DESIGN CHARACTERISTICS OF THE 224 kW MAGDALEN ISLANDS VAWT

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SUMMARY

The evolution of the main design features of the Magdalen Islands VAWT is described. The turbine has a rotor height of 120ft (36.58m) and diameter 80ft (24.38m). It was operated as a joint project between NRC and Hydro-Quebec in grid-coupled mode from July 1977 to July 1978 when the rotor was destroyed in an accident. The accident, although unfortunate, tested the basic integrity of the design in a gross overspeed condition, and the rotor is being rebuilt with minor modifications. Some directions for future VAWT research are suggested.

INTRODUCTION

Early stages in the NRC laboratory development of the curved-blade Darrieus type VAWT have been described elsewhere (e.g. Ref. 1 and 2). The Magdalen Islands turbine (Fig. 1) is the largest machine of this type that has so far been built, and a recent paper (Ref. 3) describes some of the operating experience, including performance data, obtained during its field tests between July 1977 and July 1978. That paper also describes the accident that destroyed the rotor last July. The present paper is therefore limited to discussion of the factors that affected the choice of the main design features, and to some indications for future VAWT research and development effort.

During the accident, which occurred in moderate winds after the rotor had been de-coupled from the remainder of the drive train while the latter was undergoing maintenance, the rotor was subjected to several hours of runaway operation at rotational speeds up to 75 rpm, approximately twice the normal design speed. Failure eventually occurred in the base attachment of one of the four guy cables; no other structural failure occurred until the rotor struck the ground. The rotor is now being rebuilt without change in its basic structural design, for installation in early summer 1979.

Briefly, the early history of its development is as follows. By 1974, following field trials and wind tunnel tests of small-scale VAWT's, it had been decided to proceed with the early development of a large-scale, grid-coupled unit. Although some opinions had suggested that dynamic problems would limit large-scale VAWT development, simple dimensional analysis showed that most of these problems could be made invariant with scale.

It had also been confirmed in small-scale tests during 1973 that aerodynamic stalling of the blades in a constant-speed VAWT could be used to flatten or lower the power output curve beyond rated wind speeds, so that no variable geometry or associated automatic control was required. Although no request for proposals for a large machine had been issued, DAF-Indal Ltd, Toronto forwarded an unsolicited proposal to the Canadian government in December 1974, for a 200 kW turbine, based upon a 3-bladed rotor of height and diameter equal to 90ft (27.43m). That company had pioneered the use of hollow extruded aluminum blades in small-scale turbines, and proposed the same blade technology for the 200 kW VAWT.

Hydro-Quebec, one of Canada's largest power companies, had already carried out studies of the application of wind energy in certain parts of its system, and had decided to procure a large-scale commercial WECS for field trials on the Magdalen Islands. The Islands' 13,000 inhabitants are supplied with electric power by Hydro-Quebec's central diesel generating station which has a total installed capacity of 39 MW. Annual mean wind speeds in most of the islands and at the turbine site are consistently close to 19 mph (8,5 m/s). The collaboration of NRC and IREQ (Institut de Recherches de l'Hydro Québec) in the WECS demonstration project was thus a natural development. IREQ's contribution to the project has in fact been larger, in terms of manpower and cost, than NRC's, since they designed and built the turbine control system, foundations and all other site details, carried out turbine installation, and provided full-time site operating and maintenance crew.

PRELIMINARY DESIGN DRIVERS

The following factors mainly affected the initial choice of the basic turbine design parameters, and resulted in a number of changes to the original DAF-Indal proposal. From the outset it was felt that the time scale and costs of development should be reduced as much as possible, and therefore a high priority was given to overall simplicity of design. The principal turbine geometric parameters were initially chosen on the basis of very little analytic study in order to get detail design started as early as possible. Figure 2 shows a calendar of events, primarily during the design phase.

(a) Blade structure As already mentioned, DAF-Indal had proposed the use of extruded aluminum one-piece airfoils for the turbine blades. They had determined that the largest available extrusions would provide an airfoil chord of about 24 inches (0.61m), and it was probably this figure more than any other single factor that set the overall scale of the turbine. Minimum-weight extruded airfoils tend to have approximately constant skin thickness and their mass centres are therefore located aft of the quarter-chord point. From the point of view of prevention of bending-torsion flutter in the wings of aeronautical vehicles, this would be an undesirable characteristic. In early 1975, the Sandia laboratories made available a film of a violent blade flutter that they had discovered during wind tunnel tests of a 3-bladed rotor. In this complex mode, blade plunge and torsion were coupled, and a subsequent approximate analysis indicated that the primary coupling between modes was probably due to coriolis forces, and that the airfoil chordwise mass centre location was relatively unimportant. However, a high blade torsional stiffness appeared to be desirable and as a result the airfoil section was thickened from the NACA 0015 used on previous small turbines to NACA 0018 for the Magdalen Islands rotor. The thicker section also increased blade bending stiffness and therefore the resistance to buckling in high winds with the rotor parked. The extruded airfoils have four integral spanwise spars, and weigh approximately 25 lbs per foot of length (37 kg/m). The blades, each about 150ft (45.7m) long, contain no internal transverse ribs, but consist of 4 lengthwise segments joined by steel bars bolted to the front and rear spars.

(b) Number of blades The number of blades was chosen to be two rather than three, in spite of the fact that this would lead to higher torque ripple and dynamic loads on the support structure. The reason was partly to reduce costs of construction, but mainly to simplify field erection: the rotor was assembled flat and lifted after assembly. Moreover, with two blades, but not with three, drive train elasticity produces an attenuation of the twice-per-rev lead-lag blade bending moment amplitude.

(c) Rotor height-diameter ratio All previous known small-scale Darrieus rotors had been built with rotor height equal to or less than the diameter. For blades of parabolic shape (a close approximation to the troposkein shape), it can be shown that unity height-diameter ratio leads to maximum total swept area for a given blade length. There are, however, advantages to increasing height-diameter ratio. For a given swept area and blade solidity, rotor rpm is increased, thus lowering torque and alternator-to-turbine speed ratio. The bending of blades to the troposkein shape is also simplified since the required curvature of the blades at the equator is approximately inversely proportional to the square of rotor height-diameter ratio. Another important factor was that, for an optimum guy cable slope of 40 - 45° to the horizontal, a height-diameter ratio of 1.5 permitted sufficient clearance between blades and cables without a long shaft extension above the upper blade attachments, thus reducing design bending moments in the central column. The final choice of $H/D = 1.5$, was not, however, based upon elaborate analysis of cost optimization, and is not necessarily considered the best choice under all circumstances.

(d) Turbine swept area As already stated, the choice of the largest available aluminum aerofoil extrusions tended to set the overall turbine scale. However, swept area is proportional to the square of blade solidity for a given blade chord and number of blades. If the solidity is defined as the ratio of the total blade chord to the turbine equatorial radius, it is usually found from performance calculations and wind tunnel tests that the highest peak values of aerodynamic efficiency are achieved with a solidity of about 0.2. This value would have led to a turbine radius of 20ft (6.10m), a height of 60ft (18.29m) and a swept area of only 1,600ft^2 (148.6m^2). The final choice of a swept area of 6,400ft^2 (594.6 m^2) was felt to be necessary in order to demonstrate the feasibility of a turbine of significant size, although it was recognized that the resultant low blade solidity (0.10) represented a compromise in terms of the maximum achievable efficiency.

(e) Spoilers All of the small VAWT's that had been built in Canada prior to 1975 had been equipped with automatic, centrifugally actuated blade spoilers to prevent overspeed and it was decided to incorporate a version of these in the Magdalen Islands turbine. Since a mechanical disk brake was also installed, for use in all normal and emergency stops, the spoilers in this case were designed as a back-up brake to be used only in the event of mechanical brake or drive train failure. Wind tunnel test data (summarized in Ref. 2) shows that only small spoiler area (of the order of 1% of turbine swept area) is sufficient to destroy aerodynamic power at all blade-to-wind speed ratios, and they are thus an attractive device from this point of view. Their failure to prevent turbine overspeed in the Magdalen Islands accident (appendix to Ref. 3) was not due to size or to failure to open but resulted from unstable operation, which in turn was due to inadequate centrifugal mass unbalance.

However, as a warning to other VAWT designers, spoilers present several problems. Fail-safe mechanical design, which should incorporate some means of ensuring that all spoilers open together, is difficult. If they are expected to slow the rotor to blade speeds well below wind speed, they will be subjected to reverse flow during every revolution, which may lead to aerodynamic instability about their hinge line. Some means of automatic or manual re-closure must also be built in. In every turbine we have built or procured, we have debated the question of deleting spoilers in the interests of simplicity, and in every case have decided to retain them one more time, including the rebuilt Magdalen Islands rotor.

(f) Blade struts As shown in Fig. 1, the rotor blades are supported by two horizontal struts of double A-frame configuration.

The design of the struts was evolved during the wind tunnel tests which are described below. They serve three main purposes: to stabilize the blades against compressive buckling in the parked, high-wind condition, to raise the blade critical flutter speed, and to provide a means of damping the possible "butterfly" mode of inter-blade resonance. In the butterfly mode, the blades oscillate out of phase in the lead-lag direction (one blade leads while the other lags), and the mode can be excited aerodynamically if its natural frequency coincides with an odd multiple of rotor rotational frequency. In constant-speed turbines this mode can be avoided by placing its natural frequency between, say, the 3P and 5P frequencies, or alternatively by providing some means of damping. In the Magdalen Islands turbine, damping was provided as insurance, although no butterfly resonance was detected during tests without damping. The method of providing damping was as follows. The horizontal struts are not rigidly attached to the central column, but to sliding rods that pass through bushings in the column. Thus, torque is transmitted to the column through the struts, but they are otherwise free to translate if butterfly mode oscillations develop. Hydraulic dampers are installed in parallel with the sliding rods inside the column. Other aspects of the strut development are described below in the context of the wind tunnel tests. It should be pointed out that it is by no means certain that some form of blade support struts are absolutely required on large-scale Darrieus type VAWT's, and they represent a fruitful area for future design simplification.

(g) Alternator type A commercial (Canadian General Electric) 300HP induction motor with a synchronous speed of 720 rpm was chosen for the Magdalen Islands turbine alternator. One of the main reasons for the choice of an induction rather than a synchronous alternator was that preliminary analysis carried out early in 1975 (item 2 in Fig. 2) had indicated favourable dynamic behaviour of the elastic rotor-drive train-alternator system. The induction alternator avoids the introduction of an additional mechanical stiffness or torsional resonant modes into the system, and in fact provides some damping of the shaft torque ripple. No problems with the alternator have been encountered during start-up or normal operation.

(h) Available methods of dynamic analysis There was one overriding design "driver", if that term is applicable, that had to be faced by the NRC laboratories at the time of the decision to proceed with the large turbine in early 1975. No computerized structural analysis methods were available in the laboratory that were applicable to the dynamic analysis of large-scale vertical axis turbines, nor were the resources available to develop them within a reasonably short time. On the other hand, NRC had available several low speed wind tunnels, including the 30 × 30ft (9 × 9m) V/STOL tunnel. It was therefore decided to base the dynamic analysis upon a series of aeroelastic wind tunnel models. The tunnel program is briefly summarized below.

AEROELASTIC WIND TUNNEL TESTS

Three scales of aeroelastic models were built for wind tunnel tests. The first set of models, at about 1/50 scale, were non-rotating models with solid strap blades for the investigation of blade collapse in high winds with the rotor parked. Because gravity loads may contribute to compressive instability of the curved blades, these models and the tunnel wind speed were scaled so as to preserve full-scale values of dimensionless stiffness quantities and also the Froude number. The results, in dimensionless form are presented in Ref. 2. For the strutted blades of the Magdalen Islands wind turbine, the wind speed for blade collapse is estimated to be well in excess of the specified maximum design wind speed of 135 mph (60 m/sec). The model tests indicated that the addition of struts approximately doubled the wind speed for blade collapse with rotor parked at the most critical angle.

A 1/24 scale aeroelastic rotor model was built and tested in 1975 (item 5, Fig. 2), to measure rotor cyclic loads and their Fourier components. The same model was driven to flutter speeds with various blade configurations in order to determine the dimensionless blade and strut stiffness parameters required to avoid flutter. The results were reported in Ref. 2. These tests incidentally confirmed the insensitivity of flutter speeds to the chordwise location of the blade mass centre.

Finally a 1/4 scale aeroelastic model was tested in early 1976 (item 8, Fig. 2). In this, and also in the 1/24 scale model tests, Froude scaling was not preserved, since gravity forces have no cyclic components in vertical axis turbines. Instead, full-scale speeds, relative stiffnesses, reduced frequencies and stress levels were preserved. The blades and central column of the 1/4 scale model were strain-gauged at a large number of locations. Sample results, in dimensionless form, were presented in Ref. 2. Of particular relevance to the final design of the full-scale rotor was the discovery that the butterfly blade vibration mode could have a natural frequency close to an odd multiple of the full-scale normal operating rotational speed (38 rpm) but that damping was effective in attenuating blade stress levels. Accordingly, the strut design was modified to incorporate damping capability, as already explained. Cyclic stress levels measured on the full-scale turbine were found to be in reasonable agreement with those measured on the 1/4 scale model in the wind tunnel. A summary of the full scale dynamic stress data at the maximum-stress location on the blades was presented in Ref. 4. The cyclic stress levels were found to be well within acceptable fatigue limits.

Although the NRC aerodynamics laboratory is wind tunnel oriented, and therefore probably biased in this direction, the use of wind tunnel models, especially for dynamic testing is recommended without hesitation in the development of large-scale wind turbines.

SOME ITEMS FOR FUTURE RESEARCH

(a) Improved aerodynamic theory In comparison with HAWT's, the aerodynamic optimization of vertical axis turbines is still in its infancy. For example, simple symmetrical airfoils are generally used for blading. Unfortunately, further design refinements are hampered by inadequacies of available performance theories that are practical for curved-blade Darrieus type rotors. Momentum streamtube theory has not yet been developed to adequately predict the difference in induced velocities between the upwind and downwind forces of the rotor. Vortex theories have been developed which seem to be superior for the idealized two-dimensional (straight-bladed) rotor, but their adaptation to full three-dimensional flow is a formidable problem. In this state of affairs it is not even certain how to specify the most desirable airfoil characteristics. Low drag airfoil technology has not been much explored, but is potentially important because in constant-speed turbines parasite drag losses produce constant energy dissipation at all wind speeds.

(b) Torque and force filtering In two-bladed (or single-bladed) vertical axis turbines, there may be large-amplitude torque ripple, and also large-amplitude rotor drag and side force oscillations. Torque ripple can be reduced by designing the rotor and drive train so that the lowest natural torsional frequency is well below rotational frequency, but there are limits. Analysis of mechanical torque ripple filters has been carried out at NRC, and it is at least theoretically possible to reduce torque ripple to zero in constant-speed or nearly contant-speed systems. One method is to incorporate an elastically sprung flywheel in the drive train, with its natural frequency tuned to be equal to twice the rotor rotational frequency. The mass of the flywheel need only be about 2 percent of rotor mass. For turbines coupled to induction alternators, the operating speed varies by a few percent depending on power level, but there are simple bob-weight type "flywheels" that automatically retain their tuning over a range of shaft speed. These are old devices for torque smoothing in internal combustion piston engines. In the Magdalen Islands turbine, no such devices are used, and in fact the magnitude of the torque ripple (roughly ±20% of maximum mean torque) has posed no apparent problems. Analysis also indicates that somewhat analogous bob-weight filters mounted near the top of the rotor, could be used to reduce or eliminate oscillatory drag and side force oscillations in the supporting guy cables.

(c) Soft mounts Two possible forms of soft mounts are shown in sketch form in Figure 3. Figure 3(a) shows a method of attachment of guy cables at the upper rotor bearing, which provides a low rotor whirl frequency while maintaining normal guy cable tension and natural frequencies. The sloping cables are attached to a floating ring and then continued vertically to outriggers on the bearing housing. The rotor natural frequency is a function of guy cable tension and the length of the vertical cable segments. The rotor will pass through its critical speed at a low rpm during starting or stopping but at normal operating speeds, the soft mount prevents significant oscillatory loads from being transmitted to the cables. This scheme has been investigated experimentally in wind tunnel tests of the 1/24 scale model of the Magdalen Islands turbine, with excellent results.

Figure 3(b) shows, in schematic form, a type of soft mount at the base of a VAWT. The design of fully cantilevered VAWT's normally requires a central column that has high bending stiffness, with consequent high costs. Depending on the relative mass distribution in the rotor and in the base, the addition of a soft base mount raises the bending natural frequency and therefore the effective stiffness of the rotor system. A low natural frequency of the entire assembly is also introduced but this can be damped relatively easily at the base (dampers not shown in the diagram). Further investigation of systems of this type may eventually make possible the cost effective development of large-scale VAWT's with no guy cable supports.

(d) Single blade rotors A 12ft (3.7m) diameter single-blade rotor was tested in the NRC V/STOL wind tunnel about 6 years ago, and was subsequently operated for some time outdoors. No serious problems were encountered, and performance was approximately equal to that of a multi-blade rotor of the same solidity. In late 1976, the 1/4 scale aeroelastic model of the Magdalen Islands turbine was modified by removing one of its blades and installing counter-weights. Wind tunnel tests showed no structural dynamic problems, and in particular no resonant condition corresponding to the two-bladed butterfly resonance. Cost estimates for large-scale turbines indicate that substantial cost reductions may be possible for single-blade rotors. Increase in blade solidity to the equivalent of a two-bladed rotor permits a lower blade material mass while retaining required blade stiffnesses. There is a possible drawback, however, and this may be true for single-blade horizontal axis turbines as well: they look strange, particularly when rotating.

CONCLUSION

The constant-speed curved-blade Darrieus type VAWT, of which the Magdalen Islands turbine is only one example, has been demonstrated at medium scale, and represents a potentially cost-effective WECS configuration because of its basic simplicity. It is still in its infancy, however, and can benefit from further research and development, provided always that cost reduction is kept as the main target.

REFERENCES

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3. P. South and A. Watts - Magdalen Islands VAWT Field Test. Paper presented at Workshop on Economical and Operational Requirements and Status of Large Scale Wind Systems, Monterey, Calif. 28 - 30 March 1979.

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DISCUSSION

Q. To what extent were your comments on the use of experimental models to determine dynamics effects affected by the fact that you have a relatively large wind tunnel to perform your experiments? On a commercial basis, analytical programs might be more cost effective, notwithstanding the fact that model demonstration really does provide the right answer.

A. We were indeed lucky to have a large wind tunnel, and I also really didn't mean to imply that you should abandon analytical methods. There are advantages and disadvantages to each. The wind tunnel approach gives you an experimental answer for one design configuration, but it's much easier to change the variables in an analytical approach.

Q. What have you experienced on the sensitivity of this type of rotor to gusts?

A. If you refer to constant speed rotors so that the rotor inertia is not involved, they really are responsive to the gust scale that is of the same order of magnitude as the rotor dimensions. In that case, the power can fluctuate over a very wide range very rapidly.

Q. Have you experienced extra stresses due to response of gusts in that situation?

A. I don't really know whether I can answer that or not. We have taken blade stress data in the field and have put data through spectroanalysis. We find that the largest blade stresses are all at the precise multiples of speed where one finds them in non-turbulent flow. If there is a little spectral bump elsewhere that is not at a precise multiple of the speed, we think that is a signature of one of the rotor natural modes, such as the butterfly mode. It is probably occurring where it is because of random bumps due to, for example, turbulence or gusting. However, the loads are not high.

Q. Can you define the geometry and the method of mounting the counterweight in a single-blade machine?

A. In both of the models that I mentioned, the counterweights were just simple weights attached to the opposite end of the horizontal blade struts. They weren't mounted up at the ends.

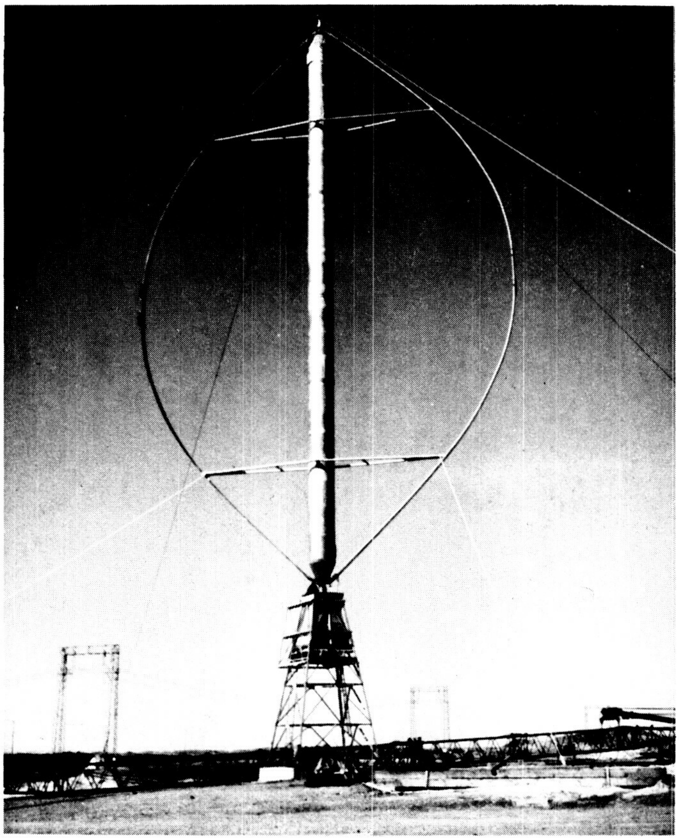
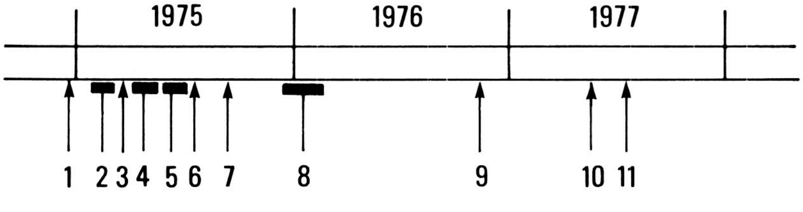
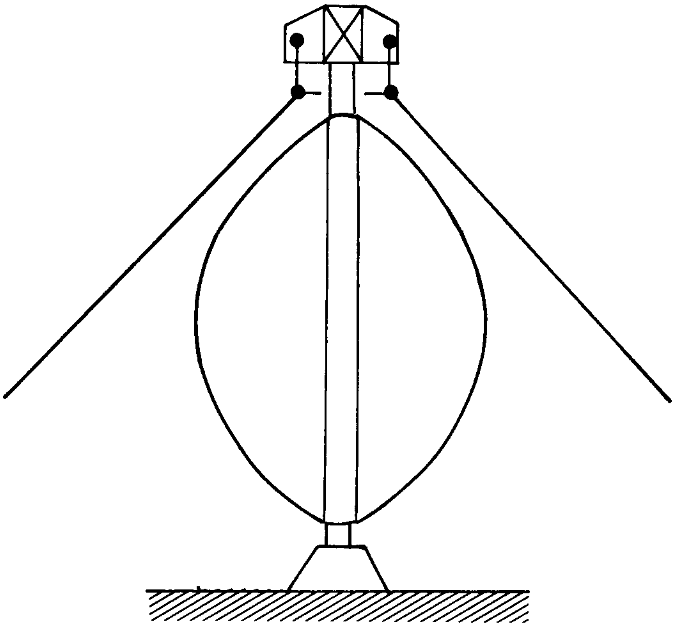


FIG. 1: 224 kw MAGDALEN ISLANDS VAWT.

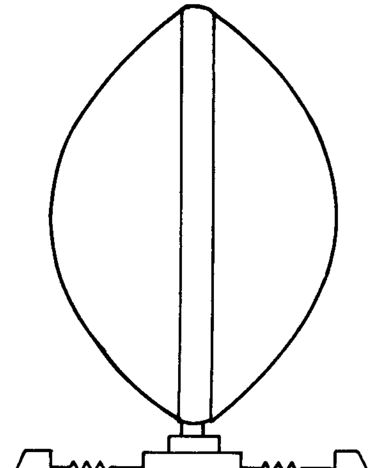


1. Receipt of proposal from DAF-Indal
2. Analysis of performance and torque dynamics
3. Main configuration freeze
4. Analysis of aeroelastic scaling rules
5. 1/24 scale aeroelastic model tests
6. Design and construction contract let to DAF-Indal
7. Choice of test site on Magdalen Islands
8. 1/4 scale aeroelastic tests
9. Delivery of turbine to Magdalen Islands
10. Erection
11. First operation

FIG. 2: DEVELOPMENT SCHEDULE – 224 kw MAGDALEN ISLANDS VAWT.



(a) Soft top mount



(b) Soft base mount

FIG. 3: SCHEMATIC SKETCHES OF TWO VAWT SOFT MOUNTS.