7th Australasian Hydraulics and
Fluid Mechanics Conference,
Brisbane, 18-22 August, 1980

Power Generation from the East Australian Current by Use of Arrays of Submerged Darrieus Vertical Axis Turbines

K.D. THOMSON

Senior Principal Research Scientist, Defence Research Centre, Salisbury, South Australia

SUMMARY An investigation is carried out on the use of submerged vertical axis Darrieus type turbines as a means of generating power from water currents. It is found that maximum power is generated when turbines are grouped in several equally spaced arrays, rather than distributed uniformly throughout the current. Estimates are made of the power potential of the East Australian current between Brisbane and Newcastle and, depending upon the width of the current, an average power of one to more than ten gigawatts appears to be achievable.

1 INTRODUCTION

Throughout the world there is increasing research effort into alternative energy sources to hydrocarbon fuels. One popular area of work concerns the large scale generation of power using the wind, which in principle is a feasible proposition since, in spite of the fact that wind is intrinsically a low-grade power source, wind turbines are reasonably efficient. Research pioneered by Canadian workers (Rangi, South and Templin (1974) for example) using the vertical axis Darrieus rotor as a wind turbine has provided a large impetus in this area. The power generated by such a turbine is given by

$$P_o = k\,\frac{16}{27}\,(\tfrac{1}{2}\rho A v^3), \qquad (1)$$

where k is an efficiency factor (about 0.6 for a Darrieus rotor of troposkein form and 0.7 for a square-rigged configuration), ρ is the fluid density, A is the silhouette area of the volume of revolution traced by the rotating turbine blades, and v is the wind speed.

Following Musgrove (1979) an alternative use for the Darrieus rotor is to submerge it in a water current. Since water density is about 10^3 times air density, a generator (referred to in this paper as an energy conversion machine (ECM)) would develop the same power in a water current of about one tenth the wind speed. Based on the South Australian wind survey of Mullett (1957), mean annual winds of about 8 ms^{-1} occur in windy areas, and therefore, for a given ECM pattern, to match the power potential in water, currents of about 0.8 ms^{-1} or higher should be sought.

Whereas a large scale Darrieus rotor, when used as a wind generator, is likely to be of troposkein form in order to withstand centrifugal loads, for underwater use it can be of square-rigged form because the centrifugal loads are less by two orders of magnitude. In this paper Darrieus rotors of square-rigged form are considered, and for convenience they have been chosen to have unit aspect ratio (height equals diameter).

In a low-grade power source such as an ocean current it is inevitable that ECMs must have a large capture area if substantial amounts of power are to be generated. Therefore of necessity this paper deals with many unusually large structures which, although of simple form, require the solution of many difficult engineering problems before they could be installed as power generators. The subject addressed is the power potential of ocean currents rather than consideration of these engineering problems.

After outlining a method which has been advanced for treating ECMs in arrays (Thomson (1980)) an estimate is made of the power potential of the East Australian current, a powerful southward flowing current which follows the Australian coast between Brisbane and Sydney.

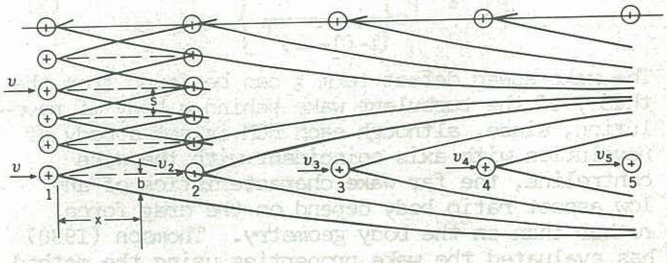

Figure 1 Representation of ECM columns as bodies of revolution and their turbulent wakes

2 ECMs in ARRAYS

In order to extract a large amount of power from an ocean current it is not sufficient to place a few ECMs in isolation, but an array (figure 1) must be considered, in which ECMs are arranged in several parallel streamwise columns, in each of which downstream ECMs are shadowed by those upstream. Methods are available for calculating the minimum spacing between wind turbines, the first being due to Templin (1974). However, the wind turbine environment is somewhat different from that of an ECM: whereas the wind turbine is located at the base of the earth's boundary layer, consideration in this paper is given to ECMs of up to 150 m diameter in water depths of about 200 m, and these can hardly be considered to lie within the boundary layer of the ocean floor.

The calculation of the power generated by an ECM in the wake of several other ECMs located upstream and laterally is a formidable problem. The approach used is to consider each ECM to generate a turbulent wake corresponding to that of a body of revolution having the same drag force, and to assume that each ECM in a column is in the wake of the immediate upstream ECM only. Thus, those ECMs further upstream are assumed to have no direct influence on the ECM under consideration. Furthermore, the effective freestream speed for an ECM is taken to be that on the centreline of the wake from the next upstream ECM. This model does not allow for deflection of wakes due to ECM rotation (Magnus effect), the constraints on wake growth caused by the presence of the ocean floor, or the interaction between ECM wakes and the ocean floor boundary layer. Furthermore, the interference of ECM wakes in adjacent columns is not included.

Referring to figure 1, ECM1 is in the current v, ECM2 is in an effective freestream of speed v_2, which is the centreline speed at station 2 in the wake of ECM1, v_3 is the speed at station 3 in the wake of ECM2, etc. If all the ECMs are equally spaced and $v_2 = v(1-\varepsilon)$, then

$$v_3 = v(1-\varepsilon)^2,\ v_4 = v(1-\varepsilon)^3,$$

$$\ldots\ldots,\ v_n = v(1-\varepsilon)^{n-1}\ .$$

Similarly, the power developed by each ECM is

ECM 1	P_o,
ECM 2	$P_o(1-\varepsilon)^3$,
⋮	
ECM n	$P_o(1-\varepsilon)^{3(n-1)}$

The total power developed by n equispaced ECMs in a column is the sum of these, namely

$$P_c = P_o\left\{\frac{1-(1-\varepsilon)^{3n}}{1-(1-\varepsilon)^3}\right\} \qquad (2)$$

The wake speed defect term ε can be found from the theory of the turbulent wake behind a body of revolution, since, although each ECM is not a body of revolution with axis coincident with the wake centreline, the far wake characteristics of any low aspect ratio body depend on the drag force rather than on the body geometry. Thomson (1980) has evaluated the wake properties using the method of Swain (1929) which was based on Prandtl's mixing length concept.

The wake semi-width b at distance x from the wake origin is calculated to be

$$\frac{b}{d} = 1.146\left(\frac{x}{d}\right)^{\frac{1}{3}} \qquad (3)$$

for a unit aspect ratio ECM of diameter d, and

$$\varepsilon = 0.475\left(\frac{x}{d}\right)^{-\frac{2}{3}}. \qquad (4)$$

In determining what ECM layout should be used to extract the maximum power from a given length and width of current, the question arises as to whether it is more efficient to fill the current segment with a large single array containing widely spaced ECMs in each column, or to have a sequence of small arrays with closely spaced ECMs. In the latter case each array would be separated longitudinally by a stretch of unimpeded current to allow the speed to recover to virtually free current conditions before being intercepted by the next array, and so on. In the first case each ECM column extracts the maximum amount of power from the stream passing through that column, but because of the large ECM spacing the lateral wake growth prohibits close spacing between adjacent columns. In the second case the ECMs in each column are closely spaced, the lateral extent of wake growth is smaller and more columns of ECMs can be used to extract power, although the power extracted per column may not be very large.

In order to resolve this question it is necessary to calculate the length L which the depleted current from an ECM array must travel before the centreline wake speed reaches virtually freestream conditions (taken to be 0.99 v in the calculations). This was estimated by treating a column of ECMs as an equivalent single ECM (of diameter d_e) having the same drag, and examining the wake recovery behind the equivalent ECM. Thus, in an analogous way to the derivation of (2)

$$C_D \tfrac{1}{2}\rho v^2 d_e^2 = C_D \tfrac{1}{2}\rho v^2\left\{\frac{1-(1-\varepsilon)^{2n}}{1-(1-\varepsilon)^2}\right\} d^2,$$

from which

$$\frac{d_e}{d} = \left\{\frac{1-(1-\varepsilon)^{2n}}{1-(1-\varepsilon)^2}\right\}^{\frac{1}{2}}. \qquad (5)$$

By (4) the length of current L required for the wake centreline speed to recover to 0.99 v (i.e., $\varepsilon = 0.01$) is given by

$$L = 330\ d_e. \qquad (6)$$

Finally, it is necessary to estimate the minimum lateral spacing between columns in order that as many ECMs as possible can be installed in each array. It has been assumed that the lateral spacing is such that the edge of the wake from an ECM such as ECM1 in figure 1 just touches ECM2 in an adjacent column distant s away. Any closer spacing will lead to a slight decrease in the effective freestream speed of ECM2, and so to a loss in power developed. ECMs further downstream in adjacent rows will experience a small but negligible interference from upstream ECMs. If the current width is w and it is desired that a column of ECMs lies along each edge of the current as well as within it, then the number of columns N per array is given by

$$N = \frac{w}{s} + 1\ , \qquad (7)$$

and s can be found from (3), being the value of b when x is the ECM spacing in a column (see figure 1).

For a given length and width of ocean current and a given size and arrangement of ECMs, equations (1) to (7) are sufficient to estimate the power that can be extracted from the current.

3 POWER POTENTIAL OF THE EAST AUSTRALIAN CURRENT

The East Australian current (Hamon and Tranter (1971) for example) arises from the action of the south-east Trade Winds piling up water in the Coral Sea. The land barriers of Australia and New Guinea constrain the outflow from the Coral Sea to move generally southward along the Australian coast. This current is supplemented between January and March by equatorial waters driven by southward-moving monsoon winds. North of Fraser Island there is a further inflow of water from the lagoon of the Great Barrier Reef. Full velocity is reached in the area off Cape Byron; the current then flows along the edge of the continental shelf and veers out to sea somewhere between Sydney and Eden. The current is variable in width and speed. According to Hamon and Kerr (1968) its width varies between 40 and 150 km, with the maximum speed occurring close to the 200 m water depth contour, which is on the average about 19 km offshore. However, there does not appear to be any information available on the distribution of speed across the current and therefore in this paper the power potential of the East Australian current has been found for a selection of current widths.

Hamon, Godfrey and Greig (1975) have provided a contour map of the surface current at 19 km average distance from the shore at various locations between Brisbane and Newcastle for the two year period May 1971 to April 1973. The current varies substantially with a maximum exceeding 1.5 ms^{-1} during spring/summer and a minimum less than 0.5 ms^{-1} during autumn/winter. Based on this information the mean surface speed of the current over a 600 km distance between approximately Brisbane and Newcastle has been calculated. It has been assumed that this is also the water speed over the range of depths covered by the ECMs. In view of the power dependence of current as v^3 and because the operation of an ECM is not dependent upon the direction of the current, the mean speed for m observations is defined as

$$\left(\frac{1}{m}\sum_{p=1}^{m} \left| v_p \right|^3 \right)^{\frac{1}{3}}$$

and was evaluated to be 1.0 ms^{-1}.

Calculations have been made of the power developed by different arrays of 50, 100 and 150 m diameter ECMs in a 600 km length of current, for a selection of current widths ranging from 5 to 50 km. As might be expected, the power developed is very nearly proportional to the current width. Figure 2 shows

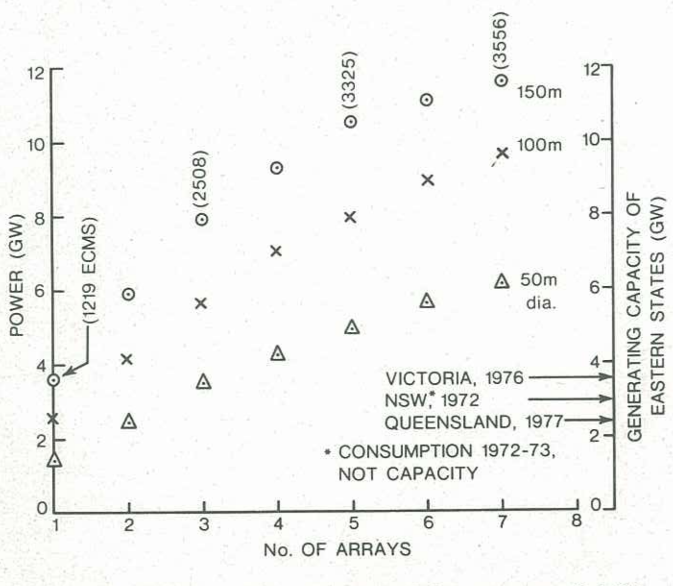

Figure 2 Average power generated by arrays of ECMs in 600 km stretch of East Australian current. Current width 50 km. Water speed 1.0 ms^{-1}

the power generated by ECM arrays in a 50 km width of current. In all the configurations covered, the depleted current at exit from an array has an arbitrarily chosen minimum speed of 0.7 ms^{-1}. Figure 2 shows that grouping ECMs in several arrays results in substantially greater power output than would be obtained from only one array. Furthermore, for a given number of arrays the power output increases markedly with ECM size.

The significance of the power levels is revealed by comparing them with the electrical power generating capacity of the eastern Australian states, marked in figure 2. If the East Australian current width averages 50 km, its potential power of nearly 12 GW would approximately satisfy the combined power requirements of Australia's Eastern states. Even if the current width averages only 5 km the power potential is still sufficient to satisfy about one half of Queensland's needs. The power potential of the East Australian current is therefore very significant indeed. Figure 2 illustrates, however, that a massive engineering undertaking is required before this power can be generated, there being a need to manufacture and instal some thousands of large ECMs.

4 DISCUSSION

A proposal is made for generating very significant quantities of power for the eastern states of Australia. Only preliminary estimates of the power potential of water currents have been possible because of several shortcomings in the method of approach. For example:

(a) The method of treating ECM arrays is approximate and of unknown accuracy.

(b) It has been implicitly assumed that the basic character of a water current will not change when ECMs are present. However, there will be a tendency for the current to divert around the ECM arrays instead of flowing through them, thus decreasing the power potential. Work is needed on methods of ensuring that the current diversion is minimised.

(c) An arbitrary limit has been placed on the minimum wake speed at exit from an array.

(d) No consideration has been given to the inevitable losses in converting the rotational energy of an ECM rotor to electrical energy via step-up gear boxes and electricity generators.

(e) Neither has any consideration been given to various major engineering problems such as coping with the difficult environment, dynamic balancing of ECMs, rotor blade aeroelastic phenomena, gear box design, power mixing when different ECM arrays are operating at different power levels, etc.

In spite of these shortcomings and the possibility that allowing for them will result in changed estimates of power potential, the power levels themselves are so enormous that the East Australian current must be considered as a realistic source of power in the future.

5 REFERENCES

HAMON, B.V., GODFREY, J.S. and GREIG, M.A. (1975) Relation between Mean Sea Level, Current and Wind Stress on the East Coast of Australia. Aust. J. Mar. Freshwat. Res. Vol 26, pp 389-403.

HAMON, B.V. and KERR, J.D. (1968) Time and Space Variations in the East Australian Current, from Merchant Ship Data. Aust. J. Mar. Freshwat. Res. Vol 19, pp 101-106.

HAMON, B.V. and TRANTER, D.J. (1971) The East Australian Current. Australian Natural History, Vol 17, No. 4, pp 129-133.

MULLETT, L.F. (1957) Surveying for Wind Power in Australia. Journ. I.E. Aust., March, pp 69-73

MUSGROVE, P. (1979) Windmills could come in with the tide. New Scientist, 15 Feb., p 481

RANGI, R.S., SOUTH, P. and TEMPLIN, R.J. (1974) Wind Power and the Vertical Axis Turbine Developed at the National Research Council. Quarterly Bulletin of the Division of Mech. Eng. and the National Aeronautical Establishment, 1 Apr to 30 Jun.

SWAIN, L.M. (1929) On the Turbulent Wake Behind a Body of Revolution. Proc. Roy. Soc. Lond. Series A, Vol 125, pp 647-659.

TEMPLIN, R.J. (1974) An Estimate of the Interaction of Windmills in Widespread Arrays. NRC/NAE Report LTR-LA-171.

THOMSON, K.D. (1980) The Power Potential of Coastal Currents in Eastern and Southern Australia. Mech. Engg. Trans., I.E. Aust., Vol 5, No 1, April 1980.