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ABSTRACT

The village power group at the National Renewable Energy Laboratory (NREL) has been researching the most practical and cost-effective means for producing ice from off-grid wind-electric power systems since 1993. The first phase of the project demonstrated that commercial vapor-compression ice makers could operate effectively when powered by a variable speed permanent magnet wind generator. In the second phase of the project, steady-state and dynamic numerical models of these systems were developed and experimentally validated. The third phase of the project was thorough steady-state and dynamic testing of a commercial 1.1 ton ice maker unit powered by a commercial 12 kW wind turbine alternator on an NREL dynamometer test stand. With the data from phases I-III, an economic feasibility analysis was performed. It is hoped that continued development, and eventually commercialization, of this concept will take place in the private sector in the form of small business partnerships.

INTRODUCTION

Ice production and refrigeration can bring significant health and economic benefits to rural communities in tropical and sub-tropical climate zones. Food preservation can help to reduce malnutrition and turn subsistence farming and fishing into businesses with access to distant markets. Vaccine preservation can help to limit the spread of disease. Soft drink chilling and ice candy preparation are common income-producing uses of ice in many parts of the world.

Unfortunately for many rural communities in the tropics, ice is either too expensive to produce or purchase or it is too difficult to obtain altogether. Block ice purchased in many remote fishing villages in Central America costs as much as US$0.04 per pound of ice. The actual price will depend on the size of and distance to the nearest town where the ice is purchased. Because block ice is typically packed in sawdust rather than refrigerated, significant melting can occur during transport and the customer often pays the same nominal price regardless of any loss of ice (Ref. 1).

The likely coincidence of a good wind resource and the need for ice in coastal fishing villages motivated NREL to begin investigating wind-electric ice making in 1993. The focus of the NREL investigation has been on the “directly-connected” architecture in which the variable frequency/voltage output of a permanent magnet wind generator is used to directly power an AC vapor compression refrigeration (VCR) ice maker. While there were obvious technical hurdles to overcome with this architecture, the successful application of many directly-connected AC water pumps indicated that this investigation was a worthwhile pursuit. This investigation progressed in three phases: concept demonstration, computer model validation, and dynamometer testing.

PHASE I: CONCEPT DEMONSTRATION

The first phase of NREL’s investigation of wind-electric ice making started in September 1993 and concluded in December 1994. It was a joint research project involving NREL, the University of

Colorado in Boulder, and the Bergey Windpower Company. The objective of this research was to determine whether AC ice makers could run successfully from a variable speed permanent magnet wind generator. The Bergey Windpower Company supplied the dynamometer and field test facilities and equipment.

Two commercial flake ice makers were investigated. One of the ice makers was model FM2400WE-3A manufactured by Scotsman Ice Systems of Vernon Hills, Illinois. This ice maker is two 0.6 ton (50 lbs ice/hr) units sitting on top of one ice bin. The hermetic, reciprocating compressor of each unit is rated at 1.5 hp. The condensers are water-cooled. The evaporators are configured as stationary cylinders with a moving helical auger which shaves ice from the inside of the cylinder (see Figure 1). The refrigerant expansion device is a thermostatically-controlled valve.

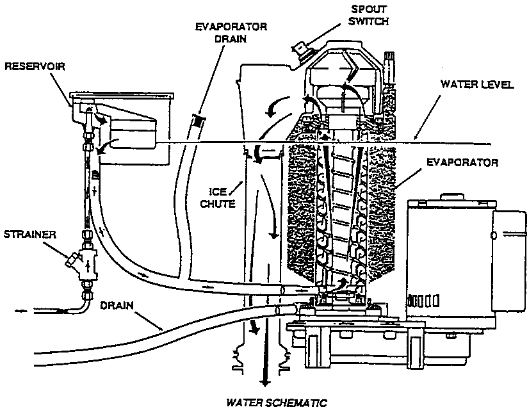


Figure 1. Scotsman ice maker.

The other ice maker was a Model 5/Coldisc D12 manufactured by North Star of Seattle, Washington. This 1.1 ton (92 lbs ice/hr) ice maker was intended for ocean-going vessels and consequently can process sea water. It has a single 4.8 hp hermetic, reciprocating compressor. The condenser is air-cooled by two fans. The evaporator is a rotating disk with a stationary auger for scraping the disk (see Figure 2). The refrigerant expansion device is a fixed-sized orifice.

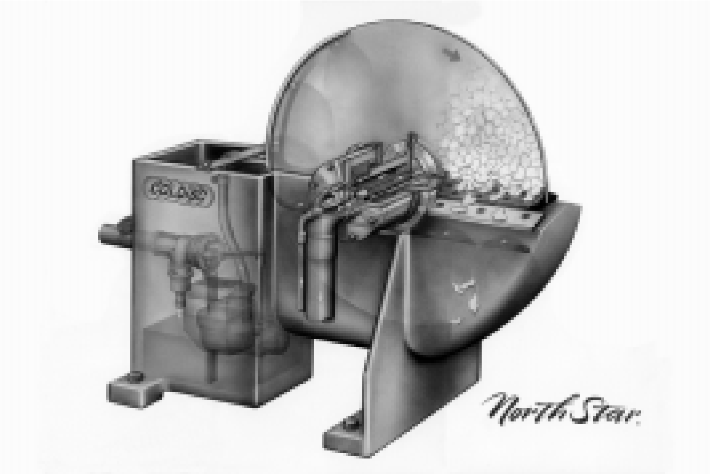


Figure 2. North Star ice maker.

Both ice makers were wired for 208-230 VAC, 60 Hz, 3-phase electrical input. Since there are various single-phase loads in both machines (e.g., controls, water pumps, disk motor, etc.), an unbalanced 3-phase load resulted when all of the components were operating.

The ice makers were first tested with a dynamometer. Only one of the Scotsman 0.6 ton units was actually field tested due to difficulty in starting the larger ice makers. Despite these problems, both the dynamometer and field test results were encouraging. Figure 3 shows a scatter plot of the field test data and a best-fit line to represent the dynamometer data. During the field testing a controller that is normally used for directly-connected water pumps was used to control the connection between wind turbine and ice maker. Much of the data scatter in Figure 3 was attributed to the inadequacy of this controller. The large deviation between the dynamometer and field results between 4 and 6 m/s wind speeds was due to frequent stopping and starting of the ice maker (the summer storm-driven winds were very turbulent). Between 6 and 10 m/s, significant ice production (i.e., 80% or more of rated production) did occur when the controller was functioning properly. There was not enough data for wind speeds above 10 m/s to make any conclusions for that regime. The results of this phase are described in detail in Ref. 2.

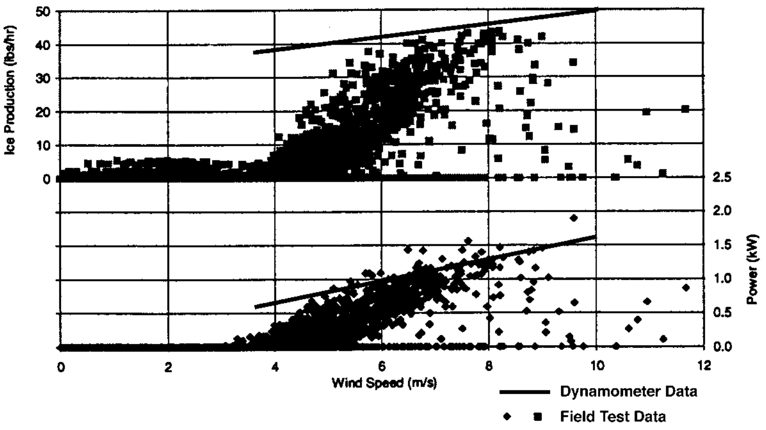


Figure 3. Results from phase I dynamometer and field tests.

PHASE II: MODEL VALIDATION

Phase II was conducted to address the ice maker starting problems that were experienced in phase I. The inability to start-up ice makers which are sized to the average power output of the wind turbine would make the "direct-connect" concept unusable. The approach taken was to first develop computer models of the steady-state and dynamic operation of the icemaker compressor so that various solutions to the start-up problem could be evaluated before proceeding with full-scale testing again. Only the compressor was considered in these models because it is the largest electrical load in the ice makers. The models were validated with a bench-scale experimental apparatus.

Description of Computer Models

The steady-state model was developed so that the effects of system changes on long-term performance could be investigated. The steady-state model includes the wind turbine rotor performance curve (i.e., C_p vs. tip-speed ratio), alternator and compressor motor electrical steady-state models, and the compressor's torque-speed curve. The torque-speed characteristics of both the wind turbine rotor and compressor were not measured directly, but instead were based on theory and indirect experimental evidence. The motor models use the standard equivalent circuit representations, the parameters of which were derived from experimental data. The model uses the steady-state equations of electrical equilibrium as well as power balance equations. The model was programmed using MathCad 5.0 software.

The dynamic model was designed to investigate the transient electrical interactions between a permanent magnet alternator and an induction motor. The wind turbine rotor and compressor characteristics were not included in the dynamic model. Various electrical and mechanical switching functions for simulating electrical switches, mechanical clutches, and other components were included. The universally accepted, nonlinear differential equations of electrical equilibrium form the basis of the model. An analytical solution of the resultant system of differential equations is impossible because of the presence of periodic coefficients. Consequently, the system of equations can only be solved numerically. The fourth-order Runge-Kutta method with adaptive step-size was the numerical solution technique used. The model was programmed with the MatLab 4.2 software package.

Validation of Computer Models

A bench-scale dynamometer apparatus was used to validate the results of the computer models. The 1-hp AC induction drive motor was powered by a variable-frequency drive. A timing gearbelt connected the shafts of the drive motor and a 600-watt permanent magnet alternator (PMA) which was provided by World Power Technologies. The three-phase output of the PMA powered a 1/3-hp AC induction load motor. The load motor was directly coupled (with a flexible coupling between their shafts) to a DC machine, which served as a dynamometer. The dynamometer was used to apply differing torques to the load motor shaft. This apparatus was fully instrumented and the data were acquired using National Instruments Labview software.

The validation of both computer models went very well. Despite the wide range of conditions over which the machines were operating, a single set of machine parameters worked quite well in both models for all conditions. This was somewhat surprising because small machines are often prone to nonlinear saturation effects, and temperature can have a significant impact on component resistances. As a general rule, most of the modeled results were within +/- 20% of the measured data. This was considered an acceptable error band for the bench-scale machinery given that the error should decrease for the full-scale equipment.

Figure 4 shows one of the validation results for the steady-state model. The “locked-rotor” condition means that the load motor shaft was restrained from moving while the alternator was sending current to it. Locked-rotor current is somewhat representative of the inrush current during normal start-up of the load motor when connected to a “firm” power source. The “no-load” test is just the opposite. That is, the load motor shaft is unrestrained and only torque from bearing friction is present. The results for both cases were excellent.

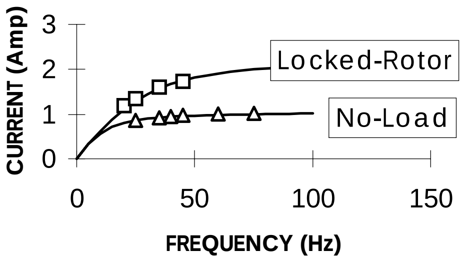


Figure 4. Steady-state model validation.

Figure 5 shows some validation results for the start-up performance of the dynamic model. The alternator output power and load motor speed are shown in the first few seconds that the load motor and alternator are switched together. The initial frequency of the alternator was 45 Hz and at that frequency the alternator was unable to start the load motor unaided. After 0.4 seconds elapsed, 72 µF series capacitors were switched into the circuit. At 2.2 seconds, the capacitors were switched out to prevent overloading. The model accurately predicted that the series capacitors boosted the power to the load motor which then successfully accelerated to its synchronous speed. The switching transients also appear in the modeled results.

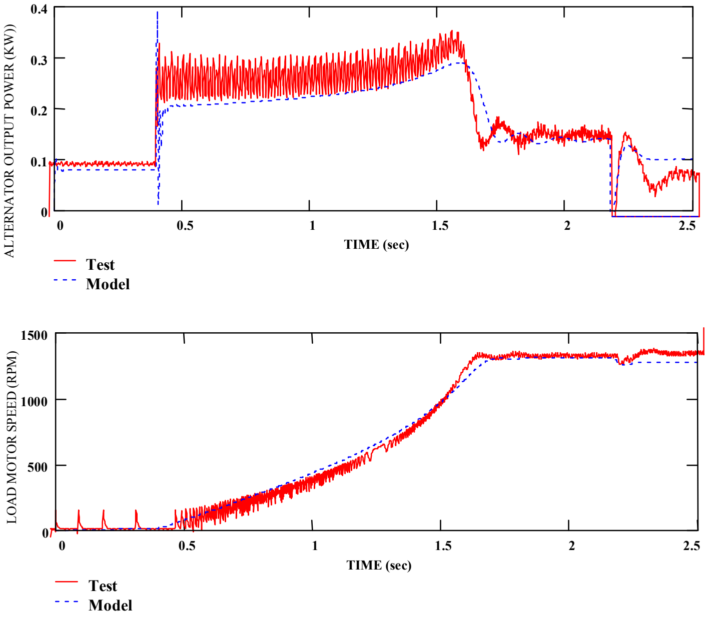


Figure 5. Validation results for dynamic model.

The Start-Up Problem Addressed

Following the validation of the models, three proposed solutions to the start-up problem were modeled and investigated. The proposed solutions were: (1) switched series capacitors, (2) a mechanical clutch, and (3) a centrifugal compressor with torque proportional to speed. Realistic full-scale parameters for a 10-kW wind turbine generator and a 4.8-hp compressor were used in the model. For all cases, the start-up wind speed was assumed to be 6 m/s. The dynamic model results showed that each of the proposed solutions would work provided that the systems were controlled correctly. That is, the series capacitors would have to be switched out and the mechanical clutch switched in at the correct moments. If not, then the systems might become unstable or just stall.

PHASE III: DYNAMOMETER TESTING

In the third phase of the NREL investigation, the North Star ice maker from phase I was chosen for in-depth dynamometer testing. The primary goals in this phase were to test the proposed series capacitor start-up solution and to characterize the system for long-term performance predictions. The series capacitor approach was chosen over other possible solutions due to its relative ease of installation and low cost.

On NREL's dynamometer test stand a variable-speed 75-kW DC machine drove a 12-kW, 230-volt Bergey Windpower Company permanent magnet alternator (PMA). A torque transducer was placed on the shaft between the DC machine and the PMA. Product ice was melted in a tank and the water was then pumped back to the ice maker. The ice/water mixture was continually stirred to prevent thermal and saline stratification. The salt concentration of the ice maker feed water was held nearly constant at 300 ppm. This apparatus was fully instrumented and the data were acquired with National Instruments Labview software (see Figure 6).

Figure 6. PMA (foreground) and ice maker(background) on dynamometer test stand at NREL.

Steady-State Results

Figure 7 shows the results of the steady-state tests. Each test, at frequencies between 40 and 80 Hz, lasted for at least 30 minutes. The ambient air temperature during these tests was 28 ºC. The power to the ice maker is increasing almost linearly with frequency because the torque of the reciprocating compressor is nearly constant. Since both power and impedance are increasing linearly with frequency, then it stands to reason that the current is very nearly constant. These results also show that the auxiliary loads (i.e., all loads except the compressor) in the ice maker account for about 25% of the total load.

The refrigerant suction temperature decreases linearly from 40 to 60 Hz, but then levels off. Suction temperature is a relatively good indicator of the quality of ice being produced. The lower frequencies produce wetter and warmer ice which is less useful than drier and colder ice. Ice production is quantified by the flowrate of feed water to the ice maker. Each liter of feed water produces about 2.2 lbs of ice. The suction temperature decrease and ice production increase with frequency is a result of all of the components in the refrigeration system operating at higher speeds and capacities.

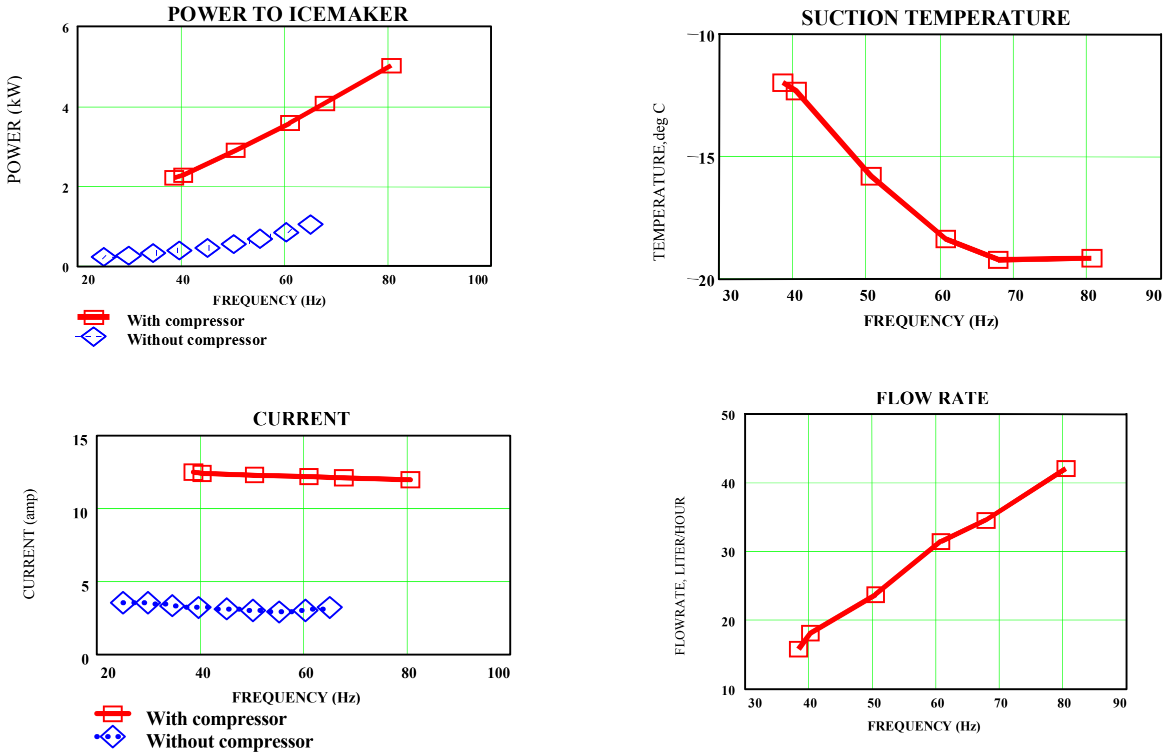


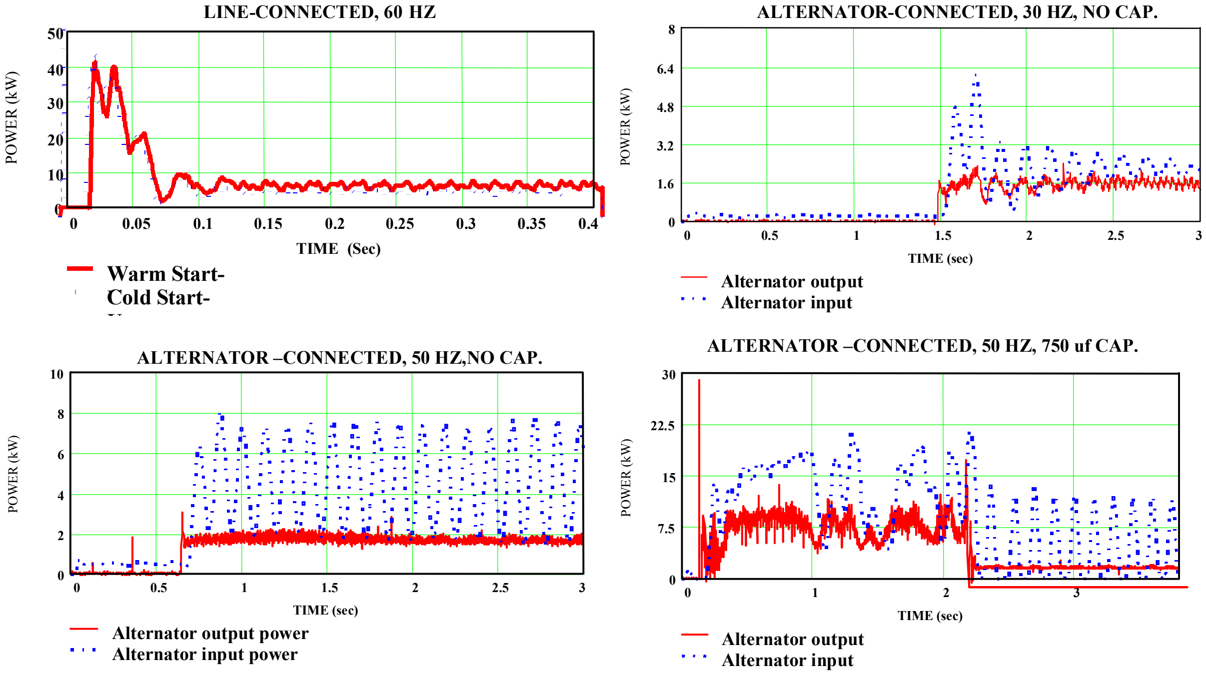
Figure 7. Results of steady-state dynamometer testing of North Star ice maker.

Start-Up Test Results

Figure 8 gives a sampling of results from the start-up tests. In the first set of tests, the ice maker was connected directly to the "line" (i.e., utility grid) at 208 VAC and 60 Hz. Start-ups were performed at both "warm" and "cold" initial conditions. The "warm" condition results when the ice maker has not been running for some time and the refrigerant temperature is nearly the same as the ambient temperature. The "cold" condition follows a recent shut-down of the icemaker. In the "cold" start-up shown, the refrigerant suction temperature was initially 0 ºC. The results indicate that there is no discernable difference between the "warm" and "cold" cases. The "line-connected" ice maker took about 0.08 second to start. At that point, the input power steadily decreased from about 7 kW until it leveled off at about 3.8 kW. This transition took about 3 minutes as the refrigerant temperatures reached equilibrium.

Only "warm" conditions were tested for the alternator-connected start-ups. This was done so that a lengthier investigation of this worst case was possible. The 12-kW alternator was able to start the ice maker successfully without series capacitors nor any other aid at frequencies between 25 and 45 Hz. The 30 Hz case shown in Figure 8 takes about 0.4 second to start the ice maker. In all of these cases the alternator speed sags after the initial connection with the ice maker, but quickly recovers afterward. This may not be the case however, when a wind turbine rotor is powering the alternator. The ice maker never started at frequencies of 50 Hz or more. The 50 Hz case in Figure 7 shows that the alternator cannot supply the required 3 kW to the ice maker to support steady operation at 50 Hz. This result has important implications for high frequency reconnections after the wind turbine is disconnected in high winds.

An attempt to start the ice maker at high frequencies was made with switched series capacitors. The capacitors were sized with the computer model, but only for the compressor load. As Figure 8 shows for the 50 Hz case, the 750 μF capacitors produced a significant increase in power. Unfortunately, electrical resonance prevented stabilization of the system and after the capacitors were switched out of the system the ice maker stalled. Apparently, the capacitors' interactions with the other single-phase motors caused the resonance. This result was repeated at 60 Hz.


LINE-CONNECTED, 60 HZ

ALTERNATOR-CONNECTED, 30 HZ, NO CAP.

ALTERNATOR –CONNECTED, 50 HZ,NO CAP.

ALTERNATOR –CONNECTED, 50 HZ, 750 uf CAP.

Figure 8. Start-Up test results for North Star icemaker.

Gusty Wind Simulation

To simulate gusty wind conditions somewhat, the speed of the drive motor was controlled such that the alternator frequency varied between 30 and 80 Hz over intervals ranging from 1 to 3 minutes. Figure 9 shows some results from this test. The ice maker responds to the changes in frequency almost immediately. Also, the relationship of average suction temperature to average frequency is the same as that from the steady-state tests.

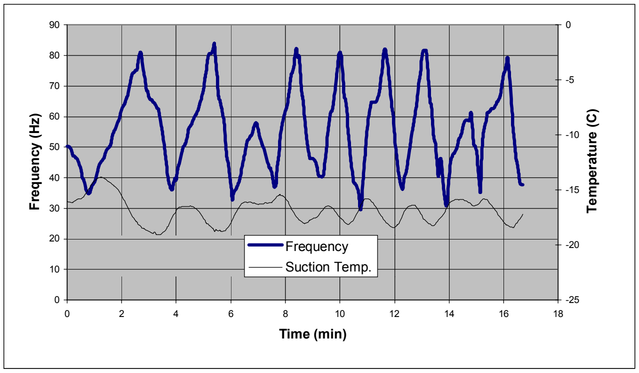


Figure 9. North Star ice maker response to simulated gusty wind conditions

Ice Production vs. Wind Speed

A prediction of the North Star ice maker's ice production as a function of wind speed was obtained by overlaying the icemaker performance curve from the dynamometer testing on top of the theoretical rotor performance curves. This process is illustrated in Figure 10. Using the intersections of the curves, the ice production curve shown in Figure 11 was constructed. The cut-in wind speed for the ice maker is 6.7 m/s. Recall from the discussion of the phase I field tests that the ice maker operation was very erratic below 6 m/s.

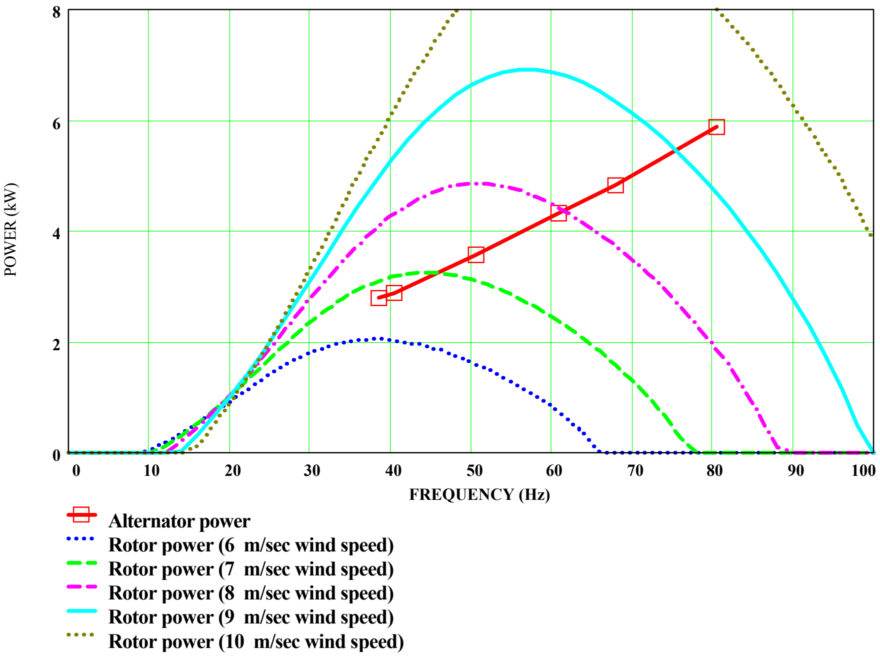


Figure 10. Overlaid ice maker and rotor performance curves.

DESIGN ISSUES: PROBLEMS & SOLUTIONS

Throughout the experimental phases of this investigation four major operational problems were experienced which must be addressed before this "direct connect" concept can be considered viable. The problems are: (1) the start-up overload problem, (2) poor quality of ice at low frequencies, (3) mechanical vibrations at high frequencies, and (4) control system failures. All of these problems can be solved from a technical point of view.

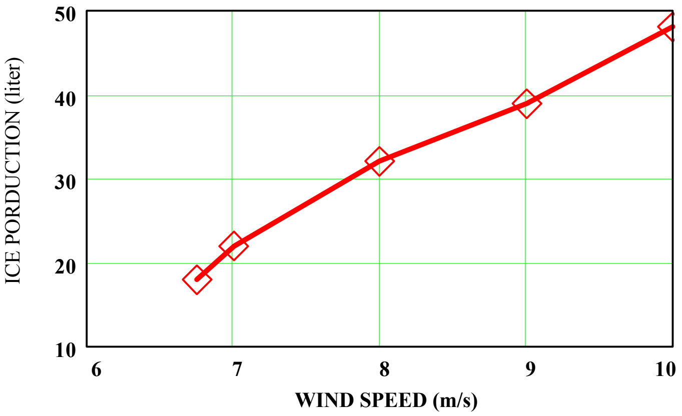


Figure 11. Ice production curve for North Star ice maker.

Start-Up Overload Problem

It is critical to the economic viability of the "direct connect" concept that one can use ice makers sized according to the average performance of the wind turbine. In general, this means that a start-up aid device will be required. Several possible "aids" have already been mentioned in this report; others are likely to exist. In regard to the switched series capacitor solution, resonances with the smaller single-phase loads in the ice maker must be avoided. One possibility is that the series capacitors are only used in the compressor circuit. Once the compressor is started the capacitors are switched out and the single-phase loads switched in. This will require controls that are somewhat more sophisticated than those used for "directly connected" AC water pumps, so perhaps this particular solution may not be appropriate for some remote locations.

Poor Ice Quality at Low Frequencies

While it is acceptable that product ice quantity varies with wind speed, poor ice quality is problematic. If only chilled water were required, then there is no need to use an expensive, complex, and power-intensive ice maker. Fortunately, it appears that the quality of ice really doesn't need to suffer at low frequencies. Thermostatic control of the refrigerant and reduction of heat transfer to the evaporator surface may hold some promise for overcoming this problem. Although thermostatically-controlled expansion valves are common in refrigeration systems, this particular North Star ice maker did not have one. Reducing heat transfer to the evaporator surface could be accomplished with a small, heavily-insulated enclosure around the evaporator unit.

Mechanical Vibrations at High Frequencies

During the phase III testing of the North Star ice maker, severe vibrations of the condenser fan blades occurred at 70 and 80 Hz and the ice maker had to be shut down. It is probable that those fan speeds corresponding to 70 and 80 Hz matched the resonant frequencies of the fan blades. Among others the following are possible ways to counter the vibration problem: (1) redesign the fan blades, (2) use three-phase condenser fan motors instead of single-phase motors, and (3) use a water-cooled condenser rather than an air-cooled condenser. The latter solution may be particularly attractive because water-cooled condensers may make the ice maker's performance less sensitive to changes in the ambient temperature and fan blade corrosion will not be an issue.

Control System Failures

Most commercial ice makers' control functions are energized by the ice maker's main power source. If that source of power produces less than rated voltage, then some of the components may stop functioning altogether. In particular, many of the contactors will fail to open or close under those conditions. If the source of power produces more than rated voltage, then there is the possibility of fuses and circuit breakers being blown or circuits being overloaded. Putting the control functions on a battery-powered system may be one way to solve this problem. If the control circuit cannot easily be changed over to DC, then a small inverter would be needed. Keeping the battery charged may require a custom-made charger because most commercially available AC battery chargers also require a constant voltage/frequency power source.

ECONOMIC FEASIBILITY ANALYSIS

An economic feasibility analysis was undertaken to determine if the "direct connect" concept will be economically competitive with other alternatives. The life-cycle cost method was used to make this evaluation. The figure-of-merit for this case is the *cost of ice (COI)* or the annualized cost of the system divided by the annual ice production. The annual ice production was predicted by an hourly simulation program, *Hybrid2* (Ref. 3). The ice production versus wind speed curve that was used for these simulations is shown in Figure 12. This curve assumes that the problems occurring at high

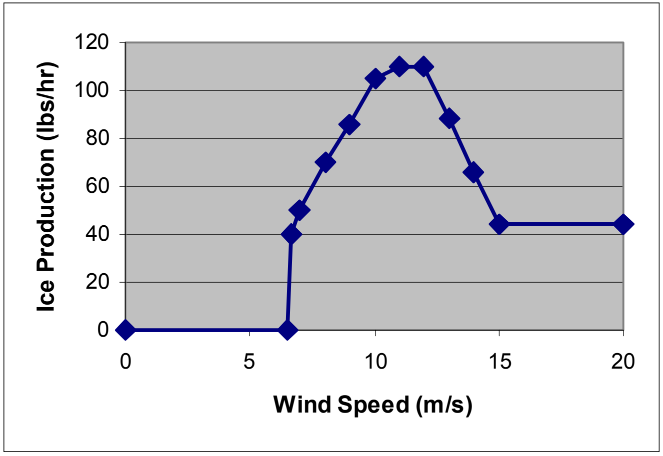


Figure 12. Ice production curve used as an input to Hybrid2 for the economic feasibility analysis.

frequencies are solved so that operation continues beyond the point at which testing ceased in phase III. Measured wind data from three coastal sites in Chile, Mexico, and Brazil provided a wide range of average wind speeds and Weibull distribution shapes for the simulations.

Sample results of the feasibility analysis are illustrated in Figure 13. This graph shows the costs of ice for several different ice making systems. *Wind-Only* refers to the "direct connect" concept of only a wind turbine and ice maker. *Diesel-Only* is only a 12-kW engine-generator powering the ice maker. *Wind-Diesel* is the same as wind-only, but with a 12 kW back-up engine-generator. *Wind-Inverter* is a wind-charged battery bank and inverter. *Wind-Hybrid* is the same as the wind-inverter system, but with a 12 kW back-up engine-generator. The wind speeds mentioned in the legend are annual average wind speeds for a particular simulation run. The fuel cost was varied in this analysis from US$1.00 to US$2.00 per gallon. For the particular case shown in Figure 13, the fuel cost is US$1.75 per gallon. The capital cost for the ice maker was assumed to be US$15,000 which should cover substantial modifications. The effect on COI by variations in total ice maker cost between US$10,000 and US$20,000 is illustrated on the graph with the "error" bars. Maintenance, operation, and periodic replacement costs of all equipment has been included in the analysis. An 8% real discount rate and a 10 year/10% interest loan was assumed. The economic life of the project was assumed to be 20 years.

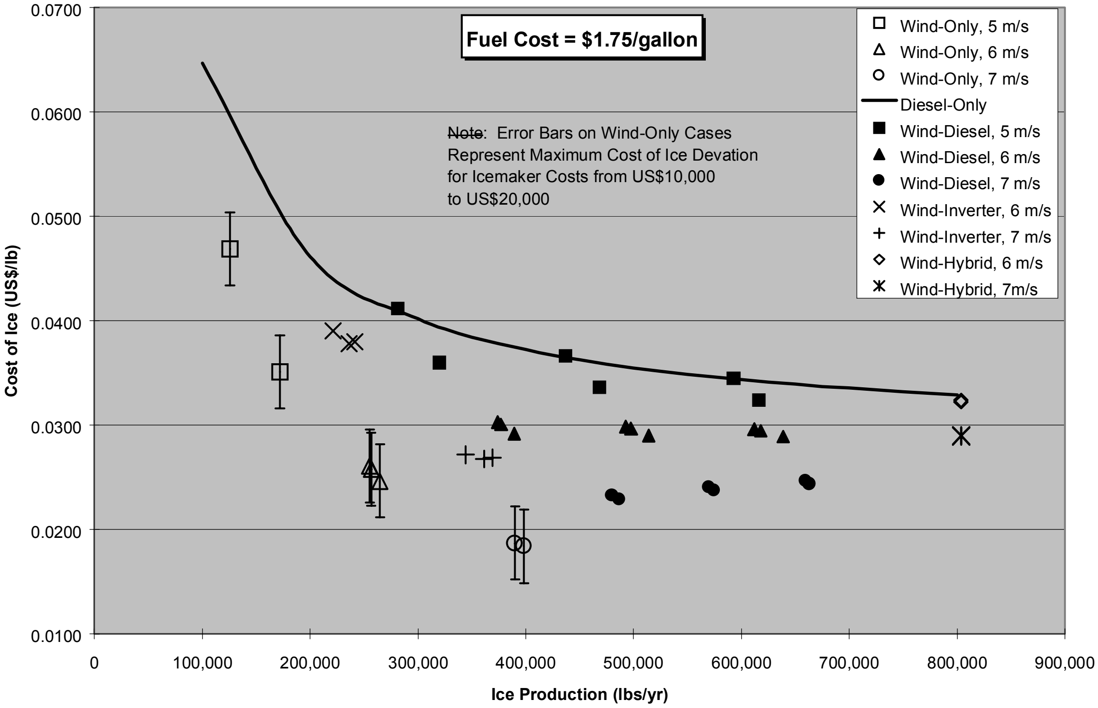


Figure 13. Sample result from economic feasibility analysis.

CONCLUSIONS AND FUTURE PLANS

Based on the results of this investigation to date, the "direct connect" concept of wind-electric ice making appears to be both technically feasible and economically competitive with other alternative wind systems. Modifications will be required before "off-the-shelf" commercial ice makers can be used for such purposes. Because back-up engine-generators only slightly increased the cost of ice and they are dispatchable, they may be a worthwhile addition to these systems. Placing a "direct connect" ice making system in a rural village will require a careful screening process. Not only is an energetic wind resource required, but the seasonal variations in wind should be well-correlated with the seasonal demand for ice. It may be necessary for some sites to choose an ice maker/wind turbine combination that produces a lower cut-in wind speed, perhaps around 5 m/s. Ice maker maintenance and community perceptions about the need for ice will also be strong determinants in project success.

Further development of this concept should continue in the private sector in the form of small business partnerships. To this end, USDOE has recently solicited proposals from small businesses for developing wind-electric ice making systems (Ref. 4).

A more detailed treatment of this topic can be found in Ref. 5.

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REFERENCES

1. Smith, G.J., “Productive Uses of Wind Power, Ice Making Project Identification, Honduras, July 1994-July 1995,” National Rural Electric Cooperative Association.

2. Davis, H.C., “Wind-Electric Ice Making for Developing World Villages,” M.S. Thesis, Dept. of Civil Engineering, University of Colorado - Boulder, 1994.

3. Baring-Gould, E.I., Green, H.J., and van Dijk, V.A.P., “Hybrid2 – The Hybrid Power System Simulation Model,” Proceedings of Windpower ’96, Denver, Colorado, American Wind Energy Association, 1996.

4. United States Department of Energy, Small Business Innovation Research (SBIR), Program Solicitation for 1998, http://sbir.er.doe.gov/sbir98sol/main.htm, Topic 33.

5. Holz, R.G. et al., “Wind-Electric Icemaking Project: Analysis and Dynamometer Testing,” NREL/TP-500-24010, 1998.