TIDAL STREAM POWER COLLECTION - PASSIVE RECTIFICATION TO A COMMON DC-BUS

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Keywords: Tidal Stream Power, Common DC-bus, Renewable energy, Passive Rectification.

Abstract

Tidal stream energy is seen as one of the most viable and clean energy sources in future. This paper describes the research on a cost effective tidal stream power generation system in which a group of 3-phase synchronous generators operating at diverse speeds are connected to a common DC bus via passive diode rectifiers. This power conversion and collection configuration reduce the amount of components required, while maximising efficiency, reliability and controllability, thereby facilitating reduction in capital costs and in operational costs. The output power of each tidal stream generator is regulated by controlling the field excitation of individual machines. The operational characteristics of the proposed power generation system are analysed and the control methods for maximum power extraction and maximum power limiting are outlined.

1 Introduction

Tidal stream turbines convert the kinetic energy present in moving sea water into mechanical energy. The power generated depends on the mass density of water, the area swept by the rotor blades, the turbine characteristic and the tidal velocity which varies from time to time. Tidal stream power is gaining increasing attention due to its high energy density, predictability and low environmental impacts [1]. The amount of potential tidal stream energy is estimated to be between 500 and 1000TWh/yr world-wide [2-4], however much of this energy remains unexploited. According to a recent estimation [5], almost 10% of the U.K's electricity needs could be met by tidal power.

However, tidal power generation is relatively expensive, mainly due to many devices being required when compared to much fewer in the case of conventional power stations, and the fact that tidal stream generators operate in submerged harsh environment [6]. A typical horizontal axis tidal stream turbine has three or four blades connected to the shaft which turns an electrical generator, usually via a gearbox to achieve the high speeds necessary for economic electrical generation. Currently, various tidal stream turbine prototype concepts with different generator systems are being developed, mainly built to maximize the energy capture, minimize costs, and improve power quality[7]. However, existing tidal turbines are complex and therefore expensive because in most designs each tidal turbine requires accurate control in order to generate grid standard power [8]. Additionally the requirement to match the variable speed of the tidal stream to the fixed voltage and frequency of the utility grid, usually achieved by variable pitch blades or a variable ratio gearbox, power electronics or a combination of these methods [9] greatly increases capital installation and running costs. Therefore, these costs must be reduced if tidal stream power is to be competitive with alternative sources of energy such as wind and solar energy.

This paper investigates the use of an offshore DC distribution network fed by a number of variable-speed tidal turbines operating at different speeds. The philosophy of the proposed system is to reduce complexity and therefore save on, capital costs and operational costs, in order to reduce the price per unit of energy generated. Moreover, allowing an easier connection of generation in parallel reduces the number of cable runs to shore and the amount of equipment installed offshore (offshore hubs, transformers and converters). The equipment for DC/AC conversion can be installed ashore instead.

2 Tidal power generation system by passive rectification to a common DC bus

2.1 Turbine nacelle configuration

Figure 1 shows the schematic of the proposed turbine nacelle configuration. The turbine implemented in the proposed system has fixed pitch blades, which are simpler, cheaper and more reliable than variable pitch blades.

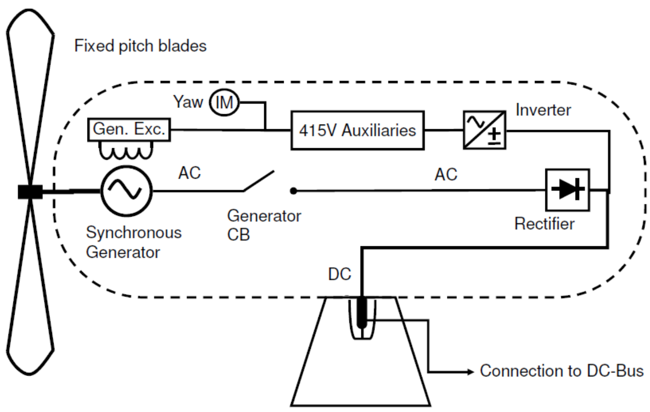

Figure 1: Nacelle electrical configuration schematic

The turbine is coupled to a generator either directly or possibly via a fixed ratio gearbox (not shown) which is simpler and cheaper than a variable ratio gearbox. The generated AC power is rectified to DC using a diode bridge rectifier which is much more cost effective and reliable than active power conversion. High voltage (HV) transmission ashore will be needed but the required AC transformation in the nacelle can be avoided by using an HV generator. The rectified outputs of tidal stream turbine-generators are connected together to a common sub-sea DC link, thus avoiding the complexity of AC synchronisation. The output power of each turbine-generator can be regulated by the field excitation to achieve maximum power extraction or impose power limiting, as will be described in the subsequent sections.

2.2 Tidal farm configuration

The turbine nacelle in Figure 1 can be used as a basic building block to form a tidal farm. The electrical output generated by each individual turbine is passively rectified, and fed in parallel onto a common DC-bus as shown in Figure 2. The DC-bus transmits the power to an onshore station, where it is fed to the utility grid via a DC-AC converter and transformer. The proposed electrical configuration reduces the amount and complexity of electrical components and equipment, by effectively transferring much of the requirement for power conversion from the individual turbines to converters ashore where costs are less and the conversion can be organised in bulk. Moreover, the connection of several turbines together to a common subsea DC link reduces the number of cable runs ashore.

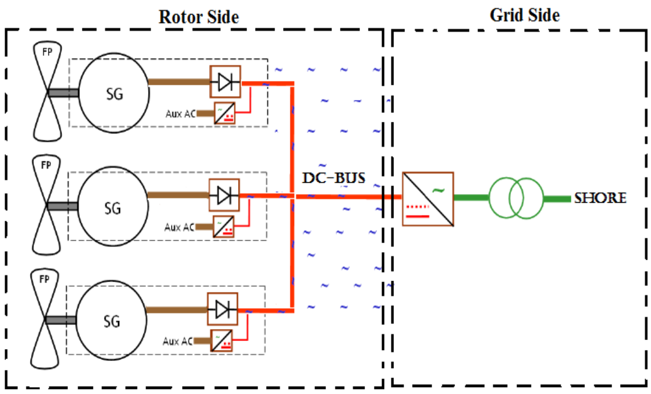

Figure 2: Proposed tidal farm topology

On the other hand, local sea conditions will inevitably cause differences in the tidal stream velocities and therefore adjacent tidal stream turbines/generators may run at different speeds. This requires adequate control of generator excitation not only to achieve stable operation of interconnected turbine-generator systems by a common sub-sea DC bus, but also to maximise the energy generated.

3 System steady-state operation

To understand the operation of such tidal stream power generation systems, the turbine rotor hydrodynamic and the operational characteristics of a synchronous generator whose output is fed to an infinitely stiff DC-bus via diode rectifier are studied separately.

3.1 Rotor hydrodynamics

The mechanical input power, P_t, available to a tidal stream turbine is given by:

$$P_t = \frac{1}{2}.\rho.A.V^3 \tag{1}$$

where $\boldsymbol{\rho}$ is the sea water density in kg/m^3, $\boldsymbol{A}$ is the area swept by the turbine blades in m^2, and $\boldsymbol{V}$ is the velocity of the moving tide in ms^{-1}. However, a tidal turbine can only convert a maximum 59.3% of the kinetic energy available in the flowing tide into mechanical energy on the rotor. This is known as the Betz Limit. The ratio of the turbine output power to its available input power is referred to as the power coefficient C_p. For a fixed pitch turbine, this coefficient is dependent on λ defined as the ratio of the turbine blade tip speed, $R\omega$, to the tidal velocity:

$$\lambda = \frac{R\omega}{V} \tag{2}$$

where ω is the angular speed of the turbine and R is the radius of the blade. The mechanical output power, P_m, of the turbine can be expressed as:

$$P_m = \frac{1}{2}.C_p(\lambda).\rho.A.V^3 \tag{3}$$

Substituting (2) into (3) the turbine output power becomes:

$$P_m = \frac{1}{2}.C_p(\lambda).\rho.A.\left(\frac{R}{\lambda}\right)^3.\omega^3 \tag{4}$$

For a given turbine, there exists an optimal λ_{opt} which yields the maximum output power:

$$P_{opt} = \frac{1}{2}.C_{p(opt)}.\rho.A.\left(\frac{R}{\lambda_{opt}}\right)^3.\omega^3 \tag{5}$$

Figure 3 shows the variations of the turbine output power as a function of the tidal velocity and rotor speed. The radius of the rotor blade is 10m, and optimal $C_{p(opt)}$ is 0.48.

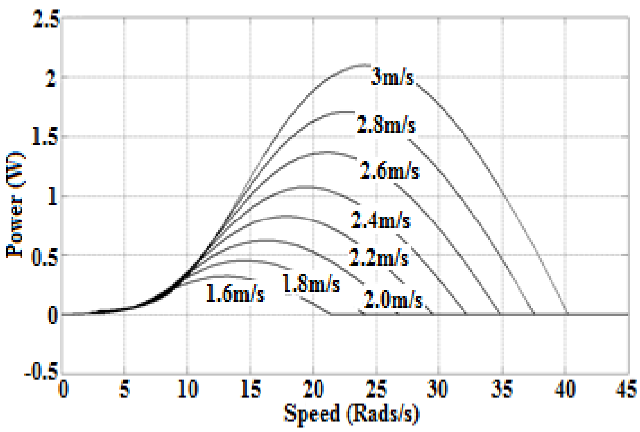

Figure 3: Turbine Power Characteristics Curve

As will be seen, for a given tidal velocity, there is an optimal turbine rotor speed which yields a maximum output power. This corresponds to the maximum power extraction operation.

3.2 Synchronous Generator

The mechanical power of the turbine can be converted into electrical power by a synchronous generator with appropriate control of the field excitation. Figure 4 shows the variations of the input power of 0.91 MW/6.6kV generator as a function of its rotational speed and field current when it is connected to an infinity stiff DC-bus via a passive rectifier. When the field current is low, the induced back emf is also low at low speeds and the diodes may be reverse biased. Consequently, power conversion will not take place until sufficient speed is reached. Thus, for a given field current, there is a minimum rotor speed below which the power conversion is inhabited. This minimum speed decreases with increase in rotor speed.

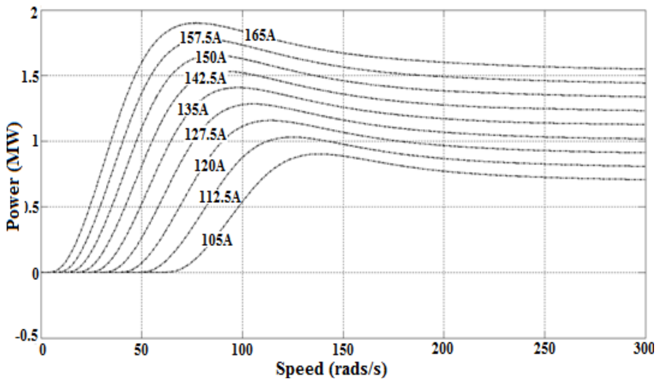

Figure 4: Generator input power curve

3.3 Steady state operation points

The systems steady state operation points can be obtained by superimposing Figure 3 onto Figure 4, and then identifying the intersection points of the two sets of curves as seen in Figure 5.

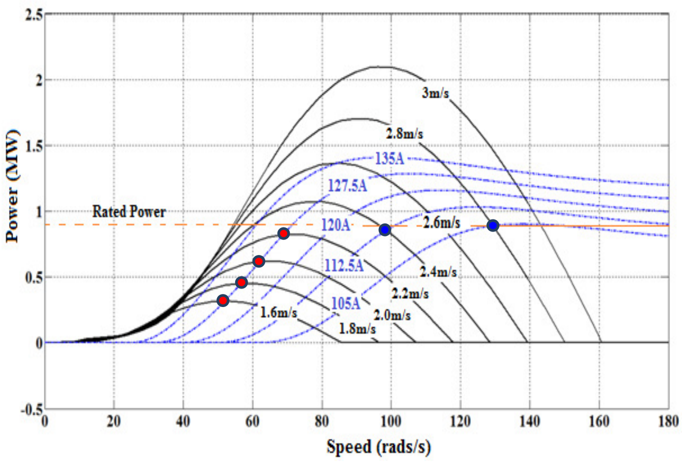

Figure 5: Steady state operation points

This means that by controlling the field excitation current, the generator's input power can be regulated to a desired steady state operation point. As will be seen, at very low tidal velocities, there is insufficient torque exerted on the turbine blades to make them rotate. As the velocity increases, the tidal turbine begins to rotate and generate electrical power. The velocity at which the turbine starts to rotate and generate power is referred to as the "cut-in" speed. As the velocity rises above the "cut-in" speed, the level of generator input power rises rapidly. It can be observed from Figure 5 that when the tidal velocity is below 2.25m/s, the maximum power extraction points, marked by the red dots, almost coincide with the intersection points when the field current is 127.5A**.** Thus by setting the field current at this value, maximum power extraction can be achieved when the tidal velocity is below 2.25 m/s. As the velocity increases further, the generator input power may exceed its rated value. In order to protect the generator from overload, the field current should be reduced as marked by the blue dots in Figure 5.

Figure 6 shows the variation of generator field current with the turbine (or generator) speed that can be employed to realise the power generation control.

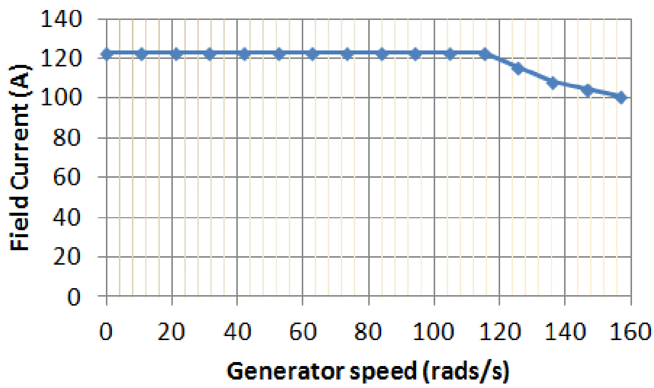

Figure 6: Steady state operation characteristics

4 Control of tidal power generation system

Based on the foregoing analysis, the control of the tidal power generation system may be organised in a cascaded manner as shown schematically in Figure 7. It consists of two control loops. The inner loop controls the field excitation current and the outer power control loop regulates the generator input power against varying operating conditions.

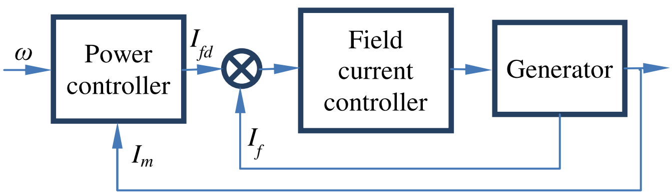

Figure 7: Schematic of tidal power generation control

For example, by measuring the turbine or generator speed, the demand field current can be set according to the relationship shown in Figure 6. This allows the maximum power extraction when the tidal velocity is below 2.25m/s, and limits the generator input power to its rated value when the velocity is above this. The other feedback mechanism may also be introduced, for example, via the measured generator phase current I_m for short circuit or thermal protection. Figure 8 shows the block diagram of the inner field current control loop.

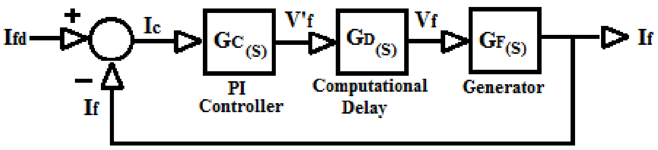

Figure 8: Block diagram of field current control loop

The error signal generated is fed into a proportional and integral controller (PI). The output signal of the controller is fed to the PWM module which consequently determines the switching instants of the H-bridge thereby regulating the machine's field current (Voltage) as shown in Figure 9.

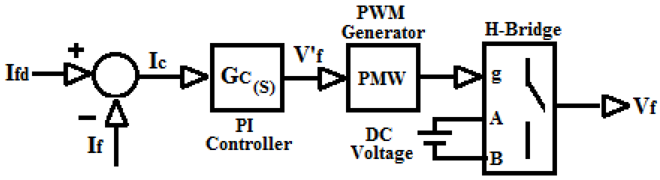

Figure 9: Field voltage regulator schematic for a separately excited brushless synchronous generator

Symmetric optimum design method is employed for selecting the control gains to achieve a minimum of 500Hz bandwidth with a damping ratio of ≈ 0.8. Thus the P and I components were calculated as:

$$K_P = \frac{(1.5T_S + T_G + 1)^2}{2K_G(1.5T_G T_S)} \quad (6)$$

$$T_i = \frac{4(1.5T_S T_G)}{1.5T_S + T_G + 1} \quad (7)$$

where Ts, T_G and K_G denotes the controllers settling time, excitation circuit time constant and the voltage gain of the field excitation of the synchronous generator, respectively.

5 Simulation results and discussion

5.1 Simulated system parameters

Turbine	Rotor diameter – 20m
	Power coefficient - 0.48(opt)
	Water density - 1030kgm^{-3}
Generator	Rated power – 0.91MW
	Voltage – 6600 Vrms
	Frequency - 50Hz

Table 1: simulation system parameters

A Matlab/Simulink study modelled three synchronous generators driven by variable speed constant-pitch tidal turbines together with diode rectifiers and field excitation control, to simulate the proposed system shown in figure 1. Tidal velocity applied to each machine was assumed to be constant at steady state, given that electrical transients are typically much faster than mechanical transients. However different constant tidal velocities were applied to each of the three generators, rising from 0 to the proposed constant value at steady state. i.e., Turbines 1, 2 and 3 were simulated to run at 3m/s, 2.2m/s and 1.6m/s, respectively, in steady-state to represent the variable nature of tidal velocity due to local sea conditions. The field voltage of each generator was regulated to keep it operating at the maximum power extraction point or within its rated limits. The rectifiers' output terminals were connected to a stiff DC bus rated at 9.3kV.

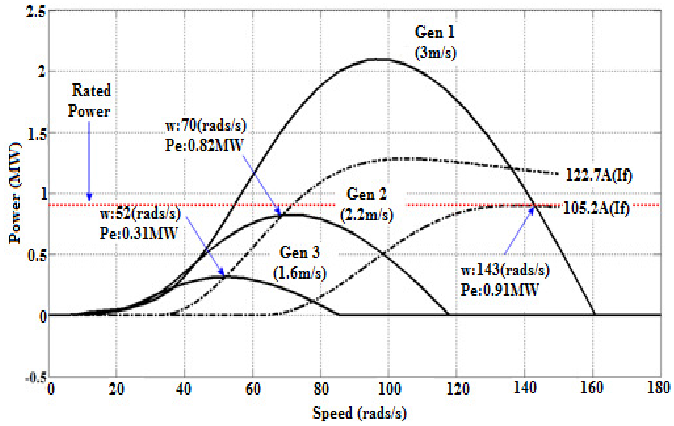

Figure 10 Turbine and Generator Power Characteristics

Figure 10 represents the peak power available at each turbine i.e. turbine 1 2.05MW, 0.82MW for turbine 2 and 0.31MW for turbine 3. However due to the generator input power limitations (0.91MW), only a fraction of the power available for generator 1 could be injected into the machine if it is to operate below its rated value. This was achieved via field current regulation. The intersection points associated the tidal velocities and field current in figure 9 represent the generators' steady state input power.

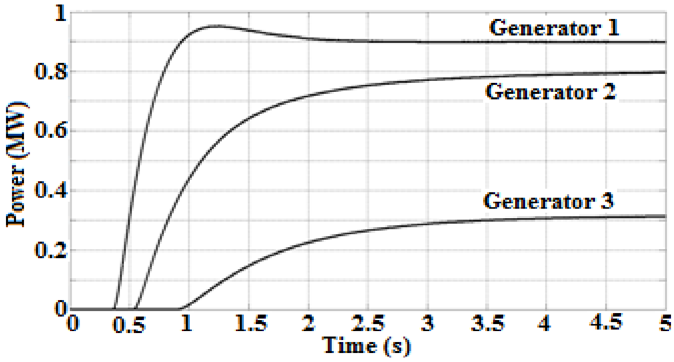

Figure 11a: Response of generator input power

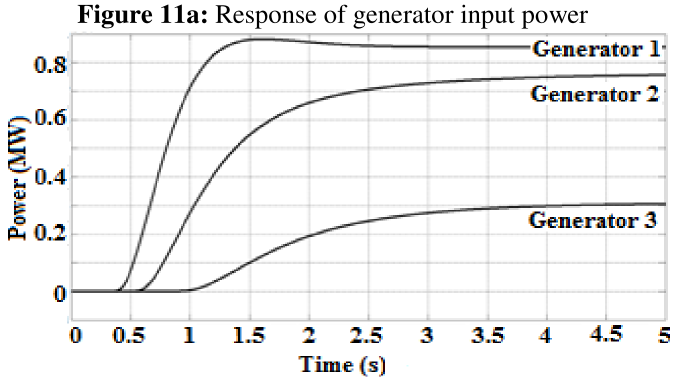

Figure 11b: Response of Generator output power

Figures 11a and 11b represent the generators' input and output power respectively. It can be seen that the output power generated by each generator is almost equal to the input power (*minus system losses*), demonstrating maximum power is extracted from each device. The system efficiency is calculated at around **90%**, which is consistent with typical generator and rectifier efficiencies. Efficiencies could be improved by better designs of these components, but this is beyond the scope of this paper.

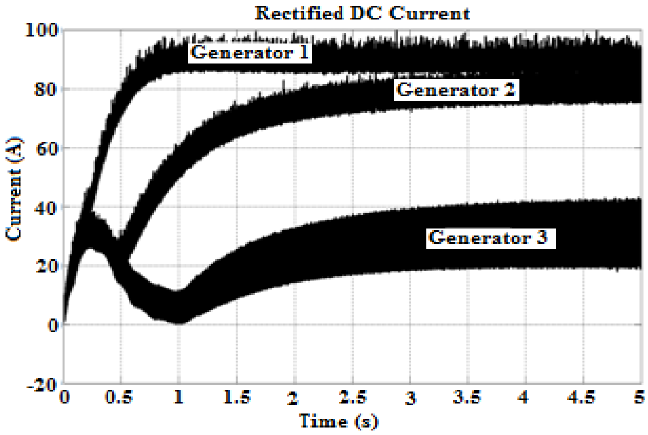

Figure 12: Generators' output current

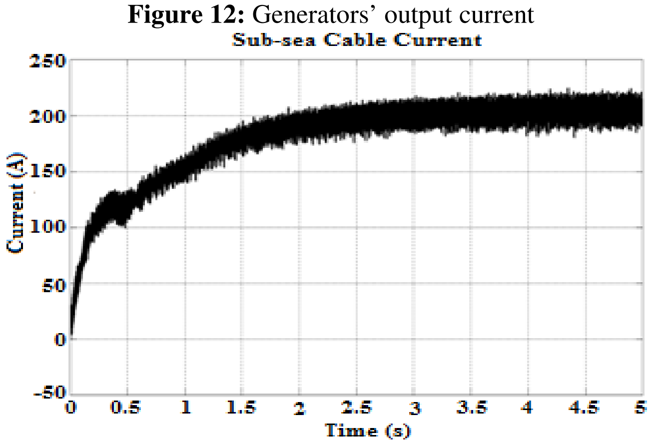

Figure 13: DC Subsea cable current

Figures 12 and 13 show the simulated transient rectifier output current of the three generators and the total current at the DC-bus or within the subsea DC power cable respectively. As can be seen, the subsea cable current is the sum of the currents generated by all three machines. The rectifier output current of each generator is effectively proportional to its input power. For example, the input power of generator 2 is 0.81MW and its rectifier output current is approximately 80A. Conversely, the input power of generator 1 is three times of that of generator 3 and the resulting average output current (power) of generator 1 is three times of that of generator 3. This shows that this simple tidal power generation topology is capable of producing current from each generator proportional to its input power with conventional voltage regulation via field current control. Figure 14 shows the dc power, measured at the DC subsea cable, it can also be observed that this equates to the sum of the power generated by all three generators as shown in figure 11b.

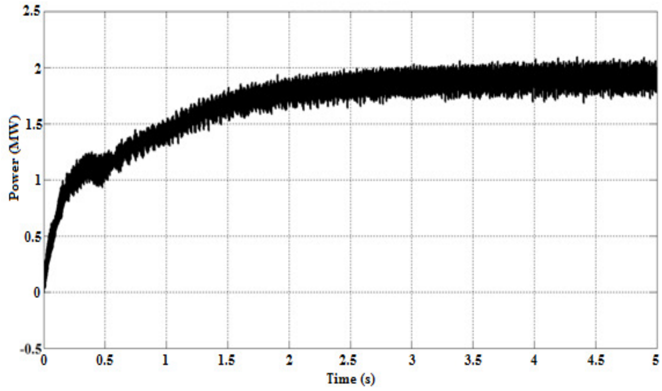

Figure 14: DC-Link circuit Power

Figure 14 shows the line-to-line voltage waveforms of the three generators. The peak-to-peak values of the line-to-line voltages of all three generators are equal to the rectifier output voltage of 9.3kV DC dictated by the DC-bus voltage.

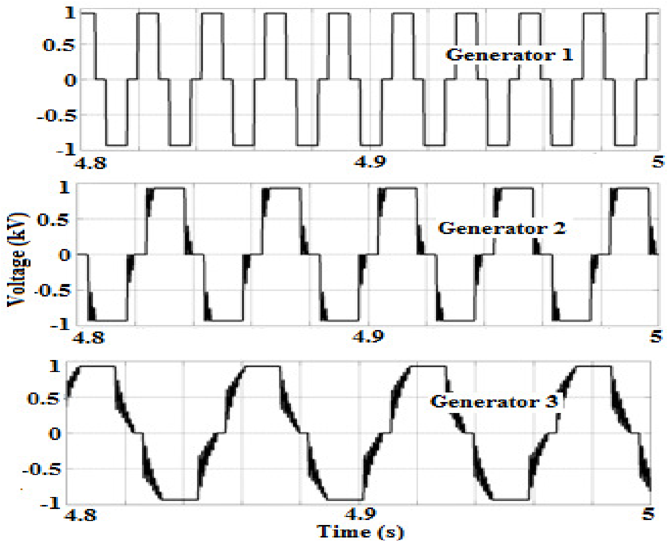

Figure 15: Generator AC Voltage waveforms

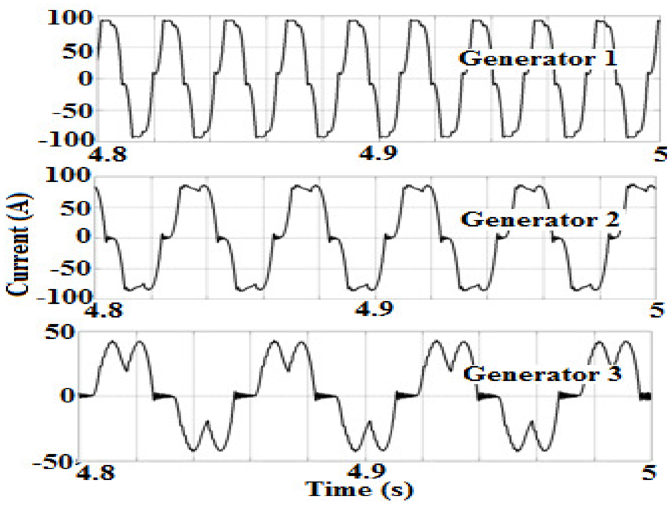

Figure 16: Generator AC current waveforms

It can be seen in figures 15 and 16 that operating frequency of each generator is different due to different input power being applied to each generator.

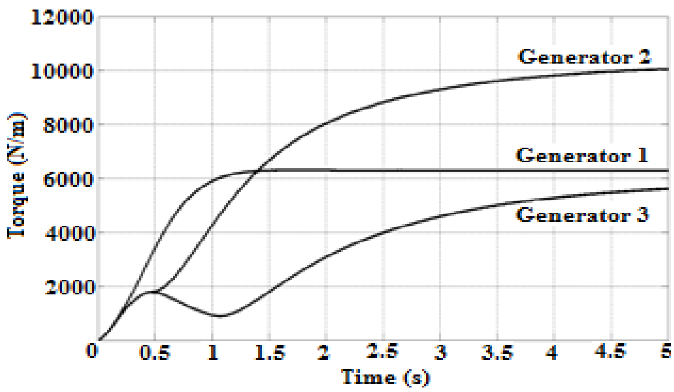

Figure 17: Generator Torque

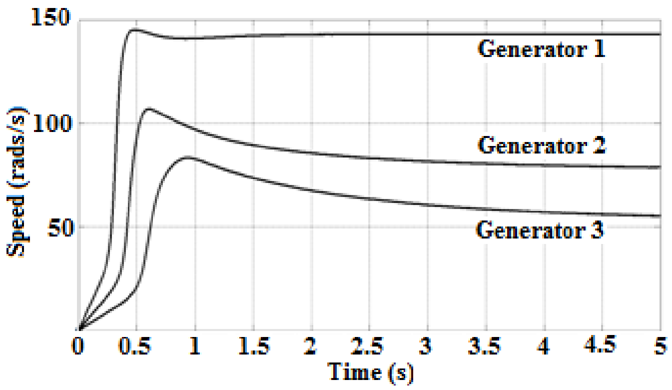

Figure 18: Generator speed

It is shown in figures 17 and 18 that when the input power applied to a generator is higher, it is driven to rotate at higher speed and produce greater current so that the resulting electromagnetic torque balances the turbine driving torque to reach equilibrium. Consequently, both the frequency and magnitude of the AC current are higher, and so is the output power. It is also demonstrated in figure 11 and figure 18 that the generators' output power is proportional to the cube of its speed i.e. if generator 2 is rotating at ≈ 70 rads/s (figure 18) and its resultant power is 0.82 MW (figure 11), generator 3, rotating at ≈ 50 rads/s, generating 0.31MW (figure.11). However for generator 1 this would be higher than the rated power therefore in order to operate within the desired/rated power limit, its torque absorption is reduced (figure 17) via field current (I_f) regulation as described section 3.3, consequently reducing its input power

6 Conclusion

Tidal stream power generation is becoming a highly researched area. In this paper a novel tidal stream power extraction system has been presented and validated through computer simulation. The studies have shown that generator field control is sufficient and effective for each generator, connected to a common DC-link via diode rectifiers, to produce electrical output current proportional to its input power, and allows the use of fixed pitch turbine blades instead of costly and more complicated variable pitch blades, or variable ratio gearboxes. Moreover, this reduces the number of cables to shore, as only the single cable from the dc-bus is required. It is expected that, due to the reduction in component count and in cable losses, power transfer and efficiency would be increased. Furthermore, the size, weight, maintenance and capital installation cost are expected to reduce while reliability would improve compared to most existing tidal power generation systems.

7 Acknowledgements

The authors acknowledge gratefully the financial support towards the ongoing research into power distribution / grid interfacing for subsea tidal generation systems carried out at the University of Sheffield, which is from a range of sources including: the Engineering and Physical Sciences Research Council (EPSRC) and Rolls Royce plc.

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