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Performance of Pitch and Stall Regulated Tidal Stream Turbines

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ABSTRACT
Controllers for a pitch and a stall regulated horizontal axial flow, variable-speed tidal stream turbine are developed, and a performance comparison is carried out. Below rated flow speed, both turbines are operated in variable-speed mode so that the optimum tip-speed ratio is maintained. One of the turbines has variable pitch blades, which above rated speed are pitched to feather in order to regulate power. The other turbine has fixed pitch blades and uses speed-assisted stall to regulate power. The control system design behind both strategies is examined in MATLAB, with the performance under turbulent flows, loading and energy yield analysis being evaluated in GH Tidal Bladed. Both strategies provide a satisfactory performance, but the out-of-plane loads on the stall regulated turbine were higher over the entire range of operation. In addition, the dynamic characteristics of the stall regulated turbine require a more complex control design. The results suggest that the pitch regulated turbine would be a more attractive solution for turbine developers.
***Keywords* -** Control, pitch regulation, stall regulation, synchronous generator, tidal power, tidal stream turbine.

I. INTRODUCTION

Tide is estimated that 20.6 T why could practically be extracted from waters around the U.K. using currently foreseeable tidal stream technologies [1]. This estimate takes into account practical constraints that will affect energy extraction such as fishing, shipping, and designated conservation areas. In [2], it was established that as much as 94 T why could be generated assuming that all areas up to a depth of 40 m are developed. Around the U.K., leases for up to 1.6 GW of wave and tidal devices have been awarded by the Crown Estate [3].

The tidal flow rate at any site will vary over time and the flow regime will be site specific [4]. As tides rise and fall they produce flood and ebb currents. A tidal stream turbine (TST) is designed to extract the kinetic energy contained in these currents. The strength of the tidal currents will vary and strong variations in flow speed will exist at any site, with the maximum speeds occurring infrequently [5]. TSTs will be subjected to turbulence and waves, which will cause further variations in flow speed [6]. This means that they need to be regulated, with a way of limiting output power and shedding mechanical load at high flow speeds [7]. Designing a turbine capable of operating at the maximum flow speed seen at a site will not be economic and it will operate at less than 100% capacity for much of the time [8].

Although developers are still designing different types of TSTs, more than 50% are based on bottom mounted, low solidity, horizontal axial flow rotors [9]. Existing and proposed designs use either variable or fixed pitch blades. Variable pitch turbines vary the pitch angle of the blades to regulate output power. The blades can be pitched to feather as the flow speed increases. This reduces the lift force on the blade; therefore, the torque on the rotor is reduced and power is regulated. Alternatively, the blades can be pitched to actively induce stall above rated flow speed [10]. On the other hand, fixed pitch designs rely on the stall characteristic of the rotor blades to regulate output power. As the TST approaches rated power, the angle of attack is such that the blade begins to stall [11].

A comparison is carried out between a variable-speed pitch regulated turbine where the blades are pitched to feather and a variable-speed stall regulated turbine that has fixed pitch blades. Models of each TST are simulated using the commercially available software GH Tidal Bladed [12]. The dynamic characteristics under both types of regulation are examined and control system design is done in MATLAB. Following control implementation, an analysis in terms of performance under turbulent flows, loading, and energy yield is carried out using Tidal Bladed. The studies show that the dynamics of each turbine model are significantly different for above rated flow speed operation. This has implications on the controller design and the loading experienced by each TST.

II. TIDAL POWER

The best mechanism for exploiting tidal energy is to employ estuarine barrages at suitable sites with high tidal ranges. The technology is relatively mature and the components are commercially available. Many of the best sites for development have been identified. However, the pace and extent of commercial exploitation of tidal energy will be significantly influenced by both the treatment of environmental costs of competing fossil fuels and by the availability of construction capital at modest real interest rates. The larger projects could require the involvement of national governments if they are to succeed.

Tidal energy is derived from the gravitational forces of attraction that operate between the earth and moon, and between the earth and sun. It is known that the gravitational force that mutually attracts any two bodies is directly proportional to the product of their masses and is inversely proportional to the square of the distance that separates the masses. The attractive force exerted by the moon on a molecule of water is given by:

$$f = KMm/ d^2 \quad (1)$$

Where
M = the mass of the moon
m = the mass of molecule of water
d = the distance of the water molecule from the moon and
K= the universal constant of gravitation.

The attractive force exerted by the sun obeys the same law, but the effect (M/ d^2) is about 2.17 times less due to the mass and the much greater distance that separates the earth and sun.

As the earth rotates, the distance between the molecule and the moon will vary. When the molecule is on the dayside of the earth relative to the moon or sun, the distance between the molecule and the attracting body is less than when the molecule is on the horizon, and the molecule will have a tendency to move away from the earth. Conversely, when the molecule is on the night side of the earth, the distance is greater and the molecule will again have a tendency to move away from the earth. The separating force therefore experiences two maxima each day due to the attracting body. It is also necessary to take into account the beating effect caused firstly by difference in the fundamental periods of the moon- and sun-related gravitational effects, which creates the so-called spring and neap tides, and secondly the different types of oscillatory response affecting different seas. If the sea surface were in static equilibrium with no oscillatory effects, lunar forces, which are stronger than solar forces, would produce tidal range that would be approximately only 5.34 cm high.

A. Types of Tide

A tidal phenomenon is periodic. The exact nature of periodic response vanes according to the interaction between lunar and solar gravitation effects, respective movements of the moon and sun, and other geographical peculiarities. There are three main types of tide phenomena at different locations on the earth.

I) Semidiurnal Tides with Monthly Variation: This type of tide has a period that matches the fundamental period of the moon **(**12 hr 25 min) and is dominated by lunar behaviour. The amplitude of the tide varies through the lunar month, with tidal range being greatest at full moon or new moon (spring tides) when moon, earth, and sun are aligned. At full moon, when moon and sun have diametrically opposite positions, the tides are highest. This is because the resultant centre of gravity of moon and earth results in the earth being closer to the sun. This gives a higher gravity effect due to the sun. At new moon, maximum tidal range is less. Minimum tides (neap tides) occur between the two maxima and correspond to the half-moon when the pull of the moon and sun is in quadrature, i.e., the resultant pull is the vector sum of the pull due to moon and sun, respectively. In this case the resultant gravitational pull is a minimum. As energy imparted to an oscillating sea level is proportional to resultant gravitational force and to amplitude of the sea level oscillation, minimum tides will result from this situation. Resonance phenomena in relation to the 12-hr-25-min period characterize tidal range.

B. Diurnal Tides with Monthly Variation

This type of tide is found in the China Sea and at Tahiti. The tidal period in this case corresponds to a full revolution (of the moon relative to the earth (24 hr 50 min).

Semidiurnal tides are subject to variations arising from the axis of rotation of the earth being inclined to the planes of orbit of the moon around the earth and the earth around the sun. The lunar equilibrium tide is aligned with the (orbit of the moon, and this is inclined at between 18.3" north and 28.6" south of the equator. Similarly, the sun's declination varies between 23.5' north and south of the equator, these angles of latitude defining the tropics. During each rotation of the earth, a point on the earth's surface will pass through different parts of the equilibrium tide envelope and therefore experience a diurnal variation in tide levels. A resonance phenomenon in relation to the 24-hr-50-min period characterizes the tidal range. Again, tidal range varies with the monthly lunar cycle.

C. Mixed Tides

Mixed tides combine the characteristics of semidiumal and diumal tides. They may also display monthly and bimonthly variation. Examples of mixed tides are those observed in the Mediterranean and at Saigon. The laws governing sea level variation in mixed tide areas can be highly complex.

D. Major Periodic Components

The following periodic components in tidal behavior can be identified:

- A 14-day cycle, resulting from the gravitational field of the moon combining with that of the sun to give maxima and minima in the tides (called spring and neap tides, respectively). This cycle is modified slightly because the moon's orbit is an ellipse, so successive spring-neap cycles can vary in amplitude by about 15%.
- A 1/2-year cycle, due to the inclination of the moon's orbit to that of the earth, giving rise to a period of about 178 days between the highest spring tides, which occur in March and September.
- The Saros, a period of 18 2/3 years required for the earth, sun. and moon to retum to the same relative positions.
- Other cycles, such as those over 1600 years [13], which arise from further complex interactions between the gravitational fields.

Maximum height reached by high water varies in 14-day cycles with seven days between springs (large tide range) and neaps (small tide range), where the spring range may be twice that of the neaps. Half-yearly variations are ±11 %, and over 18 2/3 years ±4%. The monthly cycle of semidiurnal tides is illustrated in Fig. 1.

In the open ocean, the maximum amplitude of the tides is less than 1 m. Tidal amplitudes are increased substantially particularly in estuaries by local effects such as shelving, funnelling, reflection, and resonance. Increase in tidal amplitude due to shelving results from the deep water tidal wave increasing in height as the wave slows down entering shallow water. Tidal amplitude may be further amplified by funnelling due to the shape of the coastline as the tidal bulge progresses into a narrowing estuary. Reflection of waves by the coastline may also increase tidal amplitude. Resonance is the result of a body being subjected to a small regular impulse at a frequency that is the same as, or a low multiple of, the natural frequency of vibration of that body. The driving tide at the mouth of the estuary can resonate with the natural frequency of tidal propagation up the estuary.

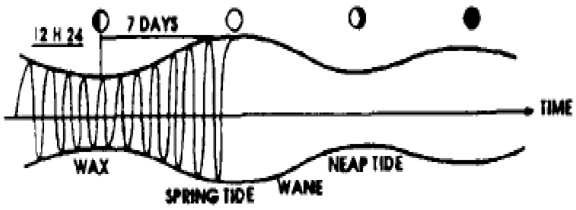

Fig 1 Monthly cycle of semidiumal tides.

III. NUMERICAL REPRESENTATION

The 3-D conservation equation set including distributed body force can be described as follows:

$$\int_{C_v} \frac{\partial \boldsymbol{q}}{\partial t} \mathrm{d}V + \oint_{C_s} \boldsymbol{F}(\boldsymbol{W} \cdot \mathrm{d}\boldsymbol{A}) + \oint_{C_s} p\,\mathrm{d}\boldsymbol{G} - \int_{C_v} \boldsymbol{B}\,\mathrm{d}V = 0 \qquad (2)$$

Where,

$$\boldsymbol{q} = \begin{bmatrix} \rho \\ r\rho C_\varphi \\ \rho C_z \\ \rho C_r \\ \rho E \end{bmatrix}, \quad \boldsymbol{F} = \begin{bmatrix} \rho \\ \rho C_\varphi \\ \rho C_z \\ \rho C_r \\ \rho H \end{bmatrix},$$

$$\mathrm{d}\boldsymbol{G} = \begin{bmatrix} 0 \\ r\,\mathrm{d}A_\varphi \\ \mathrm{d}A_z \\ \mathrm{d}A_r \\ 0 \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} 0 \\ F_\varphi \\ F_z \\ \frac{\rho C_\varphi^2 + p}{r} + F_r \\ 0 \end{bmatrix}$$

Here *V* is the volume of the control volume, *A* the surface area of the control volume, *H* the relative stagnation enthalpy, *W* and *C* are the relative speed and absolute speed, *r* the radius, *E* and *F* the inner energy and distributed body force, ρ and *p* density and pressure, Cv and *Cs* control volume and control area, *z, r,* and φ axial, radial, and circumferential components.

IV. CONCLUSION

A performance comparison and control system design was carried out for pitch and stall regulated horizontal axial flow, variable-speed TSTs. Following system linearization in Tidal Bladed, an analysis of the model dynamics was undertaken in MATLAB. Below rated flow speed, the dynamics of both TST models are stable. However, above rated flow speed the dynamics are significantly different: the pitch regulated TST is stable, whilst the stall regulated TST has unstable dynamics. Both turbines feature RHPZs. Therefore, controlling the stall regulated TST is more onerous as the controller has to stabilize the plant while restricting the bandwidth below the frequencies of the RHPZs.

Controllers were designed in MATLAB for both TST models, providing a satisfactory performance when implemented and tested in Tidal Bladed. Although the controller structure was kept as simple as possible to make implementation easier, the designs ensured adequate stability margins. It is clear from the results that the power regulation of the pitch regulated TST was superior.

Analyses of the loads showed that the out-of-plane bending moments dominate and are higher for the stall regulated TST over the entire operating range of the turbine. In fact, they are significantly higher when the turbine goes into deep stall. This is because the axial trust force is higher, which results from the fact that the blades were designed to operate at a higher angle of attack, near to the maximum lift coefficient.

Regarding the energy yields, the one obtained for the pitch regulated TST was higher. This is largely because the pitch regulated turbine is more efficient below rated flow speed; in addition, the superior performance of the pitch controller also has an effect. It should be noted that 100% availability of the turbines was assumed when carrying out this calculation. In reality, this will not be the case and one could argue that the increased complexity of the pitch machine (which requires pitch bearings, hydraulic actuators and position sensors) will mean more maintenance and increased downtime.

Designers looking to choose between the pitch and speed-assisted stall regulation methods will need to be aware of the higher out-of-plane loads generated by the stall regulated TST—especially in high flow speeds, as the axial thrust force will increase unchecked as the flow speed increases. This, together with the increased complexity of the controller would suggest that the fixed pitch speed-assisted stall regulated turbine will need to be much cheaper in order to compete with variable pitch regulated turbines on a lifetime cost basis. However, this conclusion assumes that the availability of both TSTs is comparable—something requiring further investigation.

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