Effect of the Shape of Stator Blades on the Performance Output of a Vertical Axis Marine Current Turbine

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Keywords: Vertical Axis Marine Current Turbine (VAMCT), Torque Output, Tip Speed Ratio (TSR), Computational Fluid Dynamics (CFD), Horizontal Axis Marine Current Turbine (HAMCT)

Abstract

Due to the diminishing reserves of fossil fuels and increased pollution from exploitation of these fuels, the world is focusing on the renewable energy sources. Energy from tidal waves is one of the most exciting forms of renewable energy because of its consistent nature. Hence, the predictable, consistent and reliable nature of marine currents has enthused the researchers to emphasize on harnessing energy from marine currents in order to meet the renewable energy targets. Exploitation of this technology is underway and further research is required to extract this energy optimally. Operating under water and harnessing kinetic energy has restated the importance of Vertical Axis Marine Current Turbines (VAMCTs). Recent studies have shown that the shape of the blades, within a VAMCT, has an appreciably considerable effect on its performance output. The flow field in the vicinity of the VAMCT is greatly affected by the design and shape of the stator blades. This paper presents an effort carried out to analyze the effect of the shape of the stator blades of a VAMCT on its performance output. VAMCT with curved stator blades has been analyzed and the results have been compared with the existing literature for the performance output from a VAMCT having straight stator blades. It has been shown that a VAMCT with curved stator blades performances superiorly as compared to straight stator blades. Furthermore, the operational range of a VAMCT with curved stator blades increases significantly as compared to straight stator blades.

Nomenclature		*Subscripts*	
λ	Tip Speed Ratio (-)	min	minimum
r	Radius of VAMCT (m)	max	maximum
ω	Angular Speed of VAMCT's Blades (rad/sec)	avg	average
v	Water Flow Speed (m/sec)	Inst.	Instantaneous
P	Power Output from VAMCT (W)		
T	Torque Output from VAMCT (Nm)		
θ	Angular Position of VAMCT (°)		

1. Introduction

Tidal currents contain a lot of kinetic energy. This substantial energy form has a great potential to overcome the increasing energy demand. Marine current turbines are designed to capture the kinetic energy of the tidal waves and convert it into mechanical energy, which is converted into electric energy.

Two Common types of Marine Current Turbines are Horizontal Axis and Vertical Axis Marine Current Turbines. On commercial scale several horizontal axis turbines are operating, notably propeller-type marine current turbines [1]. Recently vertical axis designs have been recognized as a potential competitor in marine environment because of its omni-directionality, low starting torque and relatively easy maintenance. It has been shown that the shape of the stator blades affects the performance output of turbines and a great deal of study has been conducted by researchers at NACA [2] to verify this for increased jet-engine performance. Recently, numerical studies have been conducted to numerically analyze the performance output of marine turbines [3 - 6].

In the present study Computational Fluid Dynamics based modeling and analysis techniques have been incorporated to quantify the effect of the shape of stator blades on the performance output of an in-house designed VAMCT. The VAMCT consists of 12 equally spaced rotor blades and stator blades respectively (figure 1). In order to analyze the effect of the shape of the stator blades, Park et. al.'s [7] VAMCT's model has been numerically created with curved stator blades. The results from the model presented in this study have then been compared with Park. et. al.'s results. It has been shown by Gareth et. al. [8] that the most important output parameters of a turbine are its Tip Speed Ratio (λ) and the Power Output (P). Tip Speed Ratio (or TSR) is the ratio between the rotational speed of the tip of the blade and the actual velocity of the flow.

$$\lambda = \frac{r * \omega}{v} \qquad (1)$$

Where r is the radius of the turbine, ω is the rotational speed of the blade/s and v is the flow velocity. Power output of a turbine is a function of its Torque Output and is expressed as:

$$P = \omega * T \qquad (2)$$

Where P is the Power Output and T is the Torque Output of the turbine.

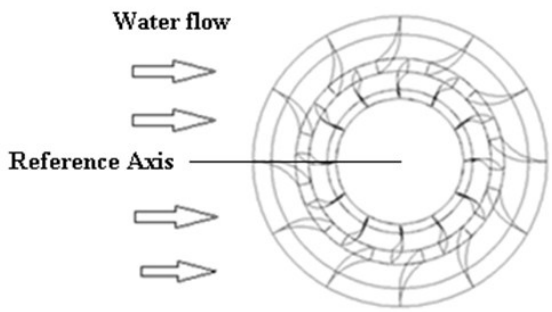


Figure 1 - VAMCT Model with Curved Stator Blades

2. Numerical Modeling

In order to analyze the effect of the shape of the stator blades on the performance output of a VAMCT, a commercial CFD tool has been used to numerically simulate the flow in the vicinity of an in-house built model. As the performance of the VAMCT has been compared with that of [7] having straight stator blades, the analysis has been carried out on the same flow characteristics and operational range of the VAMCT, i.e. TSRs of 0.01, 0.05, 0.1, 0.2, 0.4, 0.6 and 0.8. The geometric configuration of the stator blades considered in the present study shows that these blades are curved at an angle of 20º, whereas the rotor blades have been curved at 28.2º which is kept the same as that in [7]. Furthermore, the diameter and height of the VAMCT are 1.4m and 0.3m respectively. For accurate comparison, the VAMCT has been considered to be operating 1m under sea level where the flow velocity has been considered as 1m/sec.

It has been shown that Shear-Stress Transport (SST) type k – ω turbulence model predicts the performance characteristics of the turbine with reasonable accuracy [9 – 10]. This is due to the fact that SST k – ω behaves more accurately to capture extreme pressure and velocity gradients than standard k – ε model in the vicinity of the turbine's blades while behaves like k – ε in the rest of the flow domain. Sliding Mesh technique has been used to rotate the blades at required angular speeds because of its capability to capture complex flow phenomena. Three dimensional Navier-Stokes equations have been iteratively solved for transient motion of VAMCT's blades.

Figure 2 depicts the flow domain that has been numerically simulated for water flow in the vicinity of the VAMCT. The domain dimensions are the same as considered in [7] where the walls of the domain have been configured as moving walls having the same velocity as that of water flow in the domain. This reduces the effects of the boundary layer formation on the walls as the walls have been specified with no-slip boundary condition.

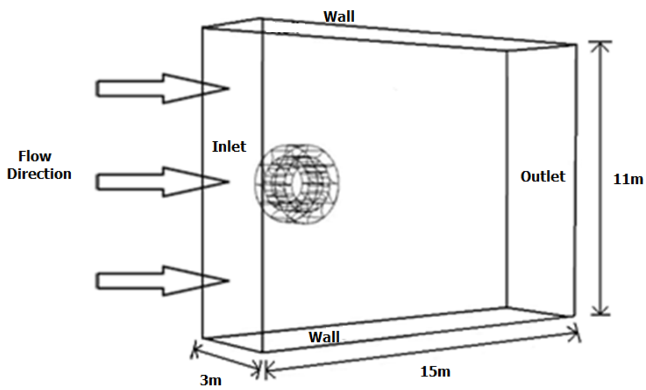


Figure 2 - Flow Domain for VAMCT's Analysis

3. Results and Analysis

This section presents the results obtained after carrying out detailed analysis on the performance output from the aforementioned VCT model. The first section outlines the discretization method used in this study while the second and third section sheds light on the performance of the VAMCTs with both curved and straight stator blades.

3.1 Mesh Independence

In order to effectively analyze the VAMCT model, it is necessary to take into account the spatial resolution considered for simulating the flow. This is so to capture the small scale flow features arising from the interaction of the VAMCT with the incident flow. Three different mesh resolutions of 1.5 million, 2.3 million and 3.5 million mesh elements have been considered and the torque output from the three VAMCT models monitored for three revolutions of the VAMCT. The results presented in table 1 for the torque output from the VAMCT models depict that:

- The solution gets converged/stable in the 3rd revolution of the VAMCT
- Mesh resolution of 2.3 million mesh elements is reasonably accurate for carrying out further analysis on the VAMCT model

It can be seen from the table that the average variations in the torque output from the VAMCT models drops below 1% in the 3rd revolution of the VAMCT and hence the performance of the VAMCT has been monitored/calculated in the 3rd revolution only. The performance of the VAMCT from the first two revolutions has been discarded because the solution has not reached a stable state, i.e. it has not become statistically steady.

It can be seen from table 1 that the difference in the average torque output between 1.5 million and 2.3 million mesh elements is 5% where average torque output means the average torque for one complete revolution of the VAMCT model. Furthermore, the difference in the average torque output between 1.5 million and 2.3 million mesh elements is 0.01% and hence mesh resolution of 2.3 million mesh elements has been chosen for further analysis on the VAMCT model.

Revolution	1.5×10^6 Mesh Elements		2.3×10^6 Mesh Elements		3.5×10^6 Mesh Elements	
	Tavg	Difference	Tavg	Difference	Tavg	Difference
	(Nm)	(%)	(Nm)	(%)	(Nm)	(%)
1st	119.12		125.89		124.91	
2nd	113.71	4.54	119.75	4.88	118.56	5.08
3rd	113.52	0.16	119.29	0.39	118.13	0.36

Table 1 - Mesh Independence Results and Convergence History of Average Torque Output from the VAMCT model

3.2 Flow Field Analysis

Figure 3 depicts the variations in the flow velocity in the vicinity of the VAMCT at TSR of 0.2. It can be seen that the flow velocity around the stator blades of the VAMCT is considerably lower as compared to the core region or the peripheries of the VAMCT. This is due to the fact that the stator blades of the VAMCT have been modeled as stationary walls with no-slip boundary condition and hence the velocity gradients are quite steep at these locations. However, due to the rotational motion of the rotor blades, the velocities around the rotor blades are higher as compared to the stator blades. Due to the interaction of the incident flow with the stator blades of the VAMCT, a large wake region has been observed downstream the individual stator blades which have huge implication on the performance output of the VAMCT. Any change in the shape of the stator blades will have direct consequences on the formation and effect of these wake regions that will affect the overall performance. It has been further observed that the flow velocities at the junction of the stator and the rotor blades show highly non-linear behavior. Velocity profiles for other TSRs show the same trend.

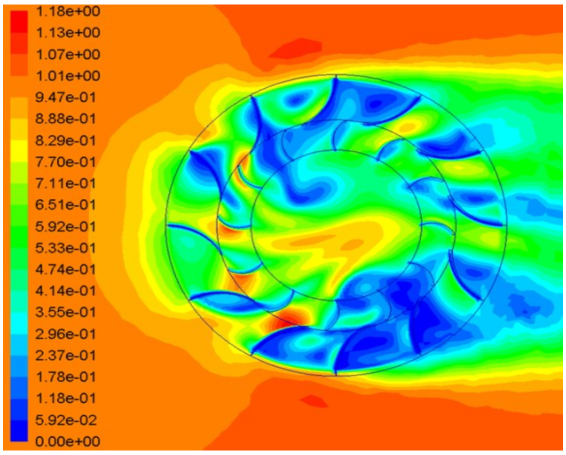
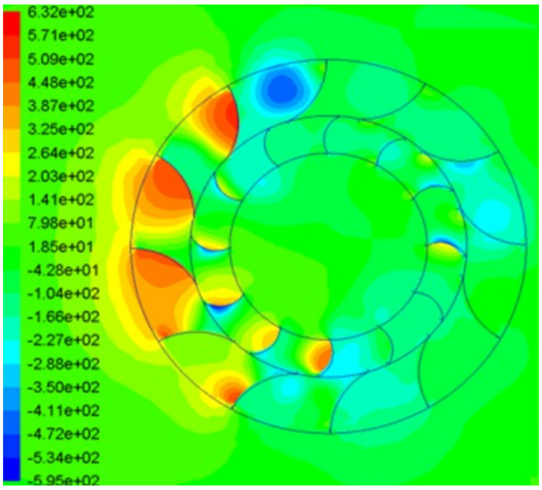
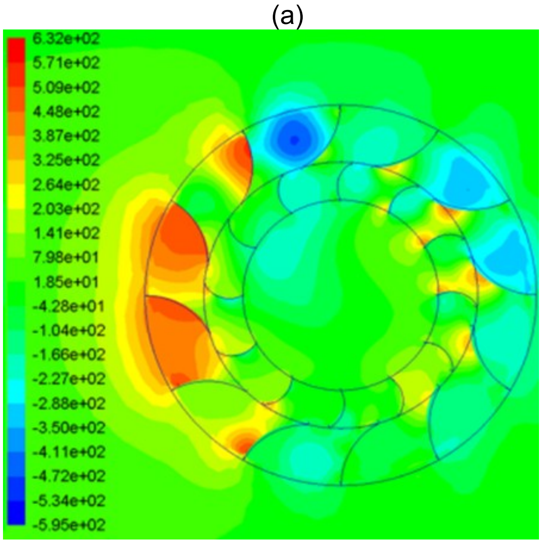


Figure 3 - Velocity variations in the vicinity of the VAMCT at TSR of 0.2

Further analyzing the flow structure in the vicinity of the VAMCT, figure 4 presents the variations in the pressure for TSRs of 0.05 and 0.6. It can be seen that high pressure region is observed at the upstream locations where the flow interacts with the stator and the rotor blades. Low pressure regions are observed at the downstream locations of the VAMCT. It can be interpreted that the areas of high pressure correspond to low velocities and vice versa. It is worth noticing that at low TSRs there exist high pressure regions above the rotor blades at the upstream locations of the turbine, thus contributing to high torque output from the turbine. However, at higher TSRs, the pressure above the rotor blades is relatively low while the pressure under the rotor blades is relatively higher. These high pressure regions under the rotor blades degrade the performance output of the VAMCT.



(a)



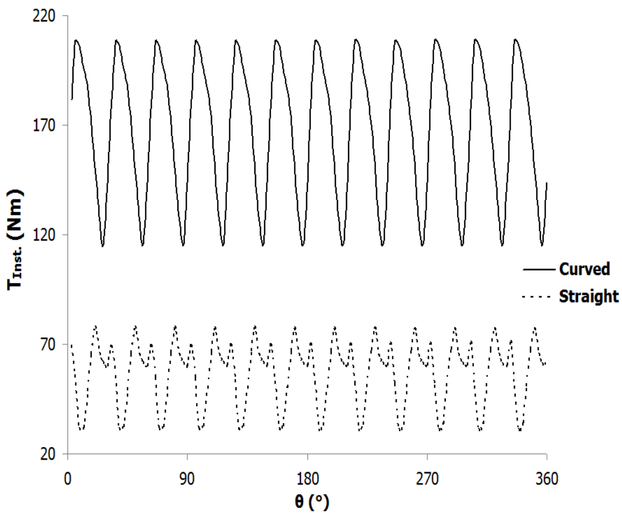
(b)

Figure 4 - Variations in the static pressure in the vicinity of the VAMCT (a) TSR=0.05 (b) TSR=0.6

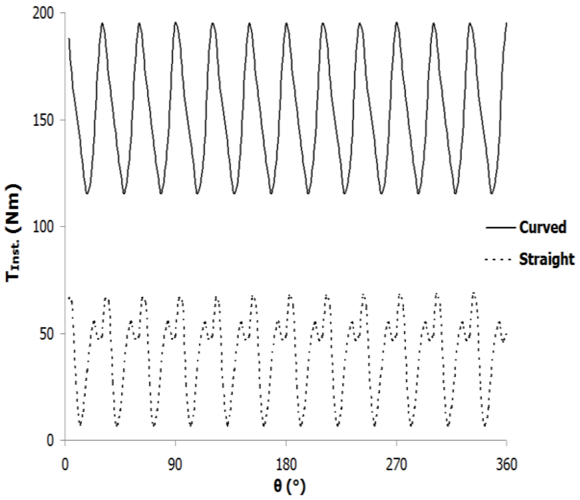
3.3 Performance Characteristics of VAMCT

Figure 5 depicts the variations in the instantaneous torque output of the VAMCT models with both curved and straight stator blades in order to compare the performance characteristics from both the models. The figure represents the cyclic variations of the torque output at various TSRs for one complete revolution of the VAMCT models. It can be seen that the torque output is uniform in each case however each torque signature is different with respect to each other, highlighting the effect of different TSRs on the power output. It can be further seen that the torque output from the VAMCT having curved stator blades is higher as compared to the VAMCT with straight stator blades. The obvious reason for such a trend is the fact that the effective blade surface area for flow in case of curved stator blades is considerably higher as compared to straight stator blades and hence the curved stator blades are under higher pressure and shear forces from the incident flow. Higher kinetic energy conversion into the mechanical energy has been observed in case of curved stator blades.

Further analyzing figure 5 reveals that as TSR of the VAMCT increases, the torque output decreases. This trend is observed to be consistent for all vertical axis turbines [4, 5, 7, 8]. It is worth noticing that the instantaneous torque output from the VAMCT model having straight stator blades at TSR of 0.4 is negative throughout its rotation. This means that the turbine is in operation in the churning condition, i.e. instead of extracting energy from the incident flow, the turbine itself is producing power. This operational condition of VAMCTs is different for different models and should be avoided. From the results presented in figure 5, it can be clearly seen that the shape of the stator blades affects the operational range of the VAMCTs. The VAMCT model with straight stator blades is in churning condition at TSR of 0.4 while the VAMCT model with curved stator blades is still producing power after extracting kinetic energy from the incident flow. Hence, the operational range of VAMCTs depends on the shape of the stator blades.



(a)



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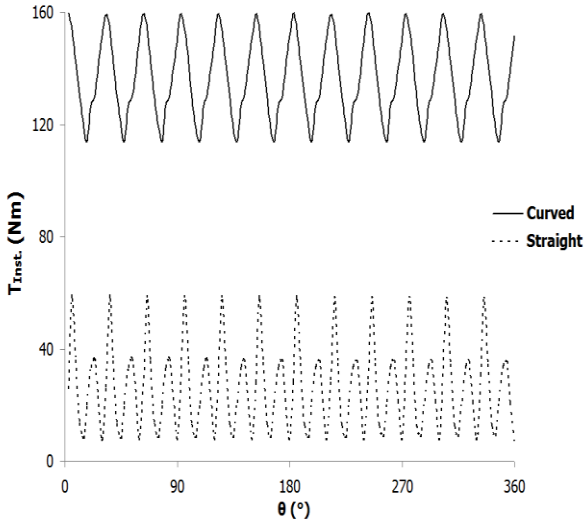

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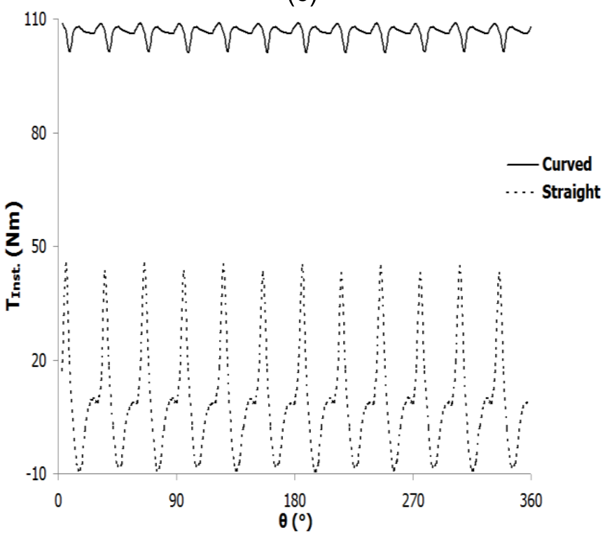

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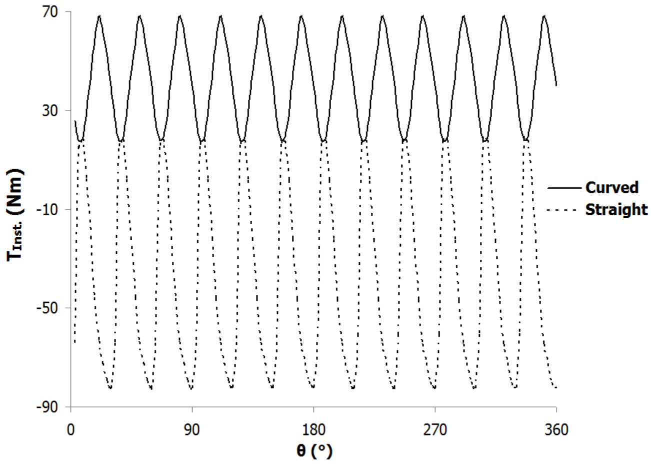

(e)

Figure 5 - Variations in Instantaneous Torque Output in one revolution of VAMCTs (a) TSR=0.01 (b) TSR=0.05 (c) TSR=0.1 (d) TSR=0.2 (e) TSR=0.4

Figure 5 further shows that the amplitude of the torque output first decreases with increasing TSR up-to a certain TSR and then starts increasing. As far as the instantaneous torque output from the VAMCT model having curved stator blades is concerned, the amplitude of instantaneous torque output is 90Nm at TSR of 0.01. At TSR of 0.2 this amplitude drops to 7Nm and then at TSR of 0.4 the amplitude is 50Nm. This trend points towards the fact that there might be an optimum value of TSR for a specific design of VAMCT for which the performance output from the VAMCT is maximum, i.e. the power output of the VAMCT model is at maximum. In order to investigate this effect, the results presented in figure 5 have been statistically analyzed and the results are tabulated in table 2 for the VAMCT model with curved stator blades.

It can be clearly seen from table 2 that the average power output, i.e. the average of power output for one complete revolution of the VAMCT model, first increases with increasing TSR up-to a certain TSR where the power produced by the VAMCT is maximum. The maximum power output from the VAMCT having curved stator blades is 30.44W at TSR of 0.2. Further increasing TSR decreases the power produced by the VAMCT until it goes into churning condition. It can be further seen that the corresponding standard deviation in the instantaneous torque output at various TSRs is minimum at TSR of 0.2. Hence, it can be concluded that the minimum relative standard deviation in instantaneous torque output from VAMCT corresponds to maximum average power produced. The same holds true for the VAMCT model having straight stator blades where the minimum standard deviation of 14.77 in the instantaneous torque output has been observed at TSR of 0.1 and Park et. al. have observed the maximum power produced from the VAMCT at TSR of 0.1 as well.

TSR	Tmax	Tmin	Tavg	Pavg	Std. Deviation in Torque Output
	(Nm)	(Nm)	(Nm)	(W)	
0.01	208.60	115.44	168.17	2.40	31.60
0.05	195.14	115.18	152.96	10.93	26.70
0.1	159.59	113.91	136.62	19.52	14.53
0.2	108.81	101.12	106.55	30.44	1.95
0.4	68.15	17.77	42.00	24.00	17.31
0.6	17.27	-67.16	-25.80	-22.11	29.19
0.8	-13.67	-160.47	-95.19	-108.79	47.00

Table 2 - Statistical Analysis of the Performance Output from the VAMCT having Curved Stator Blades at various TSRs

Figure 6 depicts the variations in average torque and power outputs from the VAMCT model having curved stator blades at various TSRs. It can be seen that as the TSR increases, the average torque output from the VAMCT decreases whereas the average power produced by the VAMCT increases to a maximum value after which it decreases. It can be seen that the maximum power output from the VAMCT model is observed at TSR of 0.25. At TSR of 0.52, both the average torque and power outputs from the VAMCT model reaches zero. Further increase in TSR creates negative torque and the VAMCT goes into the churning condition as discussed earlier.

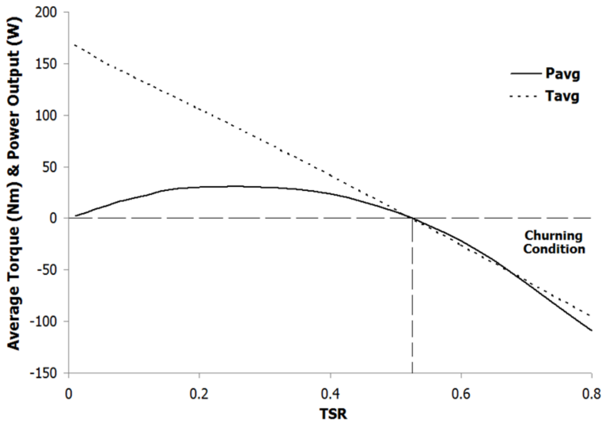

Figure 6 - Operational Range for VAMCT with Curved Stator Blades

Further analyzing the effect of the shape of the stator blades on the performance output of a VAMCT, figure 7 presents a comparison between the VAMCT models having both the curved and straight stator blades. It can be seen that the both the maximum power output and the churning condition for VAMCT having straight stator blades is at relatively lower TSR as compared to VAMCT having curved stator blades. Hence, it can be concluded that the shape of the stator blades directly affects the performance output of a VAMCT and the curved stator blades have clear advantage over straight stator blades.

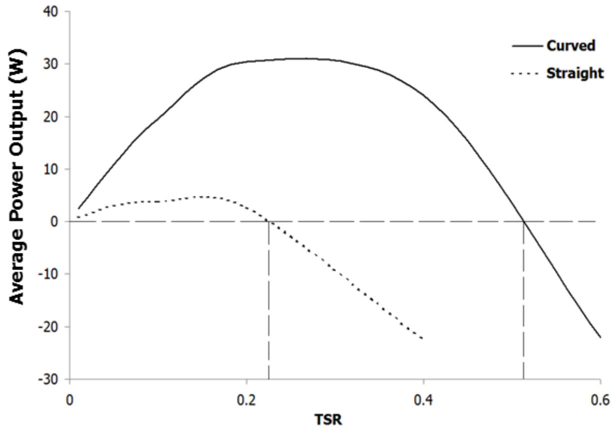

Figure 7 - Comparison of Power Output from VAMCTs with Curved and Straight Stator Blades

4. Conclusion

The shape of the stator blades of Vertical Axis Marine Current Turbines affects the performance output from such turbines. In this study, a novel design of a VAMCT having curved stator blades has been numerically simulated for various TSRs and its performance compared with a VAMCT model having straight stator blades. It has been shown that as the TSR increases, the average torque output decreases whereas the average power output increases up-to a certain point from where onwards it decreases until churning condition is reached. It has been further observed that the variations in the instantaneous torque output decreases with increasing TSR. The minimum variations in the instantaneous torque output have been observed to occur at the same TSR at which the maximum power output from the VAMCT has been obtained. Curved stator blades result in a considerably higher power output and increased operational range of the VAMCT as compared to straight stator blades. Hence, the shape of the stator blades has direct impact on the performance output of a VAMCT. It has also been concluded that Computational Fluid Dynamics based techniques are capable of capturing the complex flow phenomenon in the vicinity of VAMCTs with reasonable accuracy and hence can be used as tool for analyzing VAMCT's performance.

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