design and the supply waveform. The harmonic content of the voltage supply waveform causes additional motor losses, but these losses can be minimized, if the motor can be designed for the expected waveform. If an existing motor is used, in some cases the supply waveform can be changed using different control or filtering techniques.
III. A STATIC FREQUENCY CONVERTER SPEED CONTROL SYSTEM

A static frequency converter (SFC) speed control system converts the voltage and frequency of an alternating current (a-c) supply into a voltage and a frequency proportional to the desired speed of the motor (22)(9).

The key component in the SFC system is the silicon controlled rectifier (SCR). The SCR has capabilities analogous to a high-gain direct-current amplifier - a large current (anode current) can be controlled by a small current (gate current).

The SCR is a solid-state semi-conductor, NPNP four-layer device, which in its normal state, will block current flow in either direction. When an appropriate voltage or current pulse is applied to the gate electrode, current will flow from anode to cathode, thus permitting current to flow into the load circuit (19, p. 1). When the cathode becomes more positive than the anode, the device will again block the current.

The SCR is similar to a diode, except that conduction can be initiated at a predetermined time by applying a positive voltage at the gate. Once conduction starts, the gate exercises no more control. Conduction continues until the current from anode to cathode drops below a fixed value, called the holding current. At this point, the SCR reverts to the "off condition" and the gate regains control.

The SCR is used as a switch in the SFC system because it has only two stable states - "on" and "off" and it passes between the two states in a few microseconds (6). The voltage-current characteristics of a typical SCR are shown on Figure 2.
FIGURE 2  TYPICAL SCR VOLTAGE - CURRENT CHARACTERISTICS (19, P-4-1)
An Elementary SFC

An elementary SFC is presented first to simplify explanations. The elementary SFC (Figure 3) consists of a rectifier, a filter, and an inverter. The subsystems necessary for a practicable SFC speed control system are described later in the chapter.

Rectifier

Diodes in the rectifier circuit change the alternating-current into a direct-current output with ripple. The rectifier circuit on Figure 4 is a three-phase, full-wave bridge configuration.

Filter

The filter improves the waveform from the rectifier, i.e. lowers the ripple factor. It also has the essential function of storing and exchanging energy with the reactive motor load.

Inverter

The inverter uses SCR static switches to fabricate a stepped approximation of a sinusoidal voltage waveform from the d-c input. A simplified three-phase bridge inverter with SCR switches is shown on Figure 4 (26). The inverter requires two SCRs in each leg of the bridge, and three legs to produce a three-phase a-c output.
FIGURE 3  BLOCK DIAGRAM OF AN ELEMENTARY SFC

FIGURE 4  CIRCUIT DIAGRAM OF AN ELEMENTARY SFC
The six SCR firings in the inverter, required for the formation of one complete cycle, are shown on Figure 5 as sequenced steps one through six. The sequence of firing is fixed, regardless of d-c input voltage magnitude, but the frequency can be changed by varying the length of time each SCR is conducting. One complete cycle in one-half the time causes the output frequency to double.

The idealized line-to-neutral voltages, shown on Figure 5 for the six steps, would appear across motor winding L1 if the d-c voltage at the inverter input were 3E. The SCRs are numbered one through six, with the circled SCRs in conduction at each step. Firing at each 60-degree interval over the 360 degrees of a full cycle produces a six-step, square-wave output voltage.

Figure 6 shows the output voltage waveforms constructed from the data on Figure 5. The line-to-neutral voltage waveforms across windings L1, L2, and L3 are identical in shape, but displaced by 120 and 240 degrees, respectively; voltage waveforms are only shown for L1 and L2.

A typical line-to-line voltage waveform is shown on Figure 7 for L1-L2. L1-L2 is the difference between the line-to-neutral voltages, L1-0 and L2-0, shown on Figure 6.

A Practicable SFC

Subsystems that will perform functions unique to supplying a SCIM must be added to the elementary SFC. The subsystems are as follows:
FIGURE 5  FABRICATION OF AN A-C VOLTAGE WAVEFORM WITH A SIX-STEP INVERTER (4)
FIGURE 6  IDEALIZED LINE-TO-NEUTRAL VOLTAGE WAVEFORMS

L1 TO L2 = (L1 - 0) - (L2 - 0)

FIGURE 7  IDEALIZED LINE-TO-LINE VOLTAGE WAVEFORM
1. Feedback diodes.
2. Commutation system.
3. Voltage control system.
4. Frequency control system.
5. Reference and firing controls.

Feedback Diodes

The basic rectifier-inverter must have a resistive load for proper operation (12). An induction motor, however, contains both resistance and inductance and can be described as an inductive load. Because load current lags the voltage in an inductive circuit, load current continues to flow for some time after the load voltage has gone through zero.

The SCR has a finite holding current. When the load current drops below the holding current value, the SCR turns off, but the remaining inductive current must continue to flow. This current produces a negative voltage across the SCR, proportional to the circuit inductance and rate of change of current. If a path around the SCR is not available, the load voltage rises to the breakover voltage of the SCR and forces conduction of the current through the SCR (31).

A path for the inductive load current around each SCR in the inverter bridge can be provided by a diode in inverse parallel with each SCR (Figure 8). Thus a cyclic exchange of energy, reactive power flow, between the d-c supply and the a-c load can take place and the voltages to which the SCRs are subjected do not approach breakover voltage. Energy stored in the load inductance during the latter
FIGURE 8  AN ELEMENTARY SFC WITH FEEDBACK DIODES ADDED
part of a cycle is returned to the d-c supply during the first part of the next cycle (2, p. 185).

The reactive power flow from the load to the d-c supply must be absorbed by the rectifier-filter capacitors. The ability of the inverter to absorb regenerated power is limited to the reactive losses in the inverter and the permissible rise in the d-c bus voltage (15).

**Commutation System**

Each SCR in the inverter of an SFC is turned on by a control current applied to its gate, but there is not a simple device for turning the SCR off. The SCRs turn off naturally only when an SFC operates into a capacitive load and/or into an a-c power system. Natural commutation results from the tendency of the load or source to bring the current to zero, causing the SCR to turn off.

Auxiliary or forced commutation is accomplished by switching active elements or energized passive elements into series or parallel with the conducting SCR. The current through the SCR is driven to zero, and the cathode of the SCR is forced to be more positive than the anode.

Selection of adequate commutating elements requires that the turn-off time of the SCR be known. The turn-off time is the minimum time interval for satisfactory turn-off of the SCR and is defined as the time interval from the application of reverse anode-to-cathode voltage, until the unit can block reapplied forward voltage at a specified linear rate-of-rise. Turn-off time is broken into two intervals. Reverse recovery time is the interval between the time the device current becomes negative and the time the reverse current falls to a specified value. Gate recovery time is the minimum time interval between the
reverse recovery point and the time the device voltage crosses zero
at a specified rate of voltage rise (19, p. 3-2).

Previously, inverter circuits were "circuit commutated."
Circuit commutated turn-off was utilized extensively in the mercury-
arc inverters due to the long turn-off times of the devices. Circuit
commutated turn-off is characterized by large commutating elements,
load dependent voltage and current waveforms, and full voltage turn-off
(2, p. 183). With full voltage turn-off, an abrupt step of inverse
voltage is initially applied to the controlled rectifier that is
being commutated.

The solid-state inverter using SCRs and feedback diodes has
made possible the development of impulse commutated circuits. The
term "impulse commutation" is applied to the use of a voltage impulse
to briefly reverse the voltage on an SCR, allowing it to turn off
(2, p. 165). With impulse commutation and feedback diodes, the
inverse voltage applied to an SCR is limited to the voltage drop
(approximately one volt) across the feedback diode connected in
inverse parallel, and the reverse recovery current is limited to the
excess of the commutating current pulse over the load current
(2, p. 183). The limitation of the recovery current magnitude and
rise time is usually not a problem.

A classification system exists which divides inverter circuits
by method of commutation and subdivides by circuit configuration (16).
Six distinct classes of methods exist by which SCRs can be turned off;
only Class E commutation is practicable. Several circuit configura-
tions are possible for each of the six classes; only the three-phase
bridge inverter is presented.
Class E commutation, used with the three-phase bridge inverter, utilizes a pulse produced by an external or auxiliary source of commutating energy to turn off the SCRs. The several advantages Class E commutation offers to a motor drive system are as follows:

1. The commutation voltage is essentially independent of the load voltage.

2. The commutation circuitry has little effect on the inverter circuit except during periods of commutation.

3. A fixed turn-off pulse is available at any frequency or voltage assuring a safe turn-off time.

Two Class E commutation systems are presented: a group commutation for the three-phase bridge inverter system and an individual commutation system. Discussion of the systems follows.

The "group commutation system" commutates all phases simultaneously (17) and is connected to the d-c input side, instead of to the load side of the inverter bridge. A switching circuit allows charging a capacitor from the auxiliary d-c supply and discharging it into the input terminals of the bridge when commutation is necessary. The voltage applied to the bridge is reversed momentarily, and any conducting SCRs are, thereby, turned off. The next pair of SCRs are then fired to continue the required sequence for formation of the a-c waveform.

The group commutation system makes maximum use of capacitance because only one capacitor is used for all commutations. The charge on the capacitor can be controlled by adjusting the voltage of the auxiliary supply; therefore, the charge is independent of the voltage applied to the motor and is unaffected by the motor voltage waveform.
A commutating circuit of this type uses a static switching arrangement. As shown on Figure 9, SCR 7 is fired at each commutating instant, i.e. six times per cycle for the six-step inverter. Assuming that C is initially charged with its upper-plate negative, the bridge input voltage is reversed for a short time when SCR 8 is fired. C is now positively charged from the main supply and, due to the stored energy in L1 and L2, acquires a voltage greater than the main supply. The reverse voltage of C causes SCR 8 to turn off by natural commutation. At a convenient time before the next commutation occurs, SCR 7 is fired. C now negatively charges through the small inductor so that after a half cycle of oscillation, its voltage approaches a magnitude which is twice the auxiliary supply voltage plus the positive main supply voltage after commutation (12).

The charge available for commutation is dependent on both the main supply and the auxiliary supply voltages. When the main supply voltage is low, i.e. with the motor at standstill, the commutating charge is primarily dependent on the auxiliary supply, which then must be adequate to insure commutation of the maximum motor current. When the main supply voltage is high, the commutating energy required from the auxiliary supply decreases.

The "individual commutation system" commutates each SCR individually in the bridge. The reverse potential is produced by applying a reverse voltage pulse from an external voltage source into a transformer winding in series with each load carrying SCR (9). The transformer, designed not to saturate, is capable of carrying the load current with a small voltage drop as compared to the motor voltage (16).
FIGURE 9 AN ELEMENTARY SFC WITH A "GROUP COMMUTATION" SYSTEM ADDED

FIGURE 10 AN ELEMENTARY SFC WITH "INDIVIDUAL COMMUTATION" SYSTEM ADDED
The commutation pulse is supplied by an auxiliary d-c power supply so that a fixed turn-off pulse is available at any frequency or voltage.

The turn-off time of an SCR is equal to the width of the applied pulse. The conducting time of the load-carrying SCR is the time from the start of current flow to the application of the commutating pulse. The conducting time of any SCR may be varied over a wide range; certain control methods require this feature.

A commutating circuit is shown on Figure 10 (9)(10). When an SCR is turned on, current flows through the load and the pulse transformer secondary winding. The SCR is turned off by applying a voltage pulse from the auxiliary d-c supply through a pulse transformer to the cathode of the SCR. The feedback diode conducts and carries the excess commutating energy. The voltage drop across the feedback diode is about one volt, which is in inverse parallel with the SCR for the duration of the turn-off pulse. Thus, the pulse from the transformer reverses the voltage across the SCR, supplies the reverse recovery current, and provides the necessary turn-off time (16).

Voltage Control System

The motor equations, Chapter II, indicate load torque can be maintained throughout a given speed range if motor input voltage can be varied in approximately a direct relationship to the input frequency.

A voltage control system must be developed to allow satisfactory motor performance. The three-phase, six-step inverter supplies a constant-voltage waveform, unless the d-c input to the inverter is changed. Changing the d-c input to the inverter is a practicable
method of voltage control, and assuming that the d-c supply to the inverter is adequately filtered, the harmonic content of the inverter-output waveform does not change from that listed in Table I.

The d-c input voltage to the inverter can be varied by means of a controllable rectifier, which is "slaved" to the frequency reference, to automatically regulate the desired voltage when the frequency is changed (9)(10). A voltage feedback loop can be used to compare the output voltage with the frequency-voltage signal to control the firing of the controlled rectifier. The controllable rectifier can be either a semi-converter with three diodes and three SCRs or a converter with six SCRs. Approximate phase-back angles for the semi-converter and converter can be simply determined, but filter design and analysis of waveform supplied to the inverter are not practical using classical techniques (14).

Frequency Control System

Frequency control is accomplished in the inverter by turning on the appropriate SCR or SCRs to initiate the next part of a cycle. An oscillator performs this function by producing an output-frequency signal which is converted into a train of timing pulses. The train of timing pulses fires the SCRs and determines the inverter-output frequency. For the three-phase, six-step, square-wave inverter, six timing pulses are required per cycle.

The type of oscillator depends on the drift requirements of the system. A resistance-capacitance (R-C) oscillator using unijunction transistors is most common and is used where drift accuracies
<table>
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within one percent are acceptable. Greater accuracies can be obtained by enclosing the oscillator components in a temperature controlled atmosphere.

The oscillator circuit has no frequency or speed signal feedback; hence, the inverter system operates open-loop. The inverter output follows the oscillator, or if a failure occurs, stops completely. The inverter-output frequency is independent of the load on the inverter, and is not even transiently affected by changes in supply or line voltage.

A potentiometer is used to vary R in the R-C oscillator which varies the oscillator frequency (7), the inverter-output frequency, and finally, motor speed.

Reference and Firing Controls

The three-phase, six-step inverter requires either one or three turn-on pulses per cycle for each of the six SCRs depending on the commutation system used. Firing one or three SCRs every 60 degrees of the 360 degrees of a full-cycle produces the six-step, square-wave, inverter voltage output shown on Figure 6.

The oscillator frequency signal provides timing for reference circuitry which must supply a signal to each SCR gate-firing circuit in a predetermined sequence. A six-bit ring counter can be used to establish the square-wave gating signals spaced 60 degrees apart for the SCR gate firing circuits (15).

The gate firing circuits for the inverter SCRs must supply extended gate signals rather than short pulses; because unwanted voltage
or current reversals can occur due to the inductive load current, sometimes flowing in the SCRs and sometimes in the feedback rectifiers. The gate firing circuit utilized for each SCR must, in addition to the other requirements, be isolated from all other gate firing circuits and from the reference circuitry. Isolation is necessary because the gate circuits of three of the legs of the inverter bridge are not at a fixed potential.

An isolation technique, which can be utilized with both semiconductor and hybrid gate-firing circuitry (29), utilizes a pulse transformer connected to the SCR gate (12). A switched, high-frequency carrier on the transformer primary is rectified on the transformer secondary to provide an isolated d-c signal for firing the SCR.
IV. MODELING AND SIMULATION FOR SYSTEM ANALYSIS

Modeling and simulation are powerful tools for the analysis and design of complex systems. Analyses of phenomena in such systems as the SFC speed control system were difficult using classical, analytical techniques, but are now practical using modeling and simulation techniques on analog and digital computers. The effects of system decisions can be studied without actually constructing and testing a hardware system (3, p. 107). This is especially advantageous for an SFC because of the great cost and low thermal overload capabilities of the diodes and SCRs in the rectifier and inverter.

Models and Modeling

A model is a qualitative or quantitative representation of a system or process that shows the effects of those factors which are significant for the purposes being considered (3, p. 108). Although a model might not represent the actual phenomena in all respects, it does describe essential inputs, outputs, internal characteristics and environmental conditions, similar to those of the actual equipment.

Simulation

Simulation is the use of models and/or the actual conditions of the system or process being modeled and the environment in which it operates (3, p. 22). The model or conditions must be quantitative, but can be in physical, mathematical or some other form.
The purpose of simulation is to explore various results that can be characteristic of the real system. This is done by subjecting the model to representative data that are equivalent to the parameters of the real system.

**A Modeling and Simulation Technique for SFC System Analysis and Design**

The SFC is a complex system composed of several subsystems. The diagram of the overall system, shown on Figure 11, is composed of several "blocks," one for each subsystem. The block diagram is a qualitative model which indicates the essential inputs and outputs of the SFC system presented in Chapter III.

The qualitative system block diagram, Figure 11, and the qualitative circuit diagrams, Chapter III, for several of the "blocks" are the bases for developing a quantitative model of the static frequency converter speed control system. The development of a quantitative system model requires development of quantitative models, either analog or hardware, for each of the subsystems of the SFC. The model for each subsystem requires that approximate input and output parameters, likely to allow the overall system to meet its goals, be defined.

Simulating a complex system such as the SFC can be accomplished, if individual parts of the system are simulated separately, using approximate models. As the sensitivities of the variables associated with each subsystem are determined and the basic effects are understood, the subsystems can be set aside to be used in the overall system simulation.
FIGURE 11  A QUALITATIVE MODEL OF THE PROPOSED SFC SYSTEM
The system's ability to meet desired operating goals and to withstand inherent, destructive transient phenomena can be determined from the model by computer simulation. The computer simulation is used to study overall circuit characteristics, i.e. RMS currents, current harmonics, regulation, overload performance, short-circuit capacity, output distortion, ripple etc. for discrete frequencies over the expected operating range (1). Analog parts of the system model can be programmed on an analog computer to allow analysis of the complex, nonlinear, nonperiodic, current and voltage waveforms. Parameters can be easily varied. Time scaling permits accurate analysis and correlation of waveforms (11).

The rectifier, filter, and inverter output waveforms are of primary interest and can be analyzed by digitizing the analog data, i.e., feeding through analog to digital converters. Digital subprograms can then be used to accurately compute RMS and harmonic quantities and spectral analysis for any given waveform.

Once transient conditions and normal operating conditions for the system are understood, more accurate modeling and simulation techniques can be applied, if required. Effective selection of system components, and/or an attempt at optimization, can be realized using the information from the techniques described.

After the modeling and simulation has reached the necessary accuracy, a breadboard hardware system can be designed and a laboratory test program can be planned. After the economic feasibility is evaluated, a prototype system can be constructed for field installation and testing.
V. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The speed of the three-phase squirrel-cage induction motor can be varied over a continuous range by simultaneously controlling the input frequency and voltage. Speed is directly proportional to frequency, but the voltage must be changed in the same relationship to avoid magnetic saturation. A nonsinusoidal supply causes increased motor losses; but the losses can be minimized by motor design, by filter or control techniques to change the supply waveform, or both.

2. The static frequency converter provides control of both frequency and voltage using solid-state components. The two basic subsystems of the SFC are a three-phase full-wave bridge rectifier and a three-phase bridge inverter. The rectifier converts a fixed voltage and frequency a-c input to d-c, and the inverter converts the d-c to a variable-frequency a-c output.

3. Subsystems must be added to the rectifier-inverter to perform functions unique to supplying a SCIM. The subsystems and functions are as follows:
   a. Feedback diodes provide an alternate path for reactive current after commutation has occurred.
   b. Commutation circuitry terminates conduction of the SCRs.
   c. Voltage control circuitry automatically regulates voltage in a preset manner relative to frequency.
d. Frequency control circuitry establishes frequency and hence, motor speed.

e. Reference and firing circuitry establishes the sequence of, and insures turn-on of the inverter SCRs.

4. An SFC is a complex system which is extremely difficult to analyze using classical techniques. Modeling and simulation, using analog and digital computers, offer a method of analysis and ultimate optimization of the total system: the static frequency converter, the three-phase squirrel-cage induction motor, and the driven load.

5. The transient and steady-state values obtained from the computer model and simulation can be used as the basis for a design and test program using actual hardware circuitry at a minimum cost.

Recommendations

1. Establish quantitative system goals.

2. Develop a quantitative SFC system model, motor model, and load model.

3. Simulate system goals using the quantitative model.

4. Alter model until system goals are reached by simulation.

5. Select hardware components for a practicable system including protective circuitry.


7. Construct and test a prototype system.
BIBLIOGRAPHY


APPENDIX A

MOTOR TEST

Tests were performed in the OSU electrical machine laboratory in Dearborn Hall to determine the starting and operating characteristics of a five-horsepower SCIM with variable frequency and voltage supply. A simulated pump load was placed on the motor; i.e. load torque demanded varies inversely as the square of the motor speed.

The stator of the SCIM was connected through suitable instrumentation to a wound-rotor induction motor which was used as a frequency converter. The SCIM was driving a d-c generator which was loaded with a water rheostat to simulate a pump load.

Data on motor steady-state operation, obtained from the laboratory, are in Table A-1. Figures A-1 and A-2 show motor current on starting for supply frequencies of 20 Hz and 30 Hz.

<table>
<thead>
<tr>
<th>TABLE A-1. TEST DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Frequency (Hz)</td>
</tr>
<tr>
<td>Motor Speed (rpm)</td>
</tr>
<tr>
<td>$V_A$ (volts)</td>
</tr>
<tr>
<td>$V_C$ (volts)</td>
</tr>
<tr>
<td>$I_A$ (amps)</td>
</tr>
<tr>
<td>$I_C$ (amps)</td>
</tr>
<tr>
<td>$W_A$ (watts)</td>
</tr>
<tr>
<td>$W_C$ (watts)</td>
</tr>
<tr>
<td>$W_A + W_C$</td>
</tr>
<tr>
<td>Power Factor</td>
</tr>
</tbody>
</table>
FIGURE A-1  CURRENT WAVEFORM DURING STARTING AT 30 HZ
HORIZ. SCALE  100 M SEC / CM
STEADY STATE CURRENT 5.5 A RMS

FIGURE A-2  CURRENT WAVEFORM DURING STARTING AT 20 HZ
HORIZ. SCALE  100 M SEC / CM
STEADY STATE CURRENT 5 A RMS
The following conclusions can be drawn from the laboratory tests:

1. Motor speed is directly proportional to the supply frequency from 60 Hz to 20 Hz (with a simulated pump load and with voltage reduced directly with frequency).

2. Motor starting current is approximately 3 times rated current at 20 Hz, 4.5 times rated current at 30 Hz, and an expected 6 to 7 times rated current at 60 Hz.
APPENDIX B

FREQUENCY CONTROL AND REFERENCE CIRCUITS

Frequency control for the inverter can be accomplished with a unijunction transistor (UJT) oscillator. Six pulses are required for each a-c cycle; therefore, the oscillator frequency must be six times the required inverter frequency.

The frequency of the UJT oscillator shown on Figure B-1 is given by

\[ f = \frac{1}{T} = \frac{1}{2.3} \frac{1}{R_1C_1 \log \left(\frac{1}{1-N}\right)} \]

where \( N \) is the intrinsic standoff ratio of the UJT used. \( R_1 \) and \( C_1 \) can be selected to produce the required frequency. \( R_1 \) can be a manually adjustable or an automatically controlled potentiometer which causes frequency to be adjustable.

The output from the UJT oscillator can be used to trigger a UJT ring-counter which acts as a reference control. The ring-counter circuit shown on Figure B-2 is an application of a basic bistable circuit. Resistors \( R_6 \) and \( R_7 \) correspond to the emitter load resistor and keep the voltage at the collector of \( Q_7 \) less than the peak-point voltage of the unijunction transistors when the supply voltage is turned on.

Transistor \( Q_1 \) is turned on by the set switch and maintained in the 'On' state by current flowing through \( R_6 \) and diode \( D_1 \). When the first trigger pulse is applied, the current from \( R_6 \) is diverted to
FIGURE B-1 UNIJUNCTION TRANSISTOR RELAXATION OSCILLATOR

FIGURE B-2 UNIJUNCTION TRANSISTOR RING COUNTER
ground through the collector of Q₅, and Q₁ turns off. The voltage at base B₂ of Q₁ rises and Q₂ is turned on through C₂. At the end of the trigger pulse Q₂ is maintained in the 'On' state by the current flowing through R₆ and D₂. Each successive trigger pulse advances the count one stage to the right.

A voltage pulse is produced each time the counter steps; i.e. across resistor R₁₀ at the first step, across resistor R₁₁ at the second step, and so on. The pulses can be shaped, amplified, and isolated to assure proper firing of the inverter SCRs.