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PERFORMANCE OF A STAND-ALONE WIND-ELECTRIC ICE MAKER FOR REMOTE VILLAGES

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ABSTRACT

Two ice makers in the 1.1 metric tons/24-hour (1.2 tons/day) size range were tested to determine their performance when directly coupled to a variable-frequency wind turbine generator. Initial tests were conducted using a dynamometer to simulate the wind to evaluate whether previously determined potential problems were significant and to define basic performance parameters. Field testing in Norman, Oklahoma, was completed to determine the performance of one of the ice makers under real wind conditions. As expected, the ice makers produced more ice at a higher speed than rated, and less ice at a lower speed. Due to the large start-up torque requirement of reciprocating compressors, the ice making system experienced a large start-up current and corresponding voltage drop which required a larger wind turbine than expected to provide the necessary current and voltage. Performance curves for ice production and power consumption are presented. A spreadsheet model was constructed to predict ice production at a user-defined site given the wind conditions for that location. Future work should include long-term performance tests and research on reducing the large start-up currents the system experiences when first coming on line.

INTRODUCTION

In many remote communities in the developing world, there is a great need for ice to preserve fish and produce. It is estimated that between 40% and 50% of the fish harvest in third world countries is lost due to spoilage (Malvestuto, 1982 and Pariser, 1979). In some villages, fishermen and farmers harvest their crop at a subsistence level because there is no way to preserve excess yields. A significant market could develop if preservation were provided. The handful of refrigerated trucks available to provide transport to market put the fishermen at the mercy of the truck drivers who charge high prices and keep erratic schedules. Because many of these remote communities are also unelectrified due to the prohibitive cost of extending existing grid lines or providing power using diesel generators, renewable energy can be the most cost effective means of providing refrigeration to residents.

SYSTEM CONFIGURATIONS

Ice makers can be incorporated into wind energy systems in two ways. In the first configuration, the ice maker is attached to a mini-grid or storage system through an inverter. In this case, the ice maker is powered by constant-frequency alternating current, usually at 50 or 60 hz. All known off-the-shelf ice makers are designed to operate under these conditions. In the second configuration, the ice maker is directly coupled to a variable-speed wind turbine through a controller. This configuration is based on the experience gained from previously developed variable-frequency wind-electric water pumping systems that are currently operating successfully at more than 25 sites (Bergey, 1994). Directly-coupled wind-electric ice making has the advantages of simplicity, lower cost, and more efficient operation since it does not include an inverter or rectifier. The ice maker is powered by variable-frequency alternating current and operates over a range of frequencies from 30 to 90 hz, depending on the wind speed. It is possible that in some cases the high-end frequency can exceed 90 or 100 hz. Because commercially available ice makers are not designed to operate at variable frequencies, this configuration raises some interesting electrical and refrigeration cycle issues. To understand the problems that could arise from this type of operation, it is worthwhile to briefly examine the typical vapor-compression refrigeration cycle.

REFRIGERATION FOR ICE MAKING

A typical refrigeration cycle is shown in Figure 1a. The corresponding pressure-enthalpy diagram in Figure 1b describes the thermodynamic characteristics of the process.

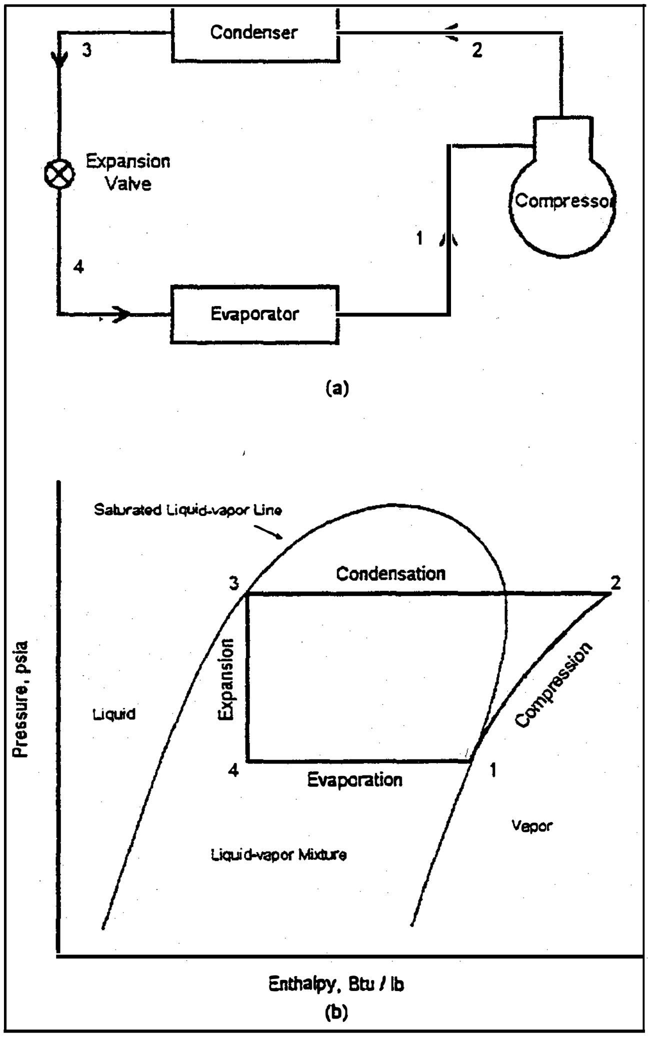

FIGURE 1. (A) FLOW DIAGRAM OF STANDARD VAPOR-COMPRESSION SYSTEM. (B) STANDARD VAPOR-COMPRESSION CYCLE ON PRESSURE-ENTHALPY DIAGRAM.

There are four primary components in a refrigeration system: a compressor, a condenser, an expansion valve, and an evaporator. Ice is formed in or on the evaporator, depending on the specific design. Under normal circumstances, refrigerant leaving the evaporator is a vapor because most refrigeration cycle compressors can be damaged if incompressible liquid refrigerant is pumped through them. In hermetic compressors, which are typically used in ice makers, the refrigerant circulated through the system is dissolved in the oil used to lubricate the compressor. Under normal constant-speed operation, proper mass-flow rates and temperatures must be maintained to assure that the oil and refrigerant separate sufficiently to perform their respective functions.

ICE MAKING WITH VARIABLE SPEED AND INTERMITTENT POWER

After consulting with various refrigeration experts and ice making manufacturers, a list of potential problems related to wind-powered ice making was compiled. These issues fall into two categories: intermittent power issues and variable frequency issues. The first category of problems listed below could occur when power is lost 1) to the mini-grid or 2) because of lack of wind in the case of the directly-coupled system.

Intermittent Power Issues

1) Some ice makers have switches that would have to be manually reset each time power is lost or there is no wind. It probably would not be difficult to omit these switches from the circuit, if desired.

2) Some ice makers have start-up and shut-down control sequences that could cause damage to the refrigeration system if power were lost and these cycles were not allowed to perform their intended function.

3) The cutter bar or auger which removes the ice from the freezing surface could freeze to that surface after power is lost if the refrigerant left sitting in the evaporator is very cold from high-speed or long-term operation. If there is insufficient time to allow this ice to melt, the auger motor, cutter bar, or speed reducer could be damaged when the unit is restarted.

4) Many ice makers have crankcase heaters that help the refrigerant and oil separate for proper lubrication of the compressor. Increased compressor wear could occur in cold climates since the crankcase heater would not run continuously. In warm climates this is not an issue.

Variable Frequency Issues

The problems associated with running an ice maker at variable speed are listed below. These potential problems apply only to directly-coupled systems.

1) With a variable-frequency power source, the dynamic stability of the expansion valve in the typical refrigeration system is questionable. The response time of the controls on a typical thermostatic expansion valve is an order of magnitude longer than the typical variation in frequency the system is likely to encounter with a wind energy source. This difference in response times could damage the compressor because there is a greater chance of pumping liquid through it and damaging the valves under this type of operation. In the refrigeration industry there have been problems with conventional thermostatic expansion valves in some variable speed applications (Kenable, 1994). To study this potential problem, two ice makers were tested—one with a conventional refrigeration cycle including a thermostatic expansion valve and one with a low-pressure receiver and liquid-overfeed system as shown in Figure 2.

In this system, the low-side receiver or accumulator separates the liquid refrigerant from the gaseous, guaranteeing that no liquid refrigerant enters the compressor.

2) Low refrigerant flow at low speeds could compromise compressor lubrication. If the mass-flow rate is too low and the necessary temperature conditions are not met, the refrigerant velocity in the condenser and evaporator may become too low and dissolved oil may not be carried back to the compressor to lubricate it.

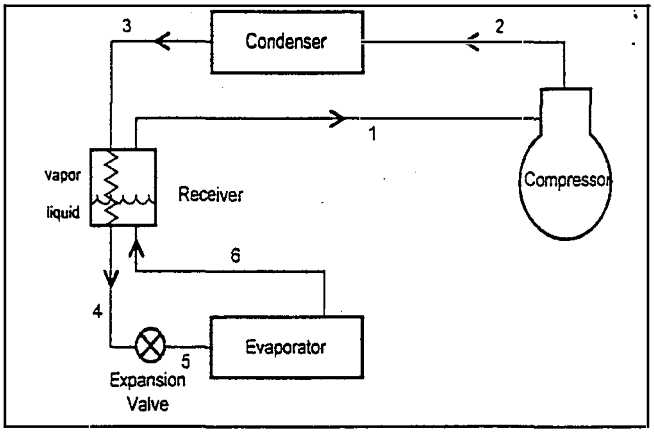

FIGURE 2. SCHEMATIC OF A LOW-PRESSURE RECEIVER, LIQUID-OVERFEED SYSTEM

3) The control system could be affected by variable electrical characteristics. As the frequency of the incoming power fluctuates between 30 and 90 hz, the corresponding voltage and current fluctuate. It is possible that the voltage or current could drop to a level where the control circuitry will not operate.

ICE MAKING EQUIPMENT

Specifications for ice making equipment were determined prior to testing to avoid as many of the potential problems above as possible, and to ensure that the test equipment met the basic criteria required for remote systems. The criteria that are most important in determining which ice making equipment would be suitable for village needs are reliability, and ease of operation and maintenance as manifested through simplicity of design and manufacturer reliability. Based on these criteria, the following general guidelines were determined for selecting a suitable ice maker for this application. It appears that a flake ice maker is the simplest and most practical option for several reasons. Block and cube ice are formed via a batch process, which may require a defrost cycle, a more complex control strategy, and uninterrupted power. Flake ice is made and harvested continuously and can therefore better withstand the intermittent nature of the wind. With no defrost cycle, all the energy consumed is used to make ice, leading to a more efficient process. Flake ice also provides the best preservation of fish and produce, because it completely surrounds the product. In general, compressor pump-down cycles should be avoided because the risk of component failure is increased. A pump-down cycle is a shut-down sequence used in some ice making equipment to ensure that the system will operate properly when turned on again. If a system with a pump-down cycle is not allowed to pump down, refrigerant may flow to where it isn't designed to be and components may fail. An air-cooled condenser (as opposed to water-cooled) would be simpler and more practical for many village applications where water is scarce. The simplest controls possible are desirable.

EXPERIMENTAL SET-UP AND DATA ACQUISITION SYSTEM

Because the mini-grid configuration poses only intermittent power issues and the directly-coupled system poses both intermittent and variable speed issues, the directly-coupled system was tested. Two ice makers were tested—one with a conventional configuration, including a thermostatic expansion valve, and another with a low-pressure receiver and liquid-overfeed system to ensure that the compressor receives only vapor.

One ice maker employed for this test was a 1.1 metric tons/24-hours (1.2 ton/day) Scotsman FM2400WE-3A, which has two ice making units electrically connected so each can be turned on separately. Although the units can be run separately, they share the same connection to a three-phase power source. When only one unit is running, ice production is reduced by half and the Scotsman produces 0.66 metric tons/day (0.6 tons/day). Ice forms on the inside surface of a cylindrical evaporator which is submerged in water, and is scraped off this surface by a helical auger. As the ice is pushed to the top of the evaporator by the auger, it is pressed to remove excess water before being released into the bin below.

The second ice maker, a North Star Coldisc D12, uses a low-pressure receiver and liquid-overfeed system. It produces 1.0 metric ton/day (1.1 tons/day). This ice maker uses an approximately 38-cm (15-in.) diameter rotating disk through which cold refrigerant passes. Ice forms as water sprays on the disk's surface and is scraped off by stationary blades when the disk rotates.

Each ice maker was instrumented to measure several performance parameters. A Campbell Scientific CR21X data logger was used to record all of the data. Thermocouples measured temperatures for the ambient air, inlet water, evaporator, condenser, compressor, ice product, and compressor motor. Magtrol power analyzers measured AC voltage, current, and power on each of the three phases from which the system voltage, current, and power were determined. Frequency measurement and system control were provided by a Bergey Windpower Company (BWC) pump control unit (PCU-10) designed for BWC's wind-electric water pumping systems. Ice production was measured based on the principle of conservation of mass by using a flow meter to monitor the amount of water that flows into the ice maker and is converted to ice. Two Maximum anemometers measured wind speed during field testing.

The following test protocol was observed for each ice maker. A baseline case was established by connecting the ice maker to a conventional grid at 60 hz, establishing equilibrium and testing all parameters mentioned above except wind speed. The ice maker was then connected to a BWC EXCEL 10-kW or 12-kW permanent-magnet alternator (PMA) depending on the test. A 75-hp dynamometer drove the 10-kW or 12-kW PMA at a variety of speeds to simulate the wind. The stability and performance of the ice maker were then tested over the complete frequency range the ice maker is likely to experience when powered by a wind turbine (i.e. from 30 to 90 hz). The dynamometer was operated at 60 cycles per second initially, then stepped down to 50 hz, up to 70 hz, down to 40 hz, up to 80 hz, down to 30 hz, and up to 90 hz to gradually verify the range over which the ice maker could be operated. All parameters except frequency and flow rate were measured and recorded at a 5-second scan rate during this test.

The frequency and flow rate were measured every second and averaged and stored every 5 seconds. Wind speed was not recorded for this test.

The ice maker's stability and performance were tested under conditions similar to real wind in a ramp-up test. In this test, the dynamometer was brought to 40 hz, held there for 10 seconds; then ramped up to 70 hz and held there for 10 seconds; then ramped down to 40 hz and held for 10 seconds. This process was repeated for approximately 10 minutes while all parameters, except wind speed, were measured and stored at a 1-second scan rate. A cut-in/cut-out test was performed to monitor system behavior when the wind fluctuates above and below the minimum speed required to start the ice maker. The PCU-10 was set at a cut-in frequency of 38 hz and a cut-out frequency of 32 hz. The dynamometer was then ramped up and down between 30 and 45 hz every 5 minutes while all parameters, except for wind, were measured at a 1-second scan and storage rate. The final test involved connecting the ice maker to a complete BWC EXCEL wind turbine in the field. All parameters except for frequency, flow rate, and wind speed were sampled every 5 seconds, then averaged and stored every minute. The frequency, flow rate, and wind speed were sampled every second, then averaged and stored every minute.

LABORATORY TEST RESULTS

In addition to determining system performance, refrigeration cycle stability and system electrical characteristics were evaluated.

Scotsman

A previous work (Davis, et al., 1994) described the test results of the Scotsman ice maker with one, 0.6 tons/day unit powered by a 10-kW Bergey PMA. This paper includes results from the same ice maker powered by a prototype of a 12-kW Bergey wind turbine with both units running. The 12-kW permanent-magnet alternator was able to provide enough current and voltage to get both units running, but below about 40 hz one unit would drop out. During the field tests, data were gathered for only one unit because the winds generally were not strong enough to power both units.

Figure 3 shows the response of power and ice production to step changes in frequency during the laboratory tests for the 12-kW PMA with both ice making units operating. As expected, the ice maker consumed more power and produced more ice as the motors turned faster at a higher frequency. The large scatter in the ice production data is an artifact of measuring production via the intermittent water flow into the ice maker. The flow of water is controlled by a float valve, similar to those found in common household toilets, which is either on or off. Hence the water flow and ice production are either higher or lower than actual most of the time. To get an accurate picture of the steady-state operation of the ice maker, the data in Figure 3 are averaged every 2 minutes and plotted on a per unit basis as power and production curves in Figure 4. Data were gathered at four frequencies: 50, 60, 70, and 80 hz, due to time constraints. Because no laboratory data were gathered with just one unit operating from the 12-kW PMA, the data in Figure 4 are the result of dividing the original, two-unit data by two. Hence, the data and curve fits represent a conservative estimate of the ice production and power of one unit operating from the 12-kW PMA. This per unit basis aids in comparing Figure 4 with the field test results in Figure 6 where only one unit was operating.

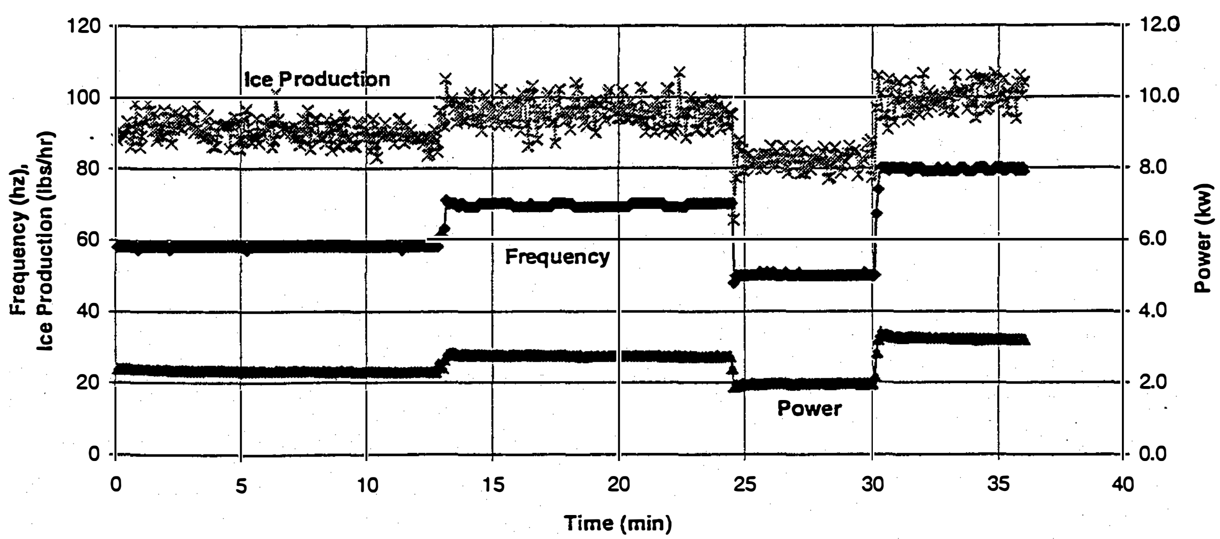

FIGURE 3. SCOTSMAN TWO-UNIT, 12-KW SYSTEM RESPONSE TO STEP CHANGES IN FREQUENCY

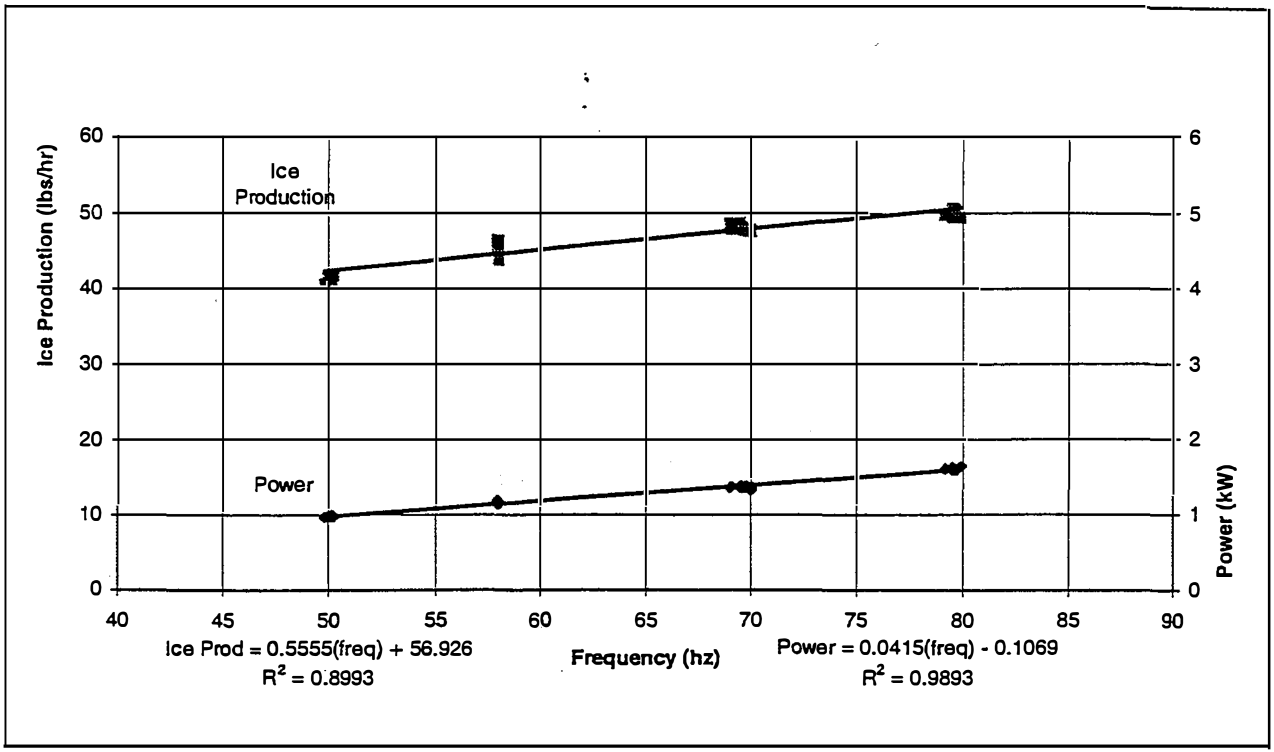

FIGURE 4. SCOTSMAN 12-KW ICE MAKER PERFORMANCE ON A PER-UNIT BASIS.

As shown in Figure 4, the power the wind turbine supplies to the ice maker never exceeds 2 kW, even though the turbine is rated at 12 kW. At this point, an oversized generator is needed to handle the ice maker's large start-up current. Once this start-up problem has been solved, more of the wind turbine's capacity can be utilized and a better match between ice maker size and wind turbine size can be achieved.

Several ice maker manufacturers expressed concern about operating their equipment over a range of voltages and frequencies indicating that problems would occur when the system operated too far above or below the rated voltage and frequency. This is true if the ratio of the voltage to the frequency does not remain constant. However, if this ratio is constant the motor will operate in a range that will not damage it. As Figure 5 shows, this ratio is constant at 2.8 over the whole frequency range of this test.

Of the potential problems identified prior to experimentation, only a few were found to be significant. The most important problem involved the large start-up currents and corresponding voltage drops that occurred when either ice maker was turned on. Induction motors generally require from six to eight times the running current at start-up as the motors accelerate up to synchronous speed. This problem was not encountered in the wind-electric water pumping systems since the centrifugal pumps used start up under no-load conditions. Reciprocating compressors, however, are fully loaded at start-up and consequently have large start-up torques.

From the 10-kW, one unit ramp-up test reported in the previous paper (Davis, et al., 1994), the refrigeration cycle was proven to be stable, indicating that the thermostatic expansion valve did not cause any of the anticipated problems. Therefore, from the testing conducted thus far, it appears that the choice of ice makers that can be incorporated into wind-electric ice making systems is not limited to low-pressure receiver, liquid-overfeed systems, but includes a much wider range of machines. The anticipated freezing of the cutter bar to the evaporator surface after power is lost following high-speed or long-term operation did occur. The auger froze in place after the ice maker had been operating for 2 to 3 hours and was cycled on and off frequently. The ice, however, melted, and the auger and motor did not appear to be damaged. Modification of the existing PCU-10 to add a cycle-delay sequence should solve this problem.

It appears that the control system on the ice maker does not operate at the low voltages the system experiences at low frequencies because the ice maker stopped or cut-out between 31 and 38 hz prior to the PCU-10 cut-out at 30 hz. Setting the cut-in and cut-out frequencies higher should ensure that the on/off control for the ice maker is determined by the PCU-10 and that the ice maker shuts off when expected. Possible additional wear on the compressor due to low refrigerant flow at low speed was not evaluated.

North Star

The 10-kW permanent-magnet alternator could not run the North Star, so the 12-kW PMA was connected to the dynamometer for the North Star laboratory tests. Under the first test conditions the 12-kW PMA could start and run the North Star provided that the main contactor coil was manually held in place during start up. The North Star, however, was not operating properly so these test data are not included. During the second set of tests a month later, the North Star ran off of the dynamometer at 60, 50, 70 and 40 hz before the unit shut down. This behavior was not

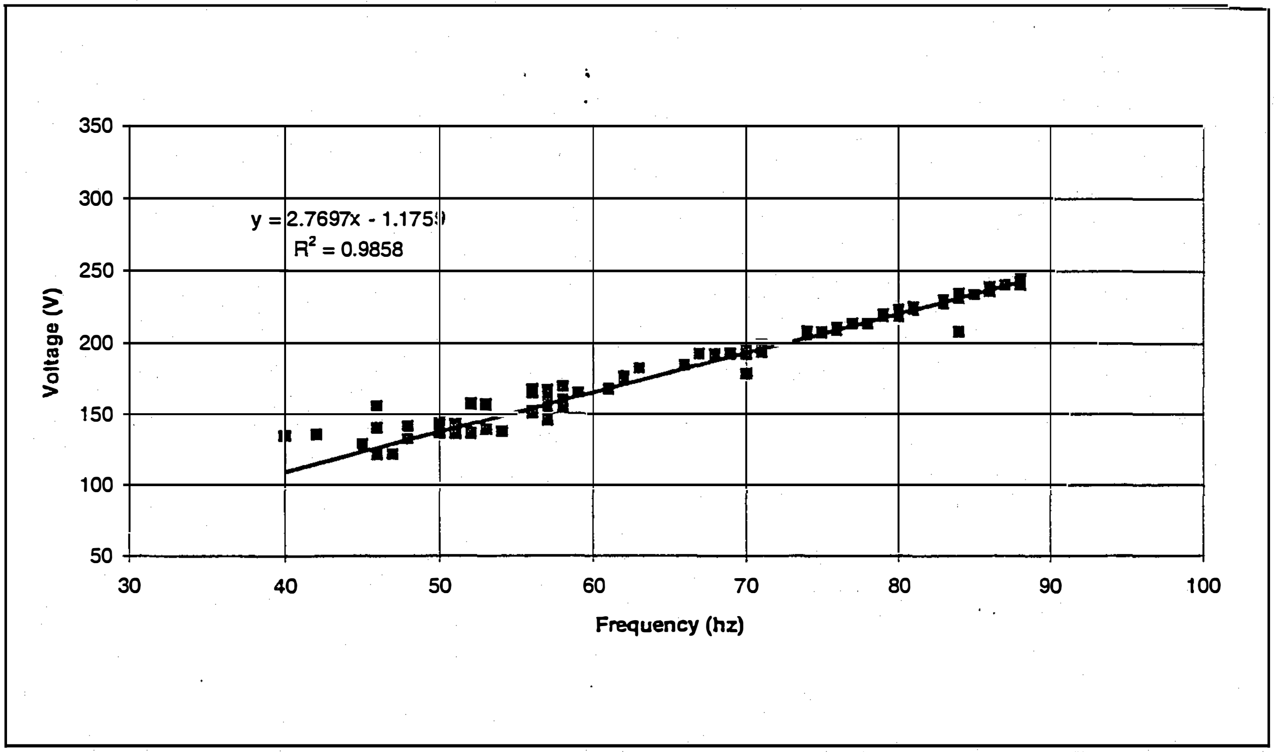

FIGURE 5. SCOTSMAN TWO-UNIT, 12-KW VOLTAGE-FREQUENCY CHARACTERISTIC

repeatable, however, since the next day when the ambient temperature was warmer, the 12-kW PMA could not start it. Apparently the North Star was operating at the boundary of operation. Four alternatives—bypassing the compressor during start-up to reduce the load on the compressor; running the ice maker from the grid to get it "cooled off" (again to reduce the compression load); trying to start the ice maker at low frequency to try to bring the compressor motor into synchronization and then up to speed; and trying to start the ice maker at high frequency to provide a higher voltage and current to better withstand the current surge—all failed to get the compressor to start and continue running.

FIELD TEST RESULTS

Since the 10-kW PMA could not run both Scotsman units, the 12-kW PMA was mounted on a 60-foot tower for field testing. Approximately 32,000 minutes of data were recorded over the month of July in Norman, Oklahoma. A good linear correlation between wind speed and frequency exists for this application.

Figure 6 shows ten-minute averages of the one-minute ice production and power data. The non-zero values of ice production at wind speeds less than 4 m/s (9 mph) are most likely caused by the float valve being stuck open slightly. There are over 3,200 data points in each of the power and ice production curves, though it does not look like 3,200 points are represented. This is because a significant portion of the data are zero values. The zero values arise from no wind at the low end of the wind speed range, designed system cut-out at high wind speeds, controller/system failure throughout the whole range of wind speeds, and possibly some other cause which has not yet been determined. Because the battery charging circuit on the PCU was not operating correctly, the battery which supplies 12 volt dc power to the controller was down part of the time, causing the ice maker not to run even when it was windy.

Unfortunately, summer winds in Norman are not strong and the high winds often come with thunder storms which usually have more erratic winds than during other times of the year. The average wind speed during July was 3.71 m/s (8.3 mph), as determined from the data gathered in this study. Because the annual average wind speed is 5.0 m/s (11.2 mph), July was not the best month to conduct field testing. Most of the storms at this location come from the Southeast in the summer and a 30- to 35-foot tree stands 100 feet south of the turbine. It is possible the wind turbine experienced turbulence caused by this tree and other surrounding buildings. From recent experience, Bergey Windpower has learned that their turbines' performance decreases somewhat when subjected to turbulence.

STAND-ALONE ICE MAKING MODEL

A model was developed to predict the amount of ice this wind-electric ice making system will produce at a variety of locations. The user of the model need only know the site elevation, annual wind speed, the Weibull shape factor, the ambient air temperature, and the inlet water temperature to the ice maker. The model calculates the average yearly and average daily ice production using a method of bins. There are two sets of calculations for each bin in the model: one to determine the capacity or ice production within each bin, and the other to determine the probability that the wind speed at a given moment will fall within that bin. For each bin this probability, the ice making capacity,

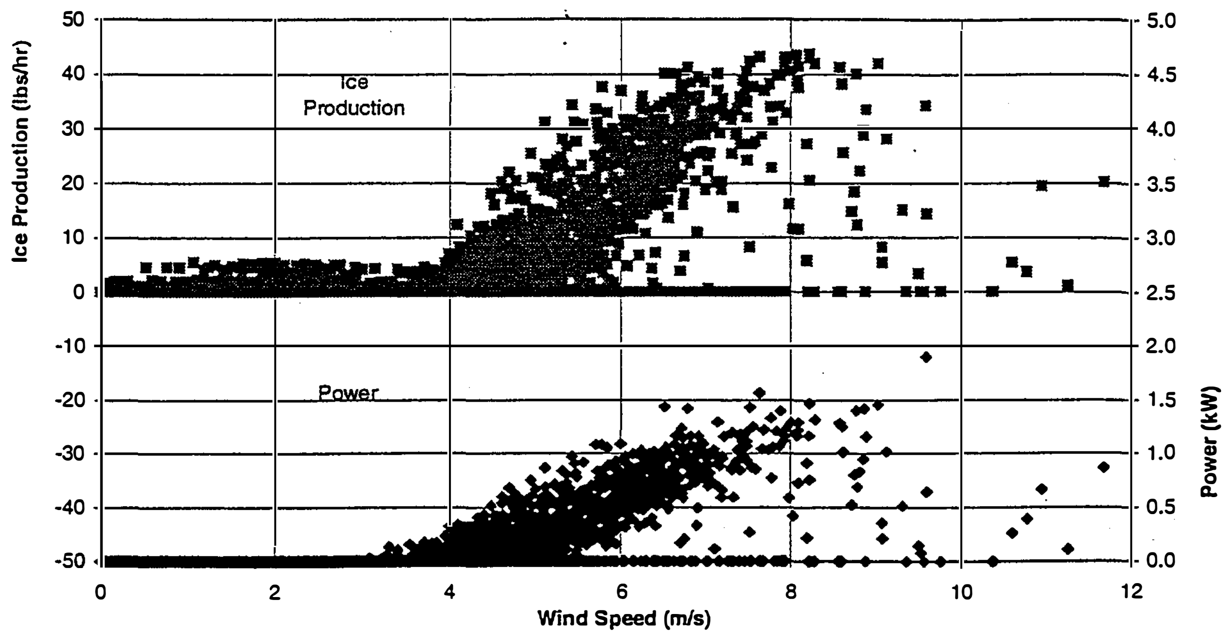

FIGURE 6. TEN-MINUTE AVERAGED FIELD TEST ICE PRODUCTION AND POWER DATA

and the time period under consideration (8760 hrs = 1 year or 24 hrs = 1 day in this case) are multiplied together to obtain the ice production in that bin over the designated time period. These capacities are then summed over the range of bins and the average annual and average daily ice production results.

For these model calculations, some fundamental relationships unique to the particular ice maker and wind turbine used need to be determined from the experimental data. These relationships are the following:

$$CAP/CAP_{rat} = f_T\ (T_a, T_i) \cdot f_C\ (f/f_{rat})$$

$$POW/POW_{rat} = f_P\ (f/f_{rat})$$

where:

CAP/CAP_{rat}	=	ice maker capacity divided by rated capacity
POW/POW_{rat}	=	power transmitted from the alternator to the ice maker (i.e. the power the ice maker consumes) divided by the rated power
f_T	=	function describing the dependance of the ice maker's capacity on temperature
f_C and f_P	=	functions describing the dependance of capacity and power on system frequency
T_a	=	ambient air temperature
T_i	=	inlet water temperature to the ice maker
f/f_{rat}	=	frequency divided by the rated frequency

The temperature function is determined from manufacturer's data and the frequency functions are determined from the experimental test results. The final equations for this system configuration are as follows:

$$f_T\ (T_a, T_i) = -0.00781\ T_a - 0.00512\ T_i + 1.807$$

$$f_C\ (f/f_{rat}) = 0.3702\ f/f_{rat} + 0.6298$$

$$f_P\ (f/f_{rat}) = 1.0482\ f/f_{rat} - 0.0482$$

The 12-kW dynamometer data with one Scotsman unit operating was the data set used to determine this correlation since the field test data include times when the controller was down. Unfortunately, there is some error involved in using the 12-kW dynamometer data because the power and capacity were never directly measured for the 12-kW case with just one ice making unit running. All laboratory performance data for the 12-kW dynamometer were obtained with both ice making units on. In order to compare the dynamometer correlations with those determined from the field tests, the 12-kW PMA, two-unit power and ice production were divided by two to get an approximation of the performance with just one unit running. The performance with just one unit running off of the 12-kW PMA is lower than one unit powered from the 10-kW PMA for two reasons. First, the 12-kW PMA is delta wound which gives it a lower voltage and higher current characteristic than the 10-kW PMA which is Y wound and has a higher voltage and lower current characteristic. The higher voltage corresponds to a higher frequency so the ice maker connected to the 10-kW makes slightly more ice at this higher frequency than it would off of the 12-kW. The second cause for reduced performance is that when both units are operating, the load on the wind turbine increases and changes the current and voltage characteristic of the system by lowering the voltage and decreasing the performance of the ice maker. Therefore, two units powered by the 12-kW PMA have a lower per unit performance than one unit powered by the same PMA.

FUTURE WORK

Future work will explore ways to reduce the large start-up currents encountered in applications with high start-up torque requirements. Some options include adding capacitors, using soft-start electronics, modifying the alternator windings and modifying the control sequence of the ice makers to stagger start-up of the different motors. In the last instance each motor would be allowed to come on only when sufficient frequency and voltage have been reached to withstand the additional start-up current and voltage drop. Introducing a flywheel and clutch system is another option, but is not straightforward since the compressors on both ice makers are hermetically sealed (i.e. the motor cannot be easily decoupled from the compressor). In the case of the North Star, using a smaller compressor or two smaller compressors that come on at different times may help to mitigate this problem.

Future work should also include additional testing of the North Star unit to determine its performance both in the laboratory and in the field. Long-term testing is needed to determine if variable speed operation significantly reduces compressor life. Additional study of the containers available to store and transport ice and fish is also needed in order to evaluate local materials with appropriate thermal properties.

CONCLUSIONS

The results of this project have demonstrated that conventional ice making equipment can operate when directly coupled to a variable frequency wind turbine. The anticipated problem with conventional thermostatic expansion valves did not materialize and consequently, from experience gained thus far, a much broader range of ice making systems can be considered for this application. A model was developed based on this study's test data to predict the ice production that can be expected from a Scotsman ice maker powered by a variable-frequency Bergey wind turbine generator. Continued research is needed to address the problems caused by large start-up currents and to provide field test results and long-term performance data. Despite unforeseen problems, wind-electric ice making holds great promise in meeting an important need in remote third-world villages.

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