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PHOTOVOLTAIC POWER SYSTEM TESTS ON AN 8-KILOWATT SINGLE-PHASE LINE-COMMUTATED INVERTER

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16. Abstract

At the DOE/LeRC Systems Test Facility, a commercially available single-phase line-commutated inverter has been tested in a photovoltaic power system. Efficiency and power factor were measured as functions of solar array voltage and current. Also, the effects of input shunt capacitance and series inductance were determined. Tests were conducted from 15 to 75 percent of the 8 kW rated inverter input power. Measured efficiencies ranged from 76 percent (at 160 V and 8.0 A) to 88 percent (at 200 V and 18.7 A) at about 50 percent of rated inverter input power. Power factor ranged from 36 percent (at 160 V and 8.0 A) to 72 percent (at 200 V and 28.6 A).

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SUMMARY

At the DOE/LeRC Photovoltaic Systems Test Facility, an 8 kW off-the-shelf single-phase line-commutated inverter has been tested in a photovoltaic power system. The inverter operates in parallel with an electric utility supply line. The utility can accept power or provide power and therefore serves as a virtual energy storage system.

This type of inverter has been used to interface wind-driven dc generators with ac farm loads and their utility supply lines. There has been little experience with a solar array, where dc current, voltage, and power input to the inverter varies substantially due to changes in sun-angle, cloud-cover, and array temperature.

In the tests reported here, efficiency and power factor were measured as functions of input current and voltage from 15 to 75 percent of the 8 kW rated inverter input power. Also, the effects of input shunt capacitance and series inductance were determined.

It was found that some shunt capacitance was required to supply peak inverter input currents that sometimes exceeded the solar array's peak current capability. Increasing the series inductance resulted in both increased power factor and efficiency, as was expected.

With input capacitance of 30 000 μF and inductance of 20 mH, efficiency varied from 76 percent (160 V and 8.0 A input), to 38 percent (200 V at 18.7 A) at about 50 percent of rated input power. Losses in the input filter, the thyristor bridge, and the output transformer are included in these efficiencies.

Power factor increased with both increasing input voltage and current. It ranged from 36 percent (160 V and 8.0 A) to 72 percent (200 V and 28.6 A).

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INTRODUCTION

Photovoltaic power systems for many applications envisioned by the Department of Energy (DOE) National Photovoltaic Conversion Program present new engineering challenges. A major goal is economic generation and utilization of photovoltaic energy. Although considerable emphasis has been placed on reduction of the installed cost of solar cell arrays, it is recognized that achieving the goal also requires low-cost apparatus for the rest of the system, such as that for converting power from the generated dc form to the ac form used by common electrical equipment.

In the DOE Photovoltaic Systems Test Facility, located at Lewis Research Center (LeRC), apparatus has been provided for configuring sample photovoltaic power systems. One sample system utilizes an 8 kW single-phase line-commutated inverter connected to an electric utility line to supply electric loads. The utility serves as a virtual energy storage system receiving excess power and providing back-up power. This inverter is available commercially and is relatively inexpensive (less than $200 per kW).

This single-phase line-commutated inverter has been marketed within the U.S. to interface wind-driven dc generators with conventional ac farm load equipment and electric utility supply lines. However, there has been no prior experience in powering this inverter from a solar cell array.

The solar cell array's maximum power and also its short-circuit current is a direct function of solar insolation, which varies with sun-angle and cloud-cover. The power output at any given value of solar insolation varies from zero at short-circuit current to a maximum at about 90 percent of short-circuit current and again to zero at open-circuit. Open-circuit voltage, and also the voltage at which maximum power is available, varies with array temperature and also, to a lesser extent, with insolation. Therefore the inverter dc input voltage and current will vary during system operation and the inverter's performance will also vary.

Performance and input filter tests were made on the single-phase line-commutated inverter photovoltaic power system. All power generated was delivered to the utility network; no local ac loads were supplied during these tests. The purpose of the tests was to determine the effects of input parameter variations on inverter performance. Inverter efficiency and power factor were measured as functions of the solar array voltage and current input to the inverter. Also the effect of input shunt capacitance and series inductance was measured. Input power to the inverter varied from 15 to 75 percent of the rated 8 kW.

PRINCIPLES OF OPERATION OF LINE-COMMUTATED INVERTER

The principles of the single-phase line-commutated inverter are discussed in detail in reference 1. Some factors that will be helpful in understanding the results of the presently reported tests will be discussed here.

Figure 1 is an electrical diagram of the photovoltaic power system tested. For the purposes of this report all of the apparatus shown within the dotted box comprises the inverter. However, the principles of operation can be understood by focusing on the input inductor and the thyristor bridge, which are shown in the circuit diagram of figure 2. Also shown are current and voltage waveforms.

During the first half-cycle of the ac voltage waveform, the pair of thyristors designated by the shaded symbols is turned on. Turn-on occurs at $90^{\circ} < \omega t = \alpha < 180^{\circ}$ and current conduction continues for no longer than 180°. The alternate pair of thyristors is turned-on at $\alpha + 180^{\circ}$, and again conduction continues for no longer than 180°. This sequence of conduction by alternate thyristor pairs continues. Alternate current pulses are directed oppositely through the ac system; this constitutes the alternating current output of the inverter.

The following points regarding inverter operation, from reference 1, will be useful to the reader in understanding the results presented in this report. First, an ac voltage source is necessary to operate this type of inverter; turn-off of alternate current pulses does not occur without it. Second, the ac current output is harmonically distorted (it is not sinusoidal). Third, the output current leads the ac voltage in phase; the ac system must supply inductive reactive volt-amperes (vars) to compensate for the leading current output from the inverter. Finally, for continuous current operation, the inverter cannot operate at input voltages larger than 90 percent of the 60 Hz rms voltage presented at the thyristor bridge; at larger voltages the input current increases rapidly, causing protective fuses to blow.

Figure 3, adapted from reference 1, shows the inverter control diagram. Coordinates are the ratio of dc input voltage to peak ac voltage, and the thyristor turn-on angle, α. Between curves A and B is the region of discontinuous current operation, illustrated by the inset-X waveform. To the left of curve A, and below curve C, is the region of continuous current operation, illustrated by the inset-Y waveform. Decreasing the turn-on angle, α, along a horizontal path on the diagram (increasing current waveform continuity, at constant voltage) implies increasing average dc input current. It also implies a decreasing ratio of the peak value of the input current to its average value, and of the rms value to the average value.

FACILITY AND APPARATUS

The Systems Test Facility (STF) includes a solar cell array, an instrumentation and data acquisition system, and additional electrical equipment necessary to configure sample photovoltaic power systems. One of the sample systems utilizes the single-phase line-commutated inverter. The STF is described in detail in reference 2.

Solar Cell Array

The STF solar array consists of 240 4- by 8-foot flat solar cell panels mounted in variable-angle support frames. There are 8 rows of 30 panels each. The present array utilizes solar cell modules from three manufacturers, installed in the first two rows. The two rows have a peak power rating of 10 kW for 1000 W/m^2 insolation and 28° C operating temperature.

The modules can be electrically interconnected in various configurations. For the tests reported here the configuration was 3 series strings of 32 modules from manufacturer X, 13 series strings of 24 modules from manufacturer Y, and 26 series strings of 21 modules from manufacturer Z. The negative terminal of each series string is grounded for safety. The 42 series strings were connected in parallel through blocking diodes and fuses to a dc bus. Maximum power available from these 42 strings was 8290 W at 1000 W/m^2 at 28° C. Dirt and mismatch losses reduced maximum power to 6710 W.

Instrumentation and Data Acquisition System

The Instrumentation and Data Acquisition System includes transducers for measuring electrical parameters (voltage, current, power, and reactive power), temperature, weather parameters (wind speed, wind direction, air temperature, humidity), and insolation. It includes a data logger interfaced with the LeRC IBM-360 computer, and a combined microprocessor minicomputer data acquisition and display system which provides on-line results during STF operation.

Inverter and Input Filter

The thyristor inverting bridge circuit is rated at 40 amperes dc input current (8 kW at 200 V input). It is ordinarily manufactured and marketed for connecting wind-driven dc generators to farm ac loads and their ac utility line. Special control circuits were provided by the manufacturer to maintain the solar array input voltage constant at an adjustable preset target value. This was accomplished by input voltage feedback control of the thyristor firing angle. This regulation of current drawn from the array regulated the array voltage to the target value.

Input filter capacitance was variable between 2500 μF and 30 000 μF, in 2500 μF increments. A tapped inductor provided inductances of 5, 10, 15 and 20 mH.

Output Transformer and Utility Line

The inverter output was coupled to a 3-wire grounded neutral 60-Hz line through a 240: 120-0-120 V transformer with 2.7 percent impedance. The function of the transformer was to isolate the negative-polarity-grounded solar cell array from the grounded-neutral 3-wire ac line.

EXPERIMENTAL PROCEDURE

All tests were made during three-hour periods centered around solar noon. Insolation normal to the solar array panels was at least 800 W/m^2. This permitted the steady array and inverter operation desirable for efficiency and power factor measurements.

The first series of tests was made for all combinations of input shunt capacitance (2500, 7500, 15 000, and 30 000 μF) and input series inductance (5, 10, 15, and 20 mH). After setting up a combination of capacitance and inductance, the inverter was started. Start-up involved preloading the solar array with shunt resistance to regulate the voltage to less than 90 percent of the ac rms voltage presented at the thyristor bridge (208 V or less). The inverter was turned-on and array preload was gradually reduced. As preload decreased, the inverter delivered increased ac power to the utility, until it was receiving the entire power output of the array.

Efficiency and power factor were measured for each of the several combinations of inductance and capacitance, at inverter input current of 24 A and voltage of 200 V. Test duration for each combination ranged from 10 to 30 minutes. Data scans of all system tranducers were made in 1 minute or less. Some waveform data was tape-recorded and later analyzed into Fourier components by computer.

The second series of tests was made for three or four levels of virtually constant inverter input current, and at five levels of input voltage. Input capacitance and inductance were fixed. The range of input voltages and currents was from 160 to 200 V, and from 8.0 to 28.6 A. The several levels of constant current were achieved by disconnecting some of the 42 series solar cell strings from the dc bus; the range of voltage variation did not substantially change the current. This method is illustrated in figure 4, where typical inverter input voltages and currents are shown on the solar array's characteristic i-v curves. Voltage levels were set by adjusting the target level for the thyristor firing-angle controller.

The inverter was started as previously described. Tests at each combination of voltage and current were made over periods of from 5 to 30 minutes; data scans of all system transducers were made in 1 minute or less.

RESULTS AND DISCUSSION

As indicated in figure 1, the inverter comprises an 8 kW thyristor bridge, a series input inductor (rated at 45 A to match the 8 kW bridge), a shunt capacitor, and a 15 kVA output transformer. Efficiency is defined as the ratio of the 60 Hz power output from the transformer, to the dc power input from the solar array. Power factor is defined as the ratio of the 60 Hz power output, to the 60 Hz V-A output.

Input Filter Tests

The input filter tests were made to determine the effect of several combinations of input capacitance and inductance on inverter efficiency and power factor. At the same time some waveform data was tape-recorded, later to be analyzed into frequency components by computer. Waveform data will be discussed first.

Waveforms. - Figure 5 shows output voltage and current waveforms for 200 V and 25 A input to the inverter from the solar array; input capacitance was 30 000 μF and input inductance was 20 mH. Numerical waveform indices, form factor (f.f.), distortion factor (D.F.), and total harmonic distortion (T.H.D), are indicated for both waveforms. The inductor input current waveform differs from the inverter output current waveform only in that all current pulses are of the same polarity. Numerical indices of current waveform are equal for inductor input current and transformer output current pulses.

The numerical indices for the waveforms are defined as follows. Current form factor is the ratio of total rms value of the current waveform to its average absolute value, $(\overline{I}/I)$. Distortion factor is the ratio of the total rms value to the rms value of the 60 Hz (fundamental frequency) component of the waveform, $(\overline{I}/\overline{I}_1)$. Total harmonic distortion is equal to $\sqrt{\left(\overline{I}^2 - \overline{I}_1^2\right)/\overline{I}^2}$. The total harmonic distortion of the current waveform shown in figure 5 was 28 percent, which is considered high.

The output voltage waveform of figure 5 appears to be very nearly a 60 Hz sine wave. Its frequency components are shown in table I, and the harmonic content is small. Therefore even though the output current waveform has high harmonic content, the inverter power output was predominantly 60 Hz power. The notch in each half cycle of the voltage waveform was caused by current commutation, as turn-on of a pair of thyristors simultaneously picked up the current and decreased current through a previously conducting thyristor pair.

Effect of shunt input capacitance. - During initial shake-down operation of the inverter it was found that some shunt input capacitance was required. At lower levels of available solar array maximum power, the required peak inverter current exceeded the short-circuit current available from the array. The array then operated at zero average voltage during inverter input current pulses with array power output also zero. A 2500 μF capacitor was installed to provide the relatively high peak currents required by the inverter at low average current inputs (low solar array maximum power conditions). Inset X of figure 3 illustrates the problem. There, the peak-to-average ratio of inverter input current pulses is perhaps 3 to 1. This ratio greatly exceeds the ratio of array short-circuit current to array maximum power current. Capacitance is needed to prevent the cyclical momentary collapse of solar array voltage when inverter peak current greatly exceeds the current available from the array.

In figure 6 is shown the effect of both input capacitance and inductance on efficiency and power factor. Input voltage was 200 V and current averaged 24 A (22 to 26 A range). Shunt capacitance in excess of 2500 μF had no effect on either efficiency or power factor.

Effect of inductance. - As also shown in figure 6, increased series input inductance resulted in increases of both efficiency and power factor. As mentioned previously, the ratio of inverter rms to average current (form factor) decreases as the current waveform becomes more continuous. The effect of increasing inductance is to smooth the inverter current and therefore to reduce the form factor. During these tests the average value of the input current and the input voltage were held constant; reducing form factor tended to reduce losses and to increase efficiency. A contrary effect was that as inductance increased the inductor resistance also increased and therefore tended to increase losses. The net outcome was a small increase in inverter efficiency with increased inductance.

Power factor was much more strongly affected by inductance than was efficiency. By definition,

$$p.f. = \frac{\eta \, V I}{\overline{V}_1 \overline{I}_1}$$

where η is efficiency, V and I are dc input voltage and current, and $\overline{V}_1$ and $\overline{I}_1$ are the 60 Hz rms components of output voltage and current. For the data of figure 6, both V and $\overline{V}_1$ were constant and η was approximately constant. It follows that

$$p.f. \cong K\left(\frac{I}{\overline{I}_1}\right)$$

where K is a constant. This ratio of currents is equal to (D.F./f.f). Distortion factor was relatively constant over the range of the tests as would be expected. Results of waveform analysis showed that D.F. $\cong$ 1.04 for the tests. So power factor was proportional to the reciprocal of form factor. As was discussed above, increasing inductance reduces form factor. It follows that power factor should be increased more strongly than efficiency by increasing inductance.

As a result of the filter tests, a 30 000 μF capacitance and 20 mH inductance were selected for the subsequent performance tests. The 30 000 μF capacitance, although larger than needed, was chosen because it was readily available; it had no effect on efficiency and power factor. The 20 mH inductance was chosen to attain high power factors and efficiencies.

Performance Tests

In figure 7, efficiency data is plotted versus the reciprocal of dc input voltage, for several levels of constant current. The plot is of the form

$$\eta = 1 - \left(\frac{\text{losses}}{I}\right)\left(\frac{1}{V}\right)$$

Points shown in figure 7 are averaged points for three sets of test data. At any constant current, efficiency increases with increasing voltage. The figure 7 curves are replotted in figure 8 in the form of efficiency versus power input, for three constant input voltages. Over the range tested, efficiency was relatively high; it varied from 76 to 88 percent. Efficiency remained relatively high at low power, which is desirable for a photovoltaic power system. Maximum efficiency was attained at about half the power rating of the inverter. Not enough solar array power was available to test the inverter above 75 percent of its rated power. At 200 V dc input voltage, efficiency peaked at about 88 percent for about half rated inverter input power; at 15 percent rated power efficiency was still relatively high, at 82 percent.

Figure 9 shows power factor plotted as a function of input voltage, for several levels of constant average input current. The power factor ranged from 36 to 72 percent, but was generally low; lagging reactive volt-amperes were required from the utility line. By extrapolation of the data of figure 9 it is estimated that the maximum attainable power factor at rated input current of 40 A and 208 V input voltage, would be 77 percent. If it is assumed again that the ratio $(\bar{I}/\bar{I}_1)$ varies mainly with the reciprocal of the form factor, the power factor is

$$\text{p.f.} = k\left(\frac{V}{\text{f.f.}}\right)$$

where k is a constant. The effect of increasing average input current is to increase the continuity of the current waveform (to smooth it out) and therefore to decrease form factor. It follows that power factor should increase with increasing average current, which is what figure 9 shows. It also follows that power factor should increase with increasing voltage, which is also what figure 9 shows.

There is a limit to how far input voltage can be increased in order to attain higher power factor. As previously stated, input voltage must be less than 90 percent of the ac rms voltage presented at the thyristor bridge (for continuous current conduction). Higher voltages cause rapid current increase, and input fuses blow to protect the thyristors. Also it is not possible for a solar array always to deliver its maximum available power output at the higher voltages in order to attain the higher power factors. The solar array's maximum power voltage varies with array temperature and with insolation. At an insolation of 800 W/m^2, a 30° C change in array temperature will result in about 15 percent change in maximum power voltage. Finally, it is not to be expected that average input current from the solar array can always be kept high in order to attain higher power factors. If insolation is low, average input current will be low. Overall, it would seem that the power factor of this type of photovoltaic power system would be low for a large fraction of its yearly operating hours.

SUMMARY OF RESULTS

Tests were conducted on an 8 kW single-phase line-commutated inverter, powered by a solar array and delivering its entire power output to a utility network. Some minimum input shunt capacitance was required to provide peak inverter input currents under conditions of low maximum solar array power output; otherwise the solar array cannot deliver power to the inverter. Capacitance in excess in 2500 μF had no effect on either power factor or efficiency. Increased series inductance resulted in both higher power factors and efficiencies; the effect on power factor was stronger than on efficiency.

With input capacitance of 30 000 μF and inductance of 20 mH, efficiency varied from 76 percent (at 160 V and 8.0 A input) to 88 percent (at 200 V and 18.7 A). At high input voltage, efficiency peaked at 88 percent with input power about 50 percent of rated power. At 15 percent rated power, efficiency was still relatively high at 82 percent. Such a relatively high efficiency is desirable for a photovoltaic power system.

Power factor increased with both increasing input voltage and current. It varied from 36 percent (at 160 V and 8.0 A input) to 72 percent (at 200 V and 28.6 A input), but was considered generally low. Inductive reactive volt-amperes were required from the utility line. It is estimated that the maximum attainable power factor at 100 percent rated input current and 208 V input voltage would be 77 percent.

REFERENCES

1. Dewan, Shaski B.; and Straughen, Alan: Power Semiconductor Circuits. John Wiley & Sons, 1975.

2. Forestieri, A., et al.: ERDA/Lewis Research Center Photovoltaic Systems Test Facility. ERDA/WASA-1022/77/12, NASA TM X-73641, 1977.

TABLE I. - HARMONIC COMPONENTS OF INVERTER OUTPUT

VOLTAGE FOR 25 A dc INPUT CURRENT AT 200 V

Shunt input capacitance: 30 000 μF; series input inductance: 20 mH.

Frequency, Hz	Amplitude, V rms
60	239.3
180	1.9
300	1.5
420	1.8
540	1.7
660	2.1
780	2.0
900	1.9
1020	1.7

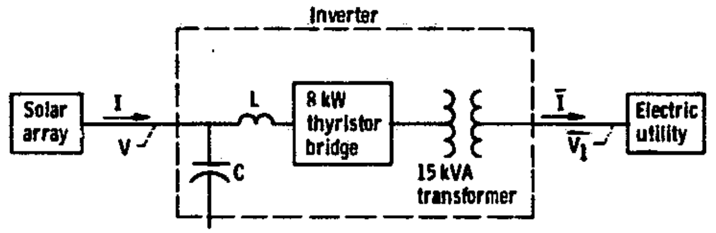

Figure 1. - Block diagram of a single-phase line-commutated inverter in a photovoltaic power system.

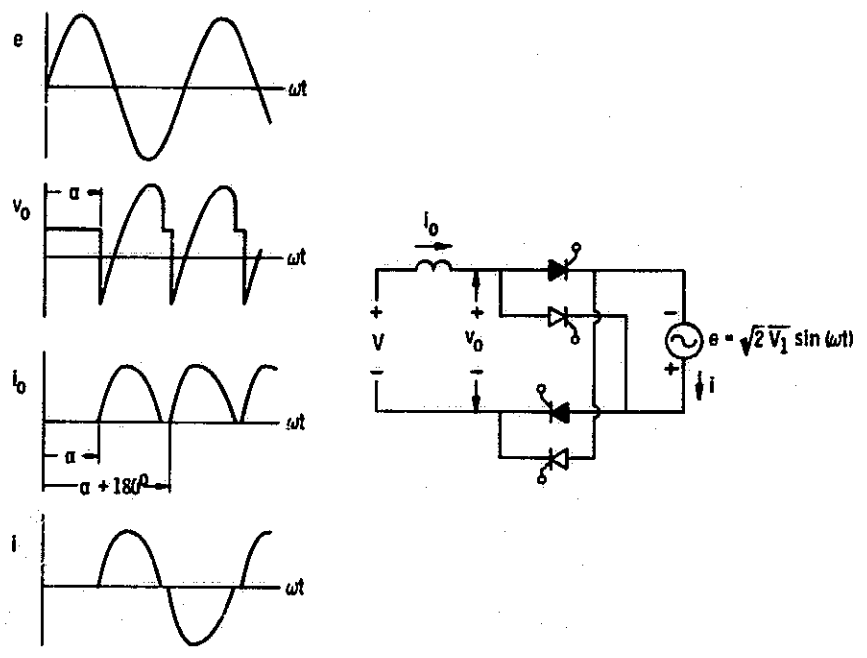

Figure 2. - Basic circuit diagram of a single-phase line-commutated inverter, and typical current and voltage waveforms.

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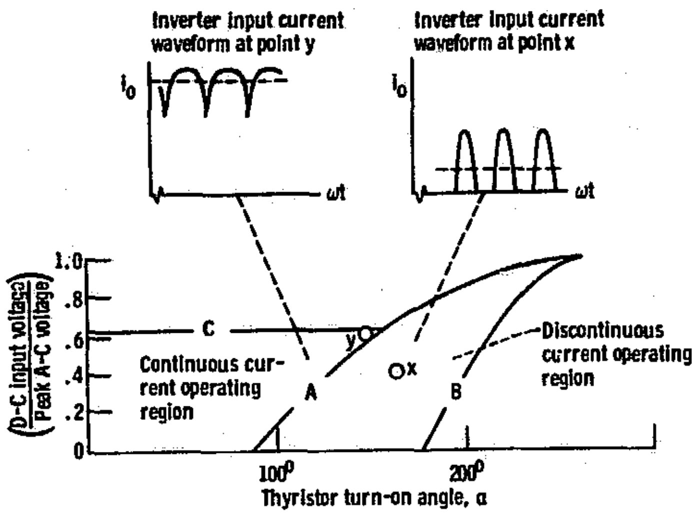

Figure 3. - Control diagram of a single-phase line-commutated inverter, with illustrations of continuous and discontinuous input current waveforms.

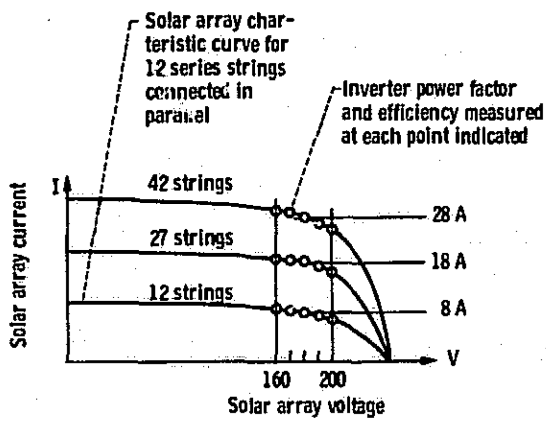

Figure 4. - Illustration of test conditions for obtaining substantially constant current input to the single-phase line-commutated inverter.

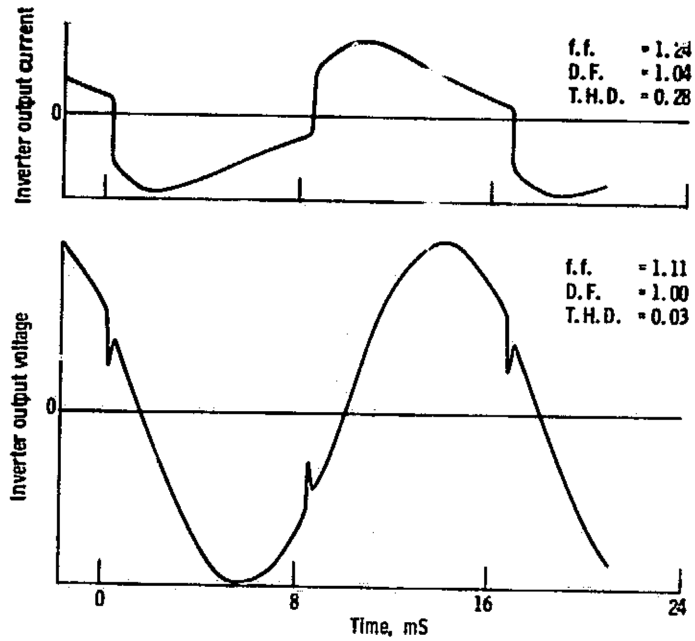

Figure 5. - Output current and voltage waveforms for 25 A and 200 V input to the single-phase line-commutated inverter (30,000 μF shunt capacitance and 20 mH series inductance).

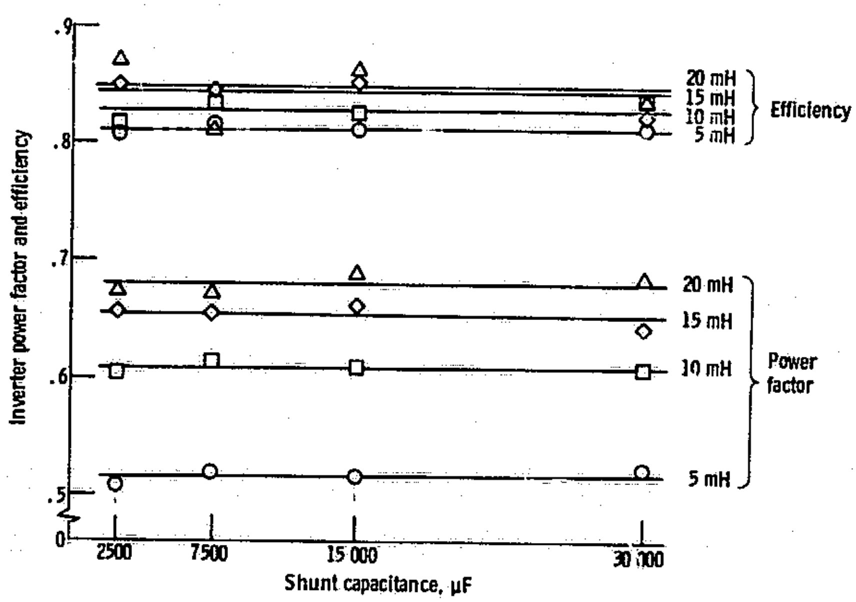

Figure 6. - Effect of input capacitance and inductance on efficiency and power factor of the single-phase line-commutated inverter, for 24 A and 200 V input conditions.

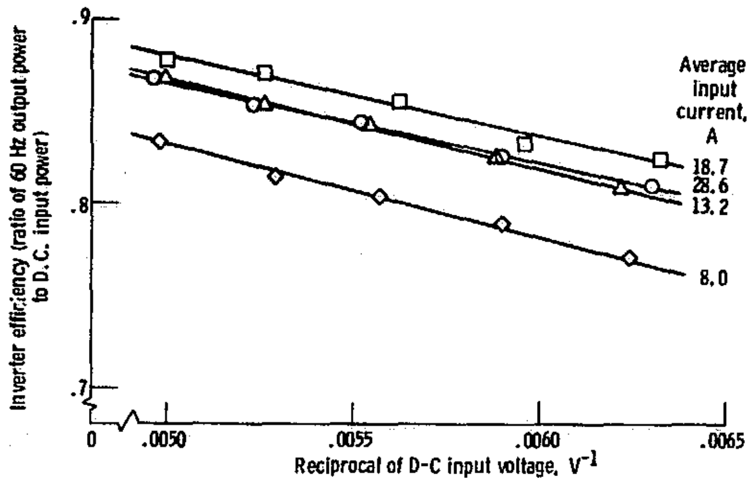

Figure 7. - Effect of input voltage and current on efficiency of the single-phase line-commutated inverter; filter capacitance 30 000 μF and inductance 20 mH.

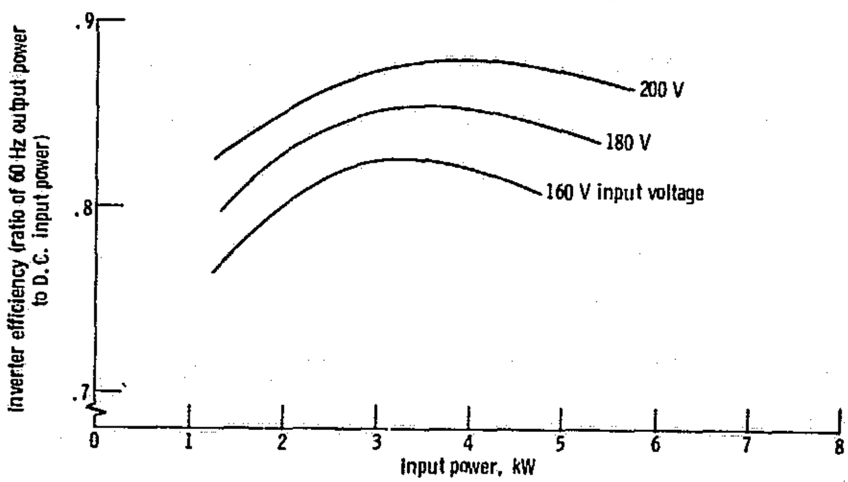

Figure 8. - Effect of input voltage and power on efficiency of the single-phase line-commutated inverter; filter capacitance 30 000 μF and inductance 20 mH.

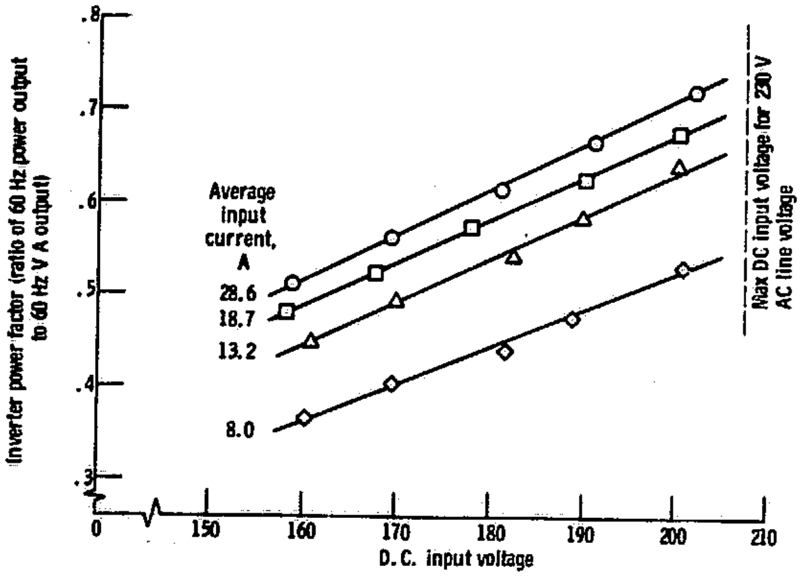

Figure 9. - Effect of input voltage and current on power factor of the single-phase line-commutated inverter; filter capacitance 30 000 μF and inductance 20 mH.