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A PHOTOVOLTAIC POWERED 20-HP DC/AC IRRIGATION SYSTEM  
AND A 3-KW NITROGEN GENERATOR \*+<sup>++</sup>

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## ABSTRACT

A 25-kWp photovoltaic power system has been providing power for irrigation and crop drying since July 1977 at an agricultural field station of the University of Nebraska, located at Mead, Nebraska. The system was designed and built by Massachusetts Institute of Technology's Lincoln Laboratory under U.S. Department of Energy sponsorship and is being operated jointly by the university and MIT Lincoln Laboratory. The system consists of a 25-kWp PV array, a battery subsystem, a power dump, an inverter, a controller and a data acquisition system. This photovoltaic power system has been used as a test facility in order to test and evaluate a variety of PV-related agricultural applications, including irrigation, crop drying and fertilizer manufacturing. Two interesting applications presently under evaluation are a 20-hp DC/AC-powered irrigation system and an on-site nitrogen fertilizer production unit.

## INTRODUCTION

In this paper two applications presently under evaluation at a 25-kWp photovoltaic test facility located in Mead, Nebraska will be discussed. The two applications are:

- a 20-hp DC/AC irrigation pumping system;
- a 3-kW nitrogen fertilizer production unit.

One of the interesting questions raised in 1978 was, "How would the operation of a DC motor compare with the inverter-AC motor combination for efficiency, reliability and

maintainability?" If a 20-hp DC motor could operate at the same efficiency as a 20-hp AC motor, then the elimination of the inverter losses would result in an approximate 10% increase in the combined efficiency of the PV-pump system. Using a DC motor not only would improve the efficiency of the system, but would also simplify the system by not requiring use of inverters. In order to make a performance evaluation between a 20-hp AC induction motor and a 20-hp DC motor, a special-purpose DC motor was procured. The DC motor operated the same turbine pump as that powered by the AC motor. Late delivery, because of a factory strike, has postponed complete evaluation until next year's irrigation season. Because delivery was not made until 15 November 1979, comparison data were taken on a limited basis. Efficiency and cost comparisons were determined. Since AC pumping systems are more common throughout the country, emphasis will be given to the DC system.

One other application presently being evaluated at the Mead site is a 3-kW nitrogen fertilizer production unit (nitrogen generator) powered by the PV system. This unit utilizes an electric arc-discharge process for manufacturing nitrogen fertilizer. It is compatible with the power levels available from on-site solar photovoltaic arrays and will provide another use for surplus electricity during those times of the year when irrigation and crop drying are not taking place. In addition to using surplus power from the solar array, the nitrogen generator produces calcium fertilizer in water solution, which presents the possibility of combining fertilizer application and irrigation in one operation. The electric arc-discharge process which is utilized by the nitrogen fertilizer generator is a modern version of the commercial process first used at the turn of the century. Of greater importance, the process does not require fossil fuel as is the case in ammonia fertilizer production. This method was abandoned when the more efficient Haber-Bosch process was developed in the

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*REA*

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1930's. Haber-Bosch combines nitrogen and hydrogen, derived from natural gas, to produce ammonia which is used in fertilizer production.

Nitrogen fertilizer generator systems suitable for use at Nebraska are currently under development at the Charles F. Kettering Research Laboratory; consequently, this project is at present a joint effort of that laboratory, MIT Lincoln Laboratory and the University of Nebraska.

DESCRIPTION OF THE MEAD PV SYSTEM

The system includes an array of photovoltaic cells (which nominally produces a maximum output power of 25 kW at an insolation of 1 kW/m<sup>2</sup>), 40 batteries which provides 90 kWh of energy storage capacity, a 22.5-KVA 3 $\phi$  inverter, a controller, a 50-kW power dump and a data collection and management subsystem. Utility power is available in parallel and is used: (1) for carrying the load whenever the battery depth of discharge becomes excessive, (2) for powering a battery charger during periodic equalization of the battery cells, and (3) for taking care of the overhead electrical power needs of all instrumentation, control, heating and cooling units. In addition, the system includes an uninterruptable power supply which is called into play whenever there is a loss of utility power. The block diagram of the system presented in Figure 1 defines the various electrical loads placed on the system and shows the interconnection of all subsystem elements.

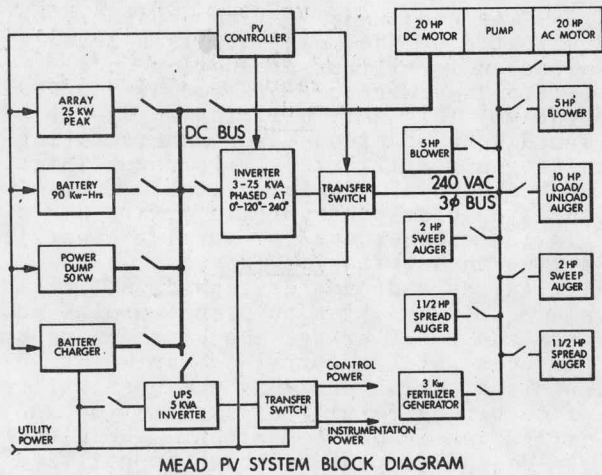


Figure 1.

DC/AC IRRIGATION SYSTEM

In support of the evaluation of a DC/AC irrigation system, and based on an optimization for the PV-array-powered system, a larger low head pumping system (1500-1800 gpm) was installed to test the performance of both a 20-hp AC motor and a 20-hp DC motor. The 20-hp DC motor operated the same turbine pump as that powered by the 20-hp AC motor which irrigated an 80-acre corn field via an automated gated pipe irrigation system. This larger pumping system also increased system efficiency and eliminated power dump usage during normal operations. This 20-hp pumping system, compared to a 15-hp system used in 1978, reduced the daily irrigation time required by 20%. Also, by better matching the load to the available solar electrical power, it provided the advantage of reducing the amount of energy transferred to and from the battery storage subsystem and permitted a reduction in the battery storage capacity from 40 kWh to 20 kWh. The irrigation system at Mead has not yet required any utility power to fulfill the irrigation needs of the 80 acres. Pictured in Figure 2 is the 20-hp DC/AC pumping plant showing the AC motor mounted in a vertical position whereas the DC motor is horizontally mounted and is supported by a steel frame. A right-angle gear drive is used which allows selection of either the DC or AC motor to supply power to the turbine pump. Each motor is operated with its individual motor starter. Power to the 240VAC 3 $\phi$  motor is supplied from either the PV array/battery through a 22.5-KVA soft-start inverter or directly from the utility. The 115-145VDC motor receives its power directly from the PV array/battery.

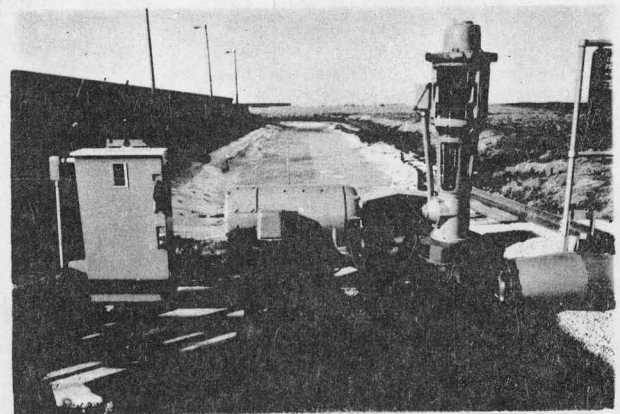


Figure 2. 20-hp DC/AC Pump

Since efficiency is always an important factor when operating a system, it was determined to procure a present-technology 20-hp DC motor in order to make a direct comparison in performance and cost between the two types of motors. In addition to high efficiency, one of the main concerns in the procurement of a DC motor was the change in rpm over a bus voltage variation of 115-145VDC. The type of motor selected was a 20-hp DC shunt motor because of its flat-speed characteristics under a varying input voltage. With this in mind, a shunt DC motor was designed with its field winding connected directly across the armature, because this would tend to regulate speed as the armature voltage decreased or increased. This feature is an inherent characteristic of a shunt motor since by reducing the field current the flux is also reduced and the speed of the motor consequently is increased. Further speed control is accomplished by adding, in this case, a 14-ohm field rheostat in series with the shunt field.

When DC motors are line-started, the inrush current is limited only by the "at-rest" resistance of the armature and may be up to ten times the full-load current. Because such DC motors have brushes and commutations that might be damaged by excessive starting currents, reduced DC voltage starters are a must for motors above 2 hp. The 20-hp DC motor at Mead uses a 3-point reduced voltage starter which by energizing the control circuit, closes the line contactor and places a resistor in series with the armature. This in turn limits the inrush current and accounts for the first point of acceleration. Following definite preset time intervals controlled by a timing relay, two more increments of resistance are shorted by the closing of contactors. The shorting of such additional increments of resistance accounts for an additional point of acceleration.

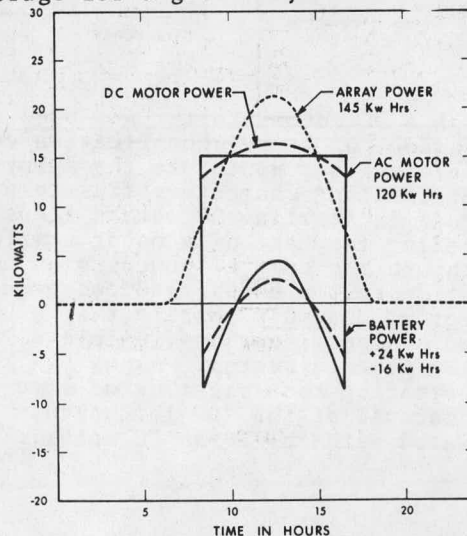
#### PERFORMANCE COMPARISONS

The performance of the AC motor-inverter has been very satisfactory, with no major problems since the inverter was modified to handle the high starting current required by AC induction motors. (1) Presently, the peak starting current supplied to the 20-hp, 240VAC, 3 $\phi$  motor from the 22.5-KVA inverter is 94 amps, 14 seconds into a 2-minute variable voltage/frequency start up. This peak starting current drops back to a running current of approximately 55 amps. All AC induction motors similar to the motor being used at Mead can withstand full-voltage starting when connected directly

across the utility line. They are strong enough mechanically to withstand the resultant magnetic stresses and locked-rotor torques developed. Unfortunately, when powering an AC motor from an inverter, a direct across-the-line connection is not possible. In this case the motor must have a "soft" start.

The DC motor has a peak starting current of approximately 250 amps at 115VDC which is limited by a 3-point resistor placed in series with the armature. The second and third points on the resistor are approximately 130 amps each. After the third point is switched out, the resistor is completely removed from the armature circuit at which time the current settles to a normal operating value. The stepping out of this resistor is preset by timed relays.

Figure 3 illustrates the input power characteristic of each motor. The 20-hp AC motor consumes a constant 15 kW of input power over approximately 8 hours, rotating at a constant speed. Depending on the motor load demand, the input power has been as high as 18.5 kW. The input power being supplied to the 20-hp DC motor has a different characteristic. It can be seen clearly how a change in array output power, which increases or decreases the bus voltage, affects the power supplied to the DC motor and, consequently, its speed. Compared to the constant rpm of the AC motor, the rpm of the DC motor is affected directly by a change in the bus voltage. In the case of the AC motor, the inverter acts as a voltage regulator which compensates for a changing bus voltage; the DC motor is powered directly from the bus voltage. Also illustrated in this figure is the fact that the DC motor requires less battery storage for a given day.



ARRAY, BATTERY, AND MOTOR POWER (21 Sept. 1979)

Figure 3.

Table 1 summarizes the performance of the DC motor operating over its designated bus voltage range of 115-145 VDC. With a 21% change in input voltage, the rpm change was only 220 (12.5%). This rpm change amounts to approximately a 200-gpm variation in flow rate.

TABLE 1  
20 HP DC MOTOR PERFORMANCE

		DC VOLTAGE		
		115	125	145
F.L.A.	60 LB. FT	131	124	116
	45	96	92	86
EFF. (%)	60 LB. FT	85	87	88
	45	87	86	89
RPM	60 LB. FT	1530	1600	1750
	45	1549	1605	1761
ΔRPM	60 LB. FT	← 220 →		
	45	← 212 →		

Results indicate that a 20-hp DC motor has the capacity to operate at the efficiency (87%) of an AC motor of similar size; thus the elimination of the inverter losses results in a 10% increase in the combined efficiency of the PV pump system (77% vs. 87%). A further evaluation will be performed during next year's (1980) irrigation experiment.

#### ECONOMIC COMPARISONS

The cost benefit that resulted by using a DC motor over a DC-AC inverter was 41%. At first the percentage was expected to be as high as 60%, but a decrease in inverter cost decreased the cost benefit. The cost of each system is shown below.

AC SYSTEM		DC SYSTEM	
20-HP AC MOTOR	875	20-HP DC MOTOR	6000
STARTER	285	STARTER	2000
3ϕ INVERTER	12500		
<b>TOTAL COST</b>	<b>\$13660</b>	<b>TOTAL COST</b>	<b>\$8000</b>

Although a DC motor starter was used in this application, a control modification could be developed that would use the array's current-limiting characteristics to an advantage in starting DC motors (thus eliminating the cost of a motor starter). Even though the cost of powering an irrigation system can be reduced by using a DC motor, one must realize that a DC-powered system is not as flexible as an AC-inverter-powered system. Also, transportation cost might be of some importance because of the 700-lb. weight associated with the 20-hp DC motor.

#### NITROGEN FERTILIZER GENERATOR

A nitrogen fertilizer generator system developed and furnished by the Charles F. Kettering Research Laboratory has recently been installed at Mead, Nebraska. This system consumes only air, water, limestone (for every three tons of calcium nitrate, two tons of limestone are used), and electric power generated by the PV array. An adjunct to the PV system's primary function of powering irrigation pumping and crop drying, the generator is used part-time and is expected to produce between one and two tons of calcium nitrate fertilizer per year.

The nitrogen fertilizer generator system operates by passing air through a high-voltage electric arc which causes nitrogen and oxygen to combine into nitrogen oxides such as NO, NO<sub>2</sub>, and N<sub>2</sub>O<sub>4</sub>. Next, these nitrogen oxides are trapped in water to produce nitrous acids. Limestone, Ca(CO<sub>3</sub>), is introduced to neutralize the nitrous acids into calcium nitrate Ca(NO<sub>3</sub>)<sub>2</sub>, a desirable form of nitrogen fertilizer. The fertilizer generator's basic components, a reaction electric cell, power, an air pump, an absorption column containing limestone and water, and a holding tank are shown in Figure 4. This cell design uses a 4-foot iron pipe 3 inches in diameter as one electrode, and a concentric second electrode at the top portion of the pipe. Three tangential air inlet ports at the top of the pipe cause the arc to descend in a spiral path, creating a vortex-shaped arc. The length of the arc and the power delivered to the reaction cell may be varied by controlling the air flow through the air inlets. This 3-kW "farm size" unit is powered by a voltage level of 1000VDC at 3A. This power is rectified-inverter AC power from the main 3ϕ inverter.

PV-POWERED NITROGEN FERTILIZER GENERATOR

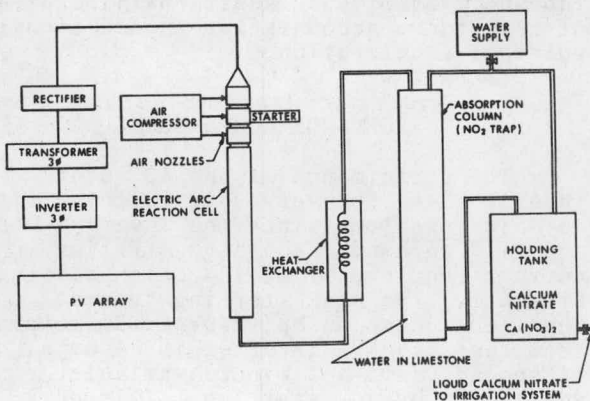


Figure 4.

A picture of the reaction cell used at Mead is shown in Figure 5 with the associated hardware needed. The reaction cell is shown with its input power being delivered by a 3 $\phi$  transformer-rectifier combination (1000 VDC at 3 amps). The three tangential air ports are shown attached to the upper left of the reaction cell. The reaction cell is long because the air must be quenched to produce the desired nitrogen oxides before passing to the absorption column. Before entering the absorption column, a heat exchanger may be used because of excess heat which is generated during the conversion. Also, another column may be placed before the absorption column if additional oxidation is required. In most cases, this improves the efficiency of the system. After the calcium nitrate is formed in the absorption column, it is pumped into a holding tank. The pumping action continues until the holding tank reaches a desired concentration level. After a desired level is reached (17% nitrogen), it is pumped to a second holding tank.



Figure 5. Reaction cell,  
Nitrogen Fertilizer Generator

#### SYSTEM PERFORMANCE

The photovoltaic array has been supplying power to the nitrogen generator since July 1979. More than 600 operating hours have been logged on the nitrogen generator to date. This generator produces approximately 16 grams N/kWh, or 480 grams per 10-hour day. A typical air-flow rate for this system operating at an input power level of 3 kW is 70-100 liters/min. Based on this performance, a 3-kW system, if run continuously, could produce between two and three tons of calcium nitrate fertilizer

per year in water solution (17% nitrogen). Three tons of calcium nitrate fertilizer, which contains 17% nitrogen, is equivalent to about 1000 lbs of 100% nitrogen fertilizer.

Tests are now being conducted which will characterize arc performance and efficiency by varying the air-flow ratios of the three air manifolds and the DC input power level. Also, plans are underway to configure an array that will power an arc directly with 1000 VDC at 3 amps. This could be an excellent match, due to the current-limiting characteristics of a photovoltaic array, since the arc operates under a current-limit condition.

#### ECONOMIC COMPARISONS

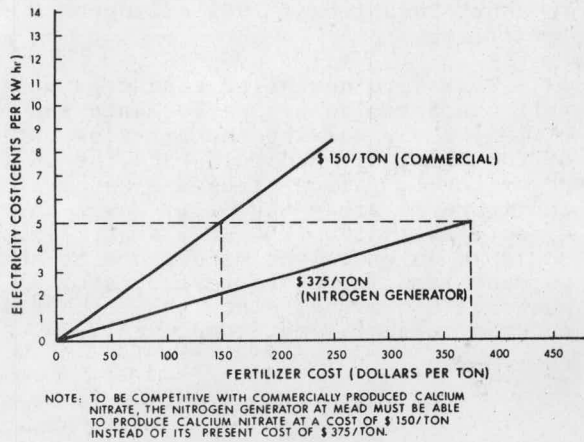
At the system's present efficiency, about 50,000 kilowatt-hours of electric power from the PV system are required to produce one ton of 100% nitrogen fertilizer. At commercial rates for electricity in Lincoln, Nebraska (about 5¢ per kWh), and based on the present efficiency of this system, the cost of calcium nitrate fertilizer (the Mead product is 17% pure nitrogen) is about \$375 per ton or, in terms of nitrogen content, about \$2200 per ton of pure nitrogen fertilizer. The current market price of calcium nitrate (with a pure nitrogen content of 15.5%) \$150 per ton delivered.

Figure 6 shows that in order to be competitive with commercially produced calcium nitrate, the nitrogen generator at Mead must be able to produce on-site calcium nitrate at a cost of \$150/ton instead of its present cost of \$375/ton. Research being conducted to increase the present system efficiency at Mead could decrease the above cost figures by a factor of two or more. A large proportion of the energy input into the system appears as "heat." The heat can be used for crop-drying or space heating in order to improve the overall economics of the system.

## REFERENCES

1. Landsman, E.E., "Motor Starting with PV Systems," 1978 IEEE PV Specialists Conference, Washington, D.C. 5-8 June 1978.

2. Treharne, R.W., "A Nitrogen Fertilizer Generator for Farm Use," Technical Note 2 Charles F. Kettering Research Laboratory, 1978.



NITROGEN GENERATOR FERTILIZER COST, MEAD, NEBRASKA

Figure 6.

## SUMMARY OF CONCLUSIONS

It can be concluded that a 20-hp DC motor has the capacity to operate at an efficiency of 87%, which is equal to the efficiency of a similar size AC motor. PV system efficiency is further increased by 10% with a DC system. The cost benefit of a DC system is approximately 41% greater as well as being less complex. Although there seem to be many advantages in operating a DC system over an AC system there are also some disadvantages. Greater care must be given a DC motor to guard against outside elements such as moisture. Maintenance is of great importance to ensure proper brush contact and bearing lubrication. Another disadvantage is weight; DC motors weigh approximately 4 times as much as a similar size AC motor. Also a DC system is not as flexible as an inverter powered system because DC applications are not as common. Further evaluation and comparison of each motor will be accomplished during 1980.

The nitrogen fertilizer generator is presently producing calcium nitrate fertilizer at \$375 per ton as compared to its commercial costs of \$150 per ton delivered. Research is being conducted to ensure that the present system size and efficiency could decrease the \$375 per ton cost figures by a factor of two or more.