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TEST PROGRAM FOR EVALUATION OF VARIABLE FREQUENCY POWER CONDITIONERS

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FINAL REPORT

APPROVED FOR U.S. GOVERNMENT ONLY. THIS DOCUMENT IS EXEMPTED FROM PUBLIC AVAILABILITY BECAUSE IT IS A TSC TEST PROGRAM PLAN WHICH IS OF LIMITED INTEREST; A REPORT OF THE TEST RESULTS IS PLANNED FOR PUBLIC DISSEMINATION. TRANSMITTAL OF THIS DOCUMENT OUTSIDE THE U.S. GOVERNMENT MUST HAVE PRIOR APPROVAL OF THE FEDERAL RAILROAD ADMINISTRATION.

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16. Abstract

A test program is outlined for variable frequency power conditioners for 3-phase induction motors in vehicle propulsion applications. The PCU performance characteristics are discussed in some detail. Measurement methods, recording techniques and data presentation are given which should yield a broad set of performance data common to most PCU designs of this type. Measurements of component electrical and temperature stresses are included. These measurements are regarded as essential for a meaningful evaluation and for formulating estimates of peak power capability and specific power (kVA/lb). A limited test program of the RFI/EMI characteristics of the PCU is also discussed, as are tests of special characteristics such as reliability and failure modes.

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PREFACE

The work described in this report was performed in the Power and Propulsion Branch of the Transportation Systems Center under the sponsorship of the Advanced Systems Division of the Office of Research, Development, and Demonstrations, Federal Railroad Administration.

The objective of this work was to outline a test program for the evaluation of different variable frequency power conditioners under consideration for use with both rotary and linear induction motors.

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LIST OF SYMBOLS

ac	alternating current
dc	direct current
dI/dt	time rate of change of current
dV/dt	time rate of change of voltage
EMI	electromagnetic interference
Hz	hertz
I	current
IC	integrated circuit
kVA	kilovolt-amperes
lb	pound
LIM	linear induction motor
MHz	megahertz
m-g	motor-generator
ms	millisecond
PCU	power conditioning unit
RFI	radio frequency interference
rms	root mean square
RPM	revolutions per minute
V	volts
vs	versus
ΔV_{ℓ}	change in line voltage

1. INTRODUCTION

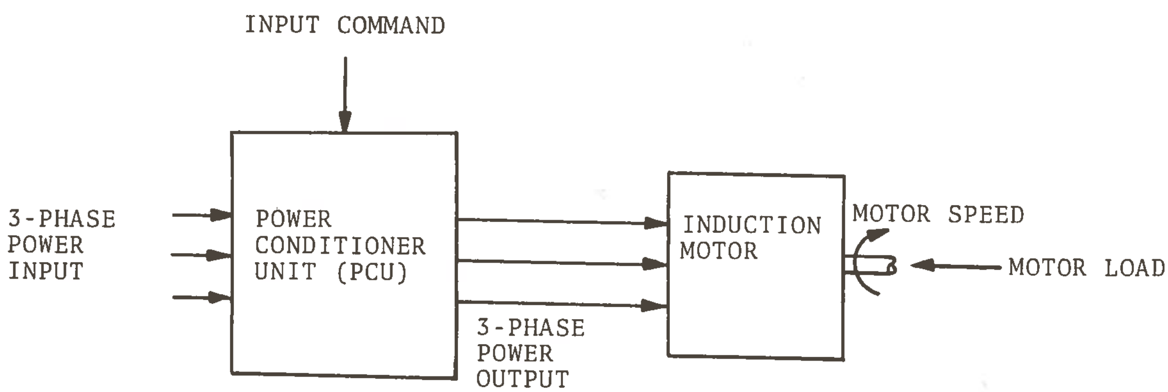
Variable frequency power conditioners are being considered for the drive of both rotary and linear induction motors (LIM) for vehicle propulsion. The most significant requirements of these power conditioners are light weight, high efficiency and acceptable reliability. However, many other performance and operating characteristics are of importance. Examples of such characteristics are power factor during acceleration, effective frequency range and harmonic power line distortion. Thus, the choice of a power conditioner should be made on the basis of sound knowledge of all characteristics.

2. DISCUSSION OF POWER CONDITIONER CHARACTERISTICS

An extensive set of measurement data is required for a thorough evaluation of the power conditioning units (PCU). The measurements recommended for the test program and for the presentation of the data are discussed in the following two sections. A simple diagram of the PCU and motor load with definition of terms is shown in Figure 1 to facilitate the discussion.

2.1 PERFORMANCE CHARACTERISTICS

The first set of measurements recommended will establish a set of operating performance characteristics for each PCU. The measurements required to develop these characteristics have been divided into five groups as shown in Table 1 and will be discussed under separate headings.



3-phase power input: 60 Hz from power lines.

3-phase power output: Variable frequency and voltage.

Motor speed: Shaft angular velocity in RPM.

Input command: Voltage, frequency, direction, etc. (control inputs).

Figure 1. Definition of Terms

TABLE 1. MEASUREMENT OF PERFORMANCE CHARACTERISTICS

MEASUREMENT GROUP	MEASURED QUANTITIES
1. Input/Output Power	Total apparent power True rms voltages True rms currents Real power Displacement reactive power Distortion reactive power Power factor Efficiency during loading and during regeneration Regulation with line voltage variations Operation with unbalanced input voltages and/or unbalanced load
2. Waveforms and Harmonics	Input and output current waveforms Input and output voltage waveforms Input current harmonics Output current harmonics Output voltage harmonics (if deemed required) Current and voltage transients
3. Control Characteristics (Excluding external control apparatus and loops)	Speed-torque (thrust) curves at constant speed command Motor speed vs. speed command at constant loads. (Linearity, null dead band, hysteresis control range.) Response to step changes in speed command
4. Component Stresses	Component peak and rms voltage, peak and rms current levels Waveforms; dV/dt and dI/dt Instantaneous and average dissipation Temperature rise
5. Special Characteristics	Device utilization factor Commutation margin Power interruption performance, overload, failure protection Effects of series line impedance

2.1.1 Input/Output Power

The first group of measurements in Table 1 is concerned with the input and output characteristics of the PCU. The measurements listed are used to generate four sets of curves such as those shown in Figures 2 to 5. The curves of Figure 2 display the real and reactive input power to the power conditioner as a function of the motor speed (or output frequency). The curves of Figure 3 display the same quantities during regeneration of power (such as during deceleration). The reactive power indicated in both figures contributes to the apparent power but not to real power and therefore should be minimized.

Figure 4 is a typical plot of the overall efficiency of the PCU. The efficiency is usually at its highest level at the maximum output power level (full load at full speed) and drops off with both load and speed. The peak efficiency and the rate of drop with power level are effectively displayed in the curves of Figure 4 and may be used conveniently for comparison with those of other PCUs.

The ability of the PCU to regulate against variations of the 3-phase ac line voltage is given by the plots of Figure 5. This characteristic is very important since a failure to regulate, as indicated by the knee in the curves, would point to the fact that the inverter rating is too high and should be dropped.

Final measurements of the input-output power characteristics include the effects of unbalance in the 3-phase input voltage and the inverter's ability to operate for various degrees of load unbalance.

2.1.2 Waveforms and Harmonics

The input/output waveforms and harmonics are listed in the second group of measurements in Table 1. The waveforms are first recorded to establish the probable distribution of harmonics and the presence of spikes or fast transients. Typical waveforms of the line-line voltage and line current are shown in Figures 6 and 7.

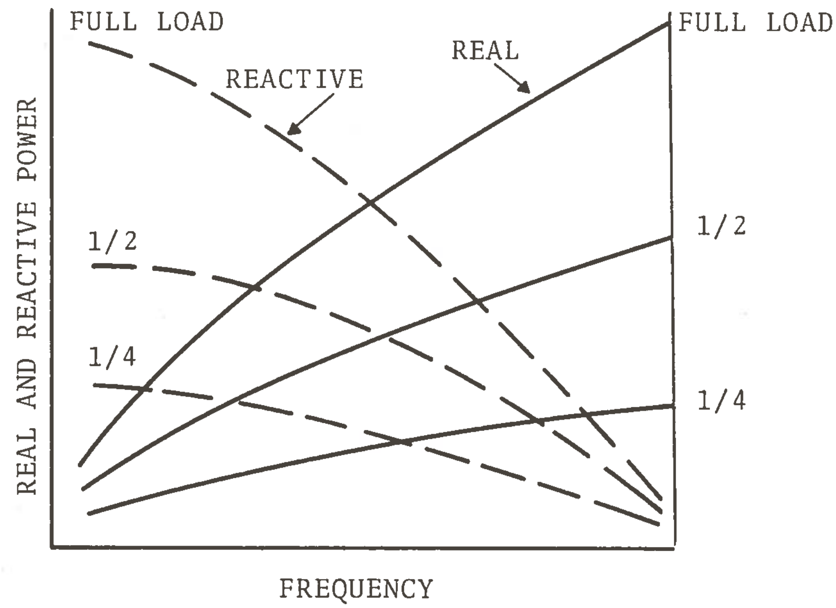


Figure 2. Representative Curves of Real and Reactive Input Power during Acceleration and Loading

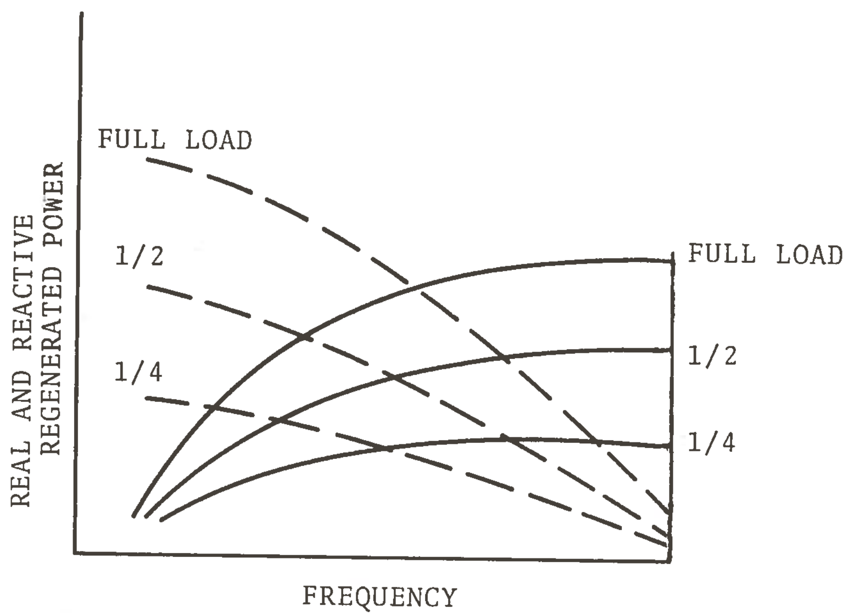


Figure 3. Representative Curves of Real and Reactive Input Power during Deceleration and Regeneration

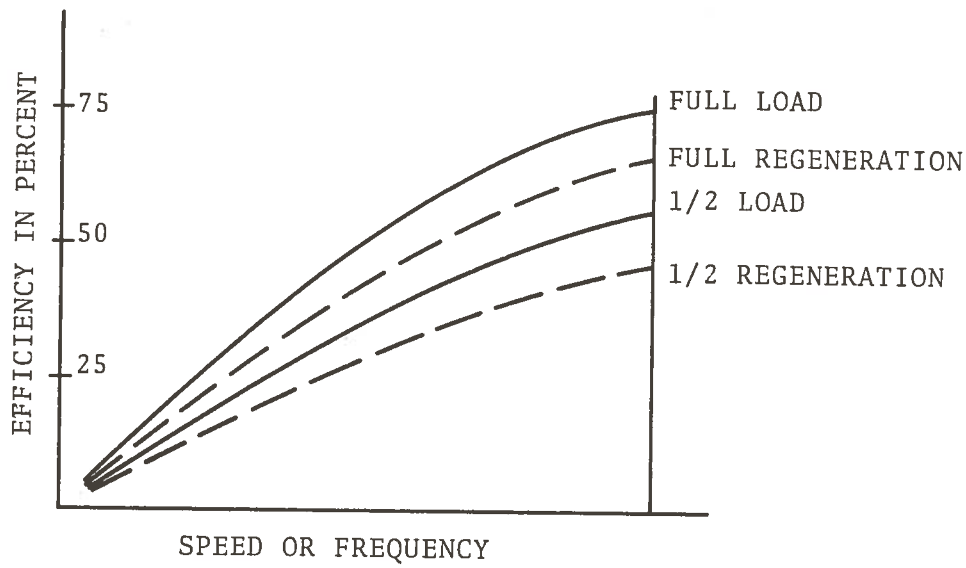


Figure 4. PCU Efficiency Curves during Loading and Regeneration as Function of Speed

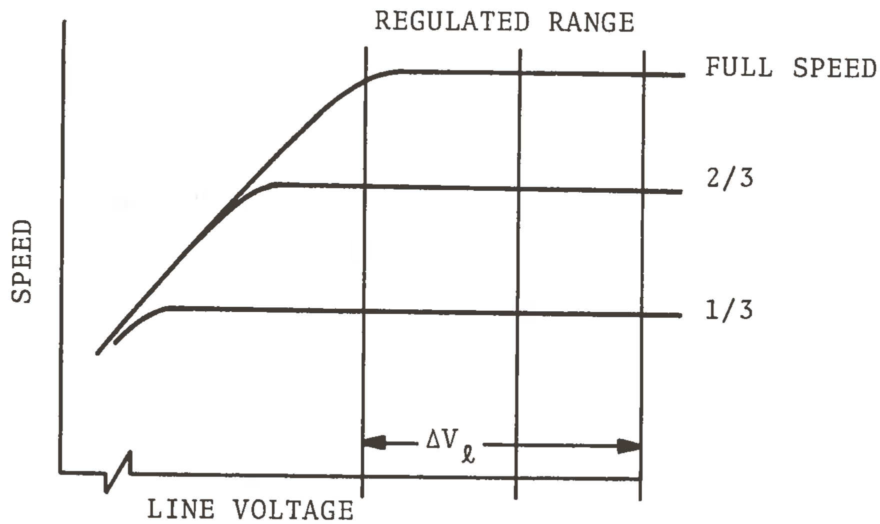


Figure 5. PCU Regulation Against Variation of Input (Line-Line) Voltage at Full Operating Load

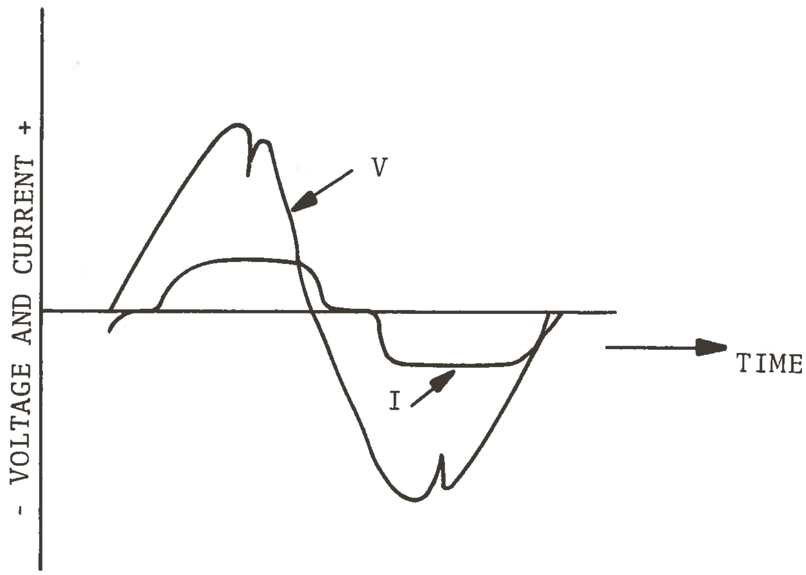


Figure 6. PCU Input Voltage and Current Waveforms

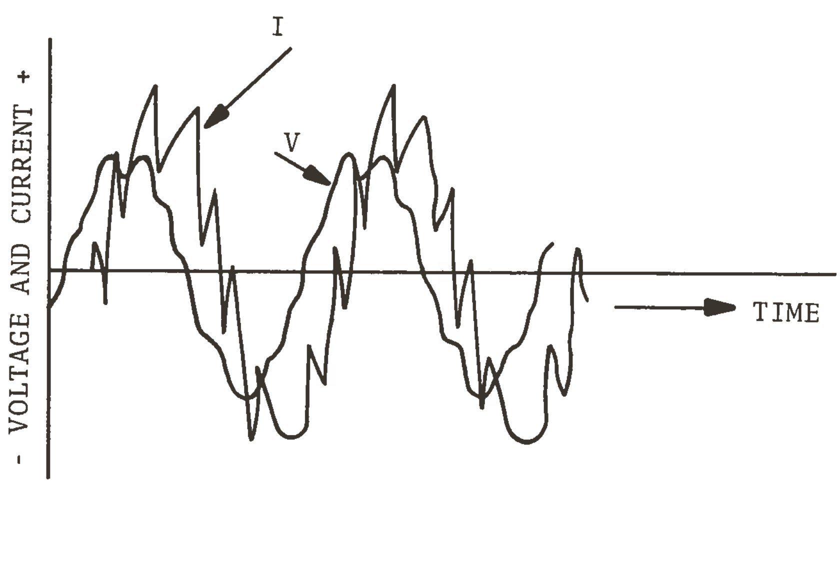


Figure 7. PCU Output Voltage and Current Waveforms

The harmonics should be measured at different power levels and motor operating frequencies. Two examples of harmonic measurements of the input current are shown in Figure 8 for full and 1/2 power level. Similar harmonic displays are given for the output current in Figure 9 for three motor speeds. The intent of the multiple display is to indicate the extreme variation in the harmonic content at different operating levels. These extremes do not necessarily occur under the operating and load conditions indicated.

Low harmonics in the input and output lines are desirable for a number of reasons. The more important ones are the reduction of distortion reactive power, control of interference, and reduction of line, transformer and motor losses. Separate measurements of EMI will be discussed in Section 3.

2.1.3 Control Characteristics

A third group of measurements is related to the control characteristics of the PCU. The tests are separated in two classes which measure (a) the static and (b) the dynamic characteristics. The motor torque-speed curves, under the control of the PCU, are the most common of the static control characteristics. A typical set of torque-speed curves are shown in Figure 10. These curves, which are recorded for three constant values of speed commands (constant PCU output frequencies) must be obtained by both positive and negative motor loading. The slopes of the curves are a function of both the motor torque-slip characteristics and the PCU output impedance. A tendency for a decrease of the slope at high torque loads indicates a saturating characteristic of the PCU which should not occur in the rated torque band of Figure 10.

Another set of static control curves is shown in Figure 11. These curves are to be plotted from measurements of the motor speed vs. PCU command speed (PCU output frequency) under a constant torque loading. These curves, which are also plotted for both positive and negative torques, yield information on linearity and control characteristics at very low speed. Figure 11 indicates

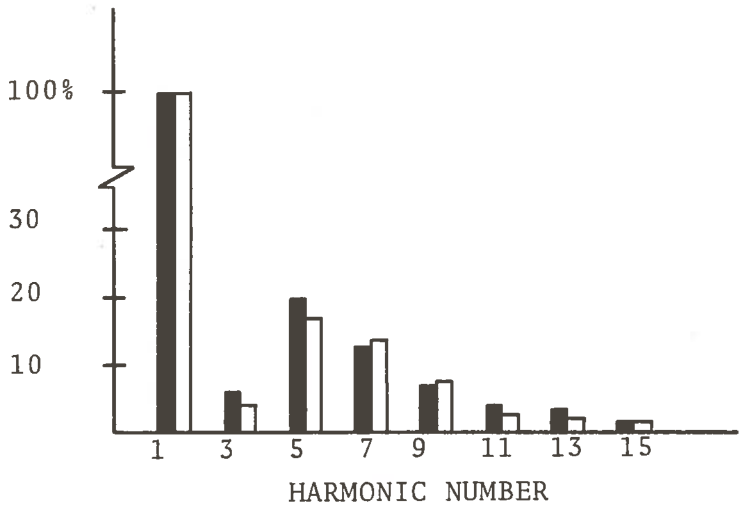


Figure 8. Representative Harmonic Content in PCU Input Current at Two Levels of Power.

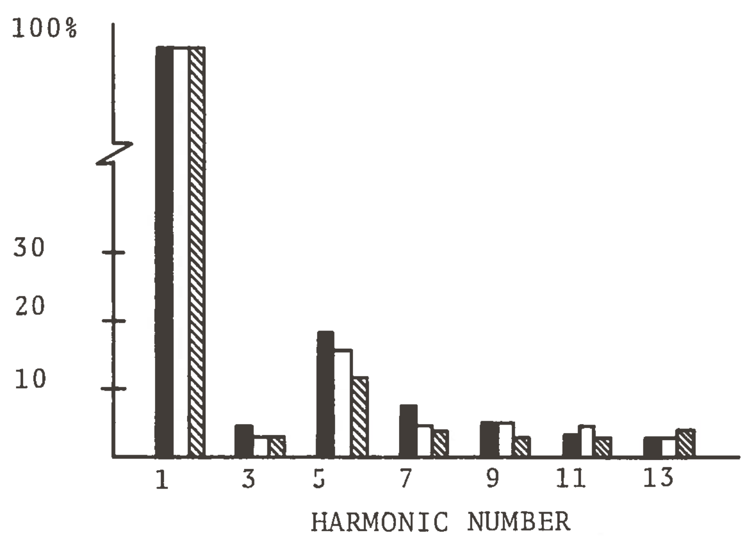


Figure 9. Representative Harmonic Content in PCU Output Current at Three Operating Frequencies

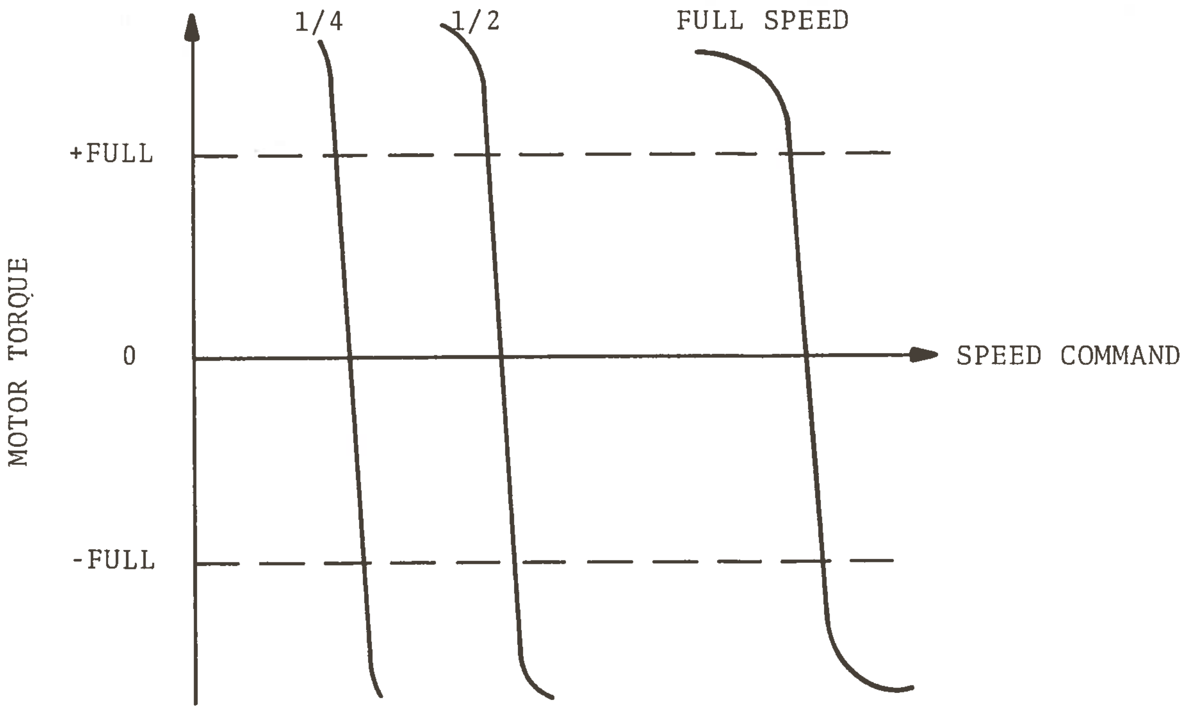


Figure 10. Speed-Torque Control Curves

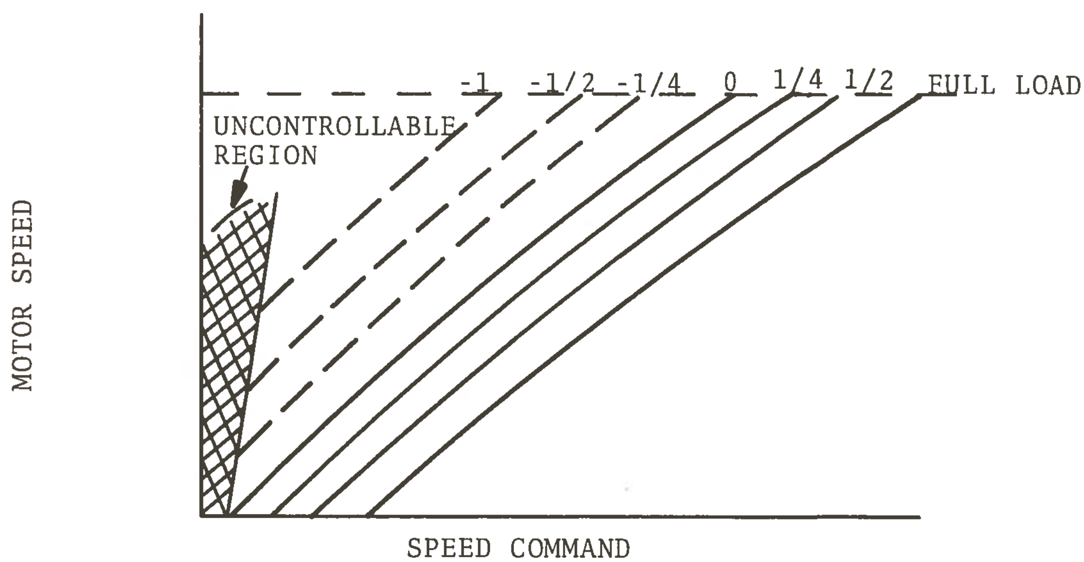


Figure 11. Control Performance under Constant Load

with a cross-hatched area a torque-speed range where the speed control is poor. This "uncontrollable" region is a result of the characteristics of a motor loaded inverter which, for some inverters, changes drastically at low frequencies. This problem may be particularly noticeable during regeneration of power.

A final control characteristic of relatively high importance is the PCU's response time to changes in command speed or frequency. Typical plots of the PCU response to incremental step changes in the command speed are shown in Figure 12, where both the motor speed and PCU output frequency are indicated. The frequency rise, which is a characteristic of the PCU alone, consists typically of a small delay time plus an exponential rise. Overshoots in this curve may occur, but these are likely to degrade control stability and are therefore undesirable. A response time of 10 ms is desirable, but not required; response times of 100 ms are acceptable. The changes of motor speed with time that result are a function of both the frequency rise time and the motor and load inertia. Smooth curves with no overshoots are desirable

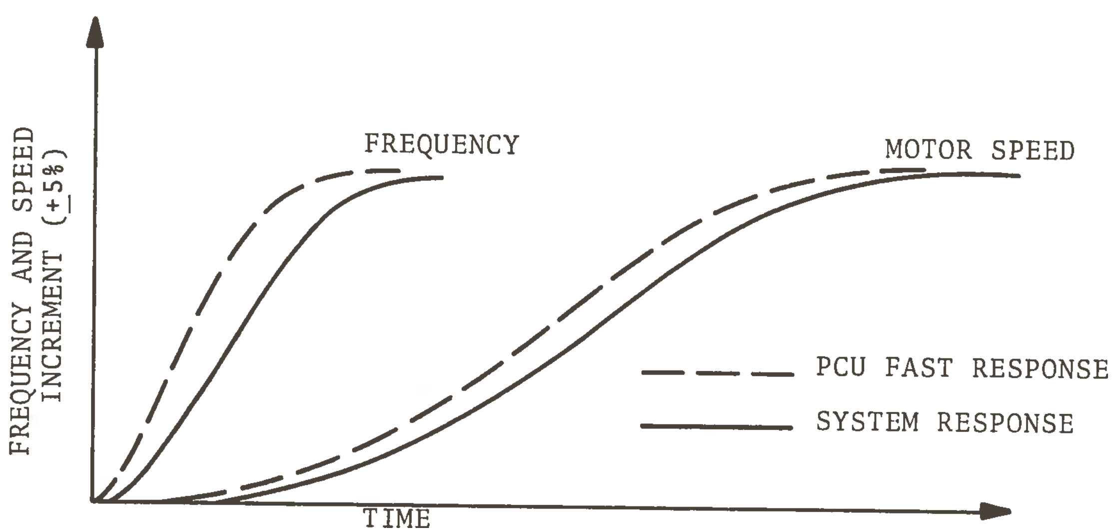


Figure 12. Control Response Characteristics

characteristics. Curves should be plotted for fractional load, full load and overload, with a step speed command increment of ±5% of full speed.

2.1.4 Component Stresses

A fourth group of measurements evaluates the electrical stresses on the main power components of the PCU. Oscilloscopes and cameras are used to obtain records of component current and voltage waveforms. The measurements of particular interest are the dV/dt and dI/dt stresses of power thyristors, instantaneous switching transients in power rectifiers, rms current in semiconductors and capacitors, and voltage spikes. All this information must be compared with manufacturers' ratings to establish a derating factor applicable to each type of component in the PCU. This information is important for a comparative evaluation which should take into consideration the differences in component stresses of the various PCU designs.

2.1.5 Special Characteristics

A final group of measurements is concerned with special characteristics of the PCU, such as power interruption characteristics, overload characteristics, failure modes and protection, reliability in general, etc. Little provision may have been made in the PCU test units for favorable performance in these areas. However, it is felt that some tests and evaluations can be made which would indicate the performance in a qualitative manner. An evaluation should also be made of the PCU maintainability.

2.2 RFI/EMI CHARACTERISTICS

Measurements of RFI/EMI characteristics must be made to establish both the effect of the equipment upon the environment and the resistance, or "susceptibility", of the equipment to external interference. Interference can result from both radiation and conduction; thus, the following four types of interference

must be considered:

a. radiated emission

b. conducted emission

c. radiated susceptibility

d. conducted susceptibility.

RFI/EMI characteristics and methods of measurement are regulated very rigorously by military and Federal specifications. The specifications that pertain to this type of equipment are primarily:

a. MIL-STD-461A, Notice 4 (EL), 9 February 1971

"Electromagnetic Interference Characteristics Requirement for Equipment, Subsystems and Systems"

b. MIL-STD-462A, Notice 3 (EL), 9 February 1971

"Electromagnetic Interference Characteristics, Measurement of,"

c. MIL-STD-463, 9 June 1966

"Military Standard Definitions and System of Units, Electromagnetic Interference Technology"

d. MIL-STD-826A (USAF), 30 June 1966

"Military Standard Electromagnetic Interference Test Requirements and Test Methods"

e. Federal Standard No. 222.

It is felt that most RFI/EMI tests can be run in the laboratory; a screen room, however, may be required.

3. WEIGHT, SIZE, AND PACKAGING

The actual weight and size of the PCU equipment should be obtained. However, it is not expected that figures obtained directly from the weight and dimensions of the test units will be good indications of what can be accomplished in this area.

The packaging techniques used in the test PCU should be studied first. A set of several packaging "rules" should be established and weight and size estimates made by applying these rules uniformly for each PCU. The rules should include uniform specific weight and volume for:

a. semiconductor heat sinks, given per watts of dissipation

b. larger ac and commutating capacitors, given per kVA

c. electrolytic capacitors, given per peak joules

d. ac inductors, given per kVA

e. dc inductors, given per peak joules

f. transformers, given per kVA

g. electronic control equipment, given per transistor and/or IC number.

The actual number of parts and their types should be evaluated against the operating conditions of the parts as found during testing. Adjustments should be made in both type and number of parts so that the operating conditions are as uniform for all PCUs as possible. In general, all parts, except the semiconductors, should operate at peak voltage, current and dissipation levels near their given 80°C ratings. The thyristors and rectifiers should be working at maximum levels of about 75% below the rated voltage, current and power dissipation levels given by the manufacturer.

4. INSTRUMENTATION AND TEST SETUP

4.1 PERFORMANCE MEASUREMENTS

A block diagram of the setup and instrumentation for the performance measurements is presented in Figure 13 and the instrument types for the desired measurements are indicated in Table 2. Figure 13 indicates a "Power System Transducer" which is used to process the input and output 3-phase currents and voltages to produce dc signals proportional to these and to the real and reactive power components. Such transducers, which are all-electronic devices and available off-the-shelf, perform the necessary vector multiplications and detection to provide measurements with a ±1% accuracy or better. A strip chart recorder is used to provide instant and permanent records. Voltage and current are measured with digital voltmeters.

A dc (motor-generator type) dynamometer is used to provide controlled loading of the PCU driven induction motor. These dynamometers, which are available as complete packages, consist of a dc motor powered by a dc generator. The shaft of the latter is driven at a relatively constant speed by an induction motor. The generator voltage is varied by control of the generator field. Electronic equipment is provided for closed-loop control of the field current holding the motor torque constant. A signal is available at the electronic circuitry proportional to the motor current and also nearly proportional to motor torque. The motor speed is measurured by the use of a tach generator.

The dc m-g dynamometer is recommended for the testing since it will both deliver and absorb shaft power. In the system shown in Figure 13 the power flow is reversed, say, from delivered to absorbed power, by adjusting the dynamometer torque level from negative to positive torque. The speed of the dc motor will drop as the generator field current is reduced, the dc current will reverse and power is pumped from the PCU driven induction motor through the dynamometer back to the ac (3-phase)lines. Another important advantage of this type of dynamometer is that a significant

TABLE 2. INSTRUMENTATION FOR PERFORMANCE MEASUREMENTS

MEASUREMENT	INSTRUMENT TYPE	TYPICAL VENDOR
Apparent Power	True rms Voltmeters and Ammeters	Ballantine Inst.
Real Power	Power System Transducer	
Displacement Reactive Power	Power System Transducer	
Motor Torque	dc Motor-Generator Dynamometer (24 HP)	GE, Reliance
Motor Speed	Tachometer Generator	GE, Singer
Motor Shaft Power	Calculated (T x ω)	
ac Current	Hall Effect Current Transducer	Pioneer Magnetics
ac Vòltage and Current	DVM	Fluke, Dana
dc Voltage and Current	DVM	Fluke, Dana
Waveforms	Oscilloscope and Camera	Tektronix, Inc.
Harmonics	Oscilloscope and Wave Analyzer	Tektronix and Gen. Radio
Instantaneous Power	Electronic Multiplier	EXAR Integrated Syst.
Temperature Rise	Thermocouple, Microvoltmeter	Fluke
Recording	4 Channel Strip Chart	H.P. MOD 1702A
PCU Frequency	Frequency Meter	H.P.

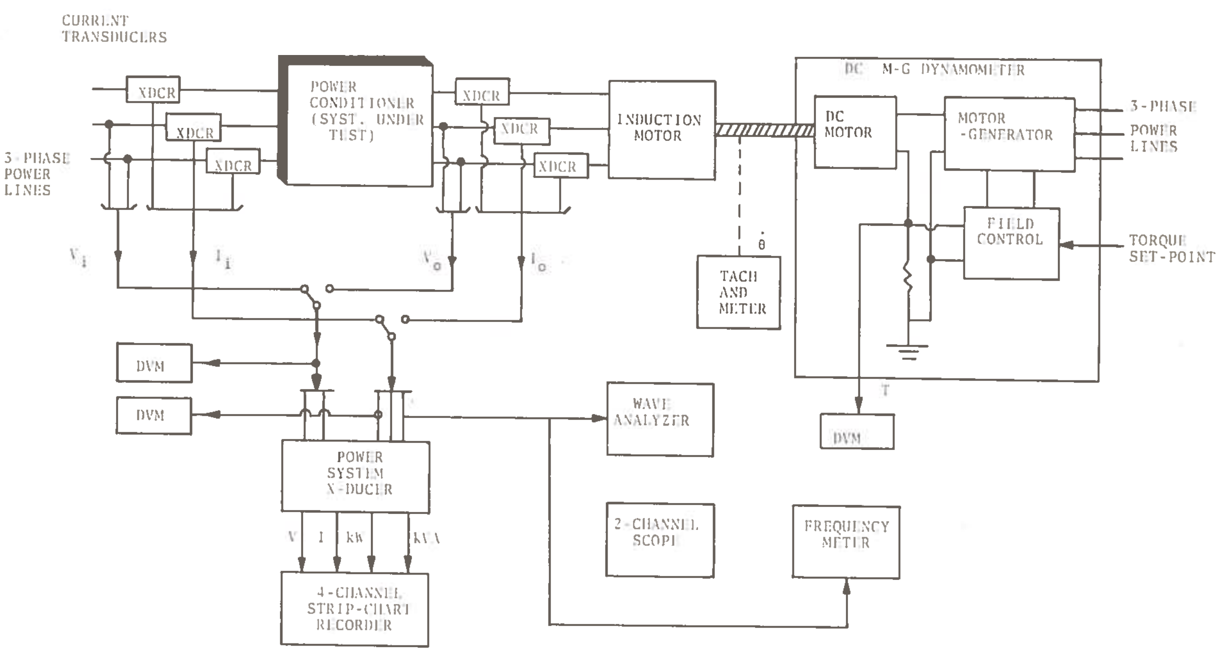


Figure 13. Instrumentation for Performance Measurements

part of the PCU load power will be returned to the power lines.

The harmonics in input and output power lines are measured with a wave analyzer. An oscilloscope with camera is used to observe and photograph the voltage and current waveforms. These should give an indication of the extent of waveform distortion and the number of significant harmonics. The oscilloscope will be used for measurement of component electrical stresses. Also, a wide band current probe, or transducer, is required. Finally, an electronic multiplier is used to provide a signal proportional to the instantaneous product of voltage and current, or instantaneous power.

4.2 RFI/EMI MEASUREMENTS

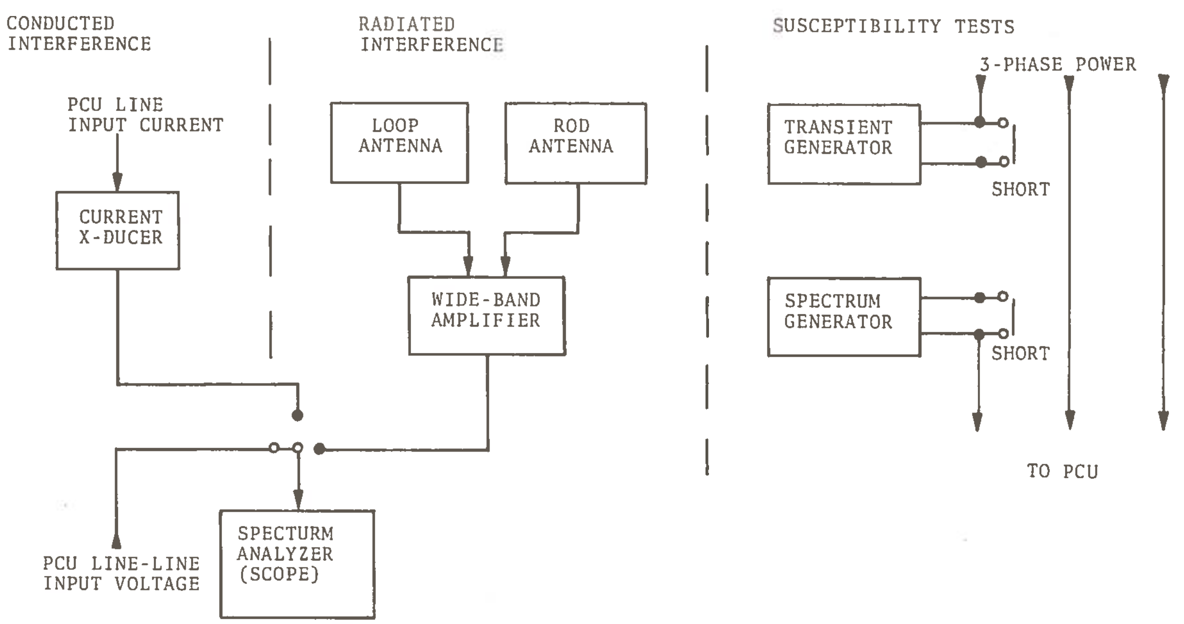
The instrumentation for a limited RFI/EMI measurement setup is schematized in Figure 14 and listed in Table 3. The conducted interference is evaluated by measuring the PCU current and voltage spectrum. The RFI and EMI radiation is evaluated by use of two antennas and a wide band amplifier providing spectrum coverage from 50 Hz to 10 MHz.

The susceptibility of the PCU is tested by introducing transients of controlled magnitude and an input noise signal of a given spectrum to the ac power line. These signals are provided one at a time by use of the shorting switches shown. Signal levels, timing and spectra are specified by MIL-STD-826 and MIL-STD-704A.

TABLE 3. INSTRUMENTATION FOR RFI/EMI MEASUREMENTS

MEASUREMENT	INSTRUMENT TYPE	TYPICAL VENDOR
50 KHz - 1 MHz Specturm Conducted	Oscilloscope and Spectrum Analyzer Plug-in	Tektronix 564 with 3L5 Plug-in
1 MHz - 36 MHz Conducted	Oscilloscope and Spectrum Analyzer Plug-in	Tektronix 564 with with 10L10 Plug-in
.5-32 MHz Current Conducted	Current Transducer	Honneywell Model 3893
20 Hz - 50 KHz Radiated	Loop Antenna	Honneywell Model 7827
50 KHz - 10 MHz Radiated	Rod Antenna with Amplifier	Honneywell Model 2855
Susceptibility	Transient Generator	Honneywell Model 4881
Susceptibility	Spectrum Generator	Honneywell Model 4894

Figure 14. Limited RFI/EMI Test Instrumentation



5. DISCUSSION AND CONCLUSIONS

A meaningful evaluation of the PCU designs must be based on a broad set of data obtained in a fairly extensive test program. The measurements recommended here for this program are common to most PCU designs of the variable frequency type and will provide data on performance characteristics during motor drive, component stress levels, unit size and weight, interference levels and estimates of reliability, failure modes, operating safety, etc.

Estimates of peak power capability and calculations of unit specific weights (in kVA per lb) will undoubtedly be among the most significant PCU characteristics in a comparative evaluation. However, peak power and specific weight depend to a high degree on component stress levels. Thus, for a useful comparative evaluation, the power and specific weight characteristics resulting from the measurements should be normalized to yield equal stress levels for all PCU designs.

The importance of other performance characteristics may in many respects be much less clear-cut. Characteristics such as high operating efficiency and low reactive power are desirable, but may be sacrificed because of other favorable characteristics, for example, a low unit specific weight. Reliability, failure modes and operating safety are also important characteristics, but would not be critical unless one or more of these characteristics were to deviate significantly from the average. It is expected, therefore, that the data on performance and operating characteristics will provide the principal criteria to facilitate a PCU selection where power capability and specific weights do not clearly indicate a choice.