Life-Oriented Control of Tidal Power Generation

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***Abstract*—Tidal turbine generator is an effective means to harness ocean power for utility level uses. A major technical obstacle to deploying tidal turbine systems is their vulnerability to intermittent torque stresses applied on shafts. In this paper, a hybrid control strategy is proposed to smooth the torques on the shaft by combining the maximum power point control and torque control, realized by PI controllers. Numerical tests show that, under this strategy, the life cycle of a typical 3kW system can be extended up to 40 times.**

Keywords—life extension; permanent magnet synchronous generator; tidal turbine; torque

I. INTRODUCTION

There is a large amount of energy in oceans in different forms such as kinetic energy, chemical energy, thermal energy, and biologic energy. Among different types of ocean energy generation systems, tidal power generation systems are gaining increasing attention because of their scalability. Industrial installations are being developed especially in European countries and the U.S., eg. the 1.2MW SeaGen S installed in Strangford Lough, NI, in 2008 [1].

Among different tidal generation technologies, the horizontal axis turbines are widely adopted because of their efficiency [2] and relatively simple design [3]. Tidal current drives a turbine to rotate, and the turbine drives a generator for producing AC electricity at variable frequency. A back-to-back converter is used to convert variable AC electricity to the fixed 60Hz AC electricity, synchronous with the grid. Due to the harsh environment such as high pressure and chemical corrosion, it is very expensive to build and maintain a power generation system underwater [4]. The density of water is about 800 times of that of air. For generating a same amount of power, the rotating speed of a tidal turbine is generally 0.32 times that of a wind turbine [5], making the mechanical torque of a tidal turbine about 3 times that of a wind turbine. Therefore, a tidal turbine is more prone to mechanical failure whereas more difficult to repair. Reliability must be taken into consideration during design process.

In recent years, many contributions have been made to enhance the performance and reliability of tidal generation systems. Compared with wind turbines, tidal turbines have smaller diameter and thicker blades to enhance the strength of the turbine rotor [6]. Permanent magnet synchronous generator (PMSG), which is brushless and excitation-free, is preferred to doubly fed induction generator (DFIG) because of its simple structure and less maintenance [6][7]. Various control methods are proposed in [8][9] to cope with tidal turbulence and parameter variations.

However, there lacks fatigue analysis of the shaft in the tidal turbine generator in literature. In existing literature, there are only shaft torque analyses on conventional turbine-generator system under system faults [10][12]. In conventional turbine-generator system, the torque on the shaft does not fluctuate much under normal conditions. During system faults, overcurrent will lead to great vibrating torques, and cause fatigue, or even damages in the shaft. On the contrary, in tidal turbine-generator system, the rotating speed fluctuates as the tidal current speed changes, resulting in torque changes all the time. This pulsating torque causes fatigue in the shaft.

In this paper, a hybrid control strategy is proposed based on a tidal turbine generation system, and realized with PI controllers. Reliability of shaft system is especially considered. Real time simulation is carried out in which the model is built based on Simulink and modified to RT-Lab environment, making it easy to design. The real time simulator with multiple CPUs accelerates the simulation significantly.

The rest of this paper is organized as follows. In Section II, the models of different part of the system are provided. In Section III, the proposed control strategy is explained. Section IV introduces the real time simulation. The simulation results are discussed in Section V, followed by the conclusion.

II. SYSTEM MODELING AND ANALYSIS

The system configuration is shown in Fig. 1. The permanent magnet synchronous generator (PMSG) is driven by the tidal turbine. The turbine applies mechanical torque on the generator and they rotate at the same speed. The back-to-back converter connects the generator and the grid. It converts variable frequency AC power, which is generated by the PMSG, to a fixed 60Hz AC power, synchronous with the grid.

A. Model of the Tidal Turbine

For a horizontal axis tidal turbine, the flow direction of the water is in parallel with the turbine axis. Tidal currents flow through the turbine, and drive the turbine to rotate. The energy efficiency is described with power coefficient [13].

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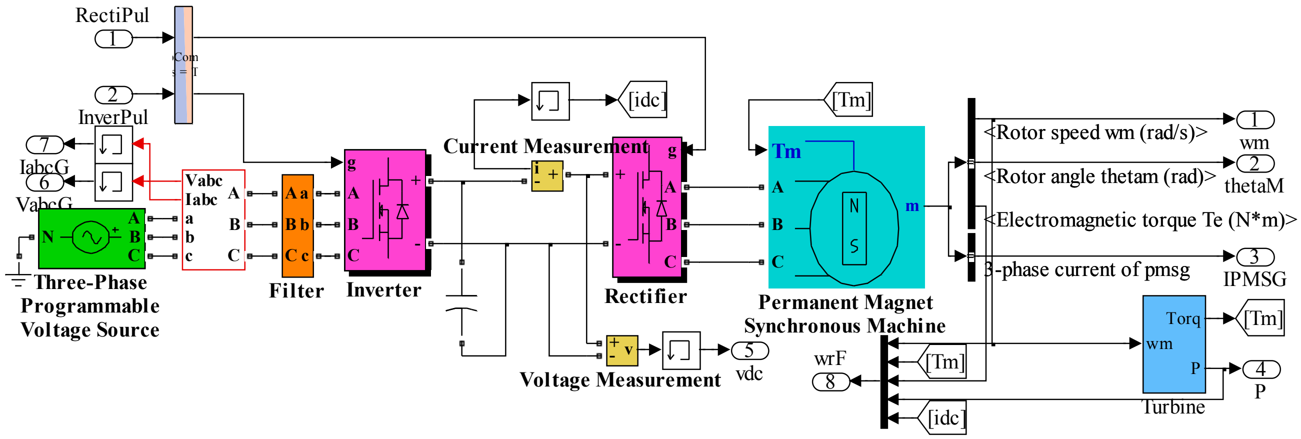

Fig. 1. Tidal generator configuration

The turbine model is

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

where P is captured power, ρ is water density, A is the area of the turbine, v is tidal current speed, C_p is the power coefficient, which is function of tip speed ratio λ.

$$\lambda = \omega R / v. \tag{2}$$

Here ω is the rotating speed of tidal turbine; R is the radius of the turbine.

The tidal turbine characteristics are drawn in Fig. 2. Captured power is very sensitive to tidal current speed because of the cubic relation in (1). At a certain tidal current speed, the power is determined by the power coefficient, which is a function of rotating speed. At each tidal current speed, the power has a maximum.

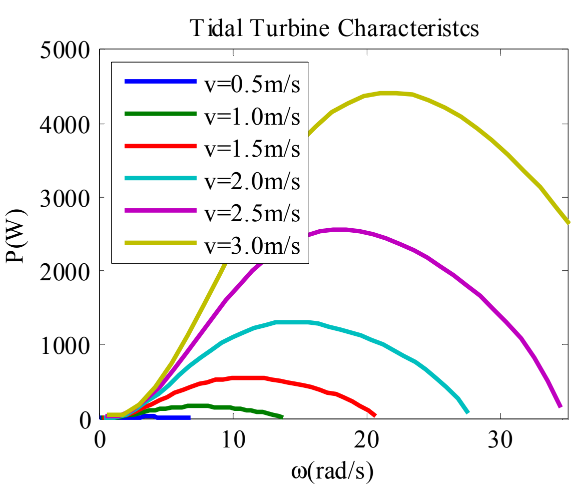

Fig. 2. Tidal turbine characteristics

B. Permanent Magnet Synchronous Generator

Permanent magnet synchronous generator (PMSG) is selected because of its high power density and simple structure. PMSG has a stator with windings, and a permanent magnet rotor, which provides strong magnet flux. In addition, it does not need excitation.

The model is built under dq0 frame for simplicity

$$v_q = R i_q + L_s \frac{di_q}{dt} + p\omega L_s i_d + p\omega \psi_m \tag{3}$$

$$v_d = R i_d + L_s \frac{di_d}{dt} - p\omega L_s i_q \tag{4}$$

where ψ_m is the flux linkage generated by the permanent magnet. R and L_s are the stator resistance and stator inductance, respectively. ω is the synchronous rotating speed, p is number of pole pairs. v_d, v_q, i_d, i_q are d-axis and q-axis voltages and currents respectively.

$$P_e = \frac{3}{2}(v_d i_d + v_q i_q) \tag{5}$$

$$T_e = \frac{3}{2} p \psi_m i_q \tag{6}$$

P_e is the electric power that the generator produced. T_e is the electromagnetic torque.

C. Shaft Torque Analysis

Tidal turbine drives the generator to rotate around a common axis. A shaft is connected between the turbine and generator directly, which is relatively vulnerable. Assume the moment of inertia of the shaft is zero, the torque on both ends of the shaft are the same. Damping and stiffness omitted, the mechanical equations are

$$J_t \frac{d\omega}{dt} = T_m - T_s, \tag{7}$$

$$J_g \frac{d\omega}{dt} = T_s - T_e, \tag{8}$$

In the equations above, J_t and J_g are the moments of inertia of turbine and generator. T_m, T_e, and T_s are the mechanical torque, electromagnetic torque, and shaft torque respectively. ω is the rotating speed.

Substitute (9) into (10), we get

$$T_s = \frac{J_g T_m + J_t T_e}{J_g + J_t}. \tag{9}$$

The shaft torque is the weighted combination of mechanical torque and electromagnetic torque. As the moment of inertia of the turbine is much greater than the moment of inertia of generator, the shaft torque is mainly determined by the electromagnetic torque. The torque has a big impact on life cycle of the shaft. According to [11],

$$N = \frac{1}{2}(6.4\times10^{-6}\frac{\tau}{R_0^3})^{-17.86}. \tag{10}$$

Where N is the number of cycles the shaft can endure. R_0 is the radius of the shaft. And τ is the maximum torque. When τ is smaller than a certain threshold, N approaches infinity.

III. Control Strategy

The relation between mechanical torque and rotating speed is

$$T_m = P / \omega, \tag{11}$$

The mechanical torque is the slope of the straight line connecting the operating point to the origin. Under the maximum power point strategy, as the tidal current speed increases, the mechanical torque becomes greater, which increases the torsional stress and has a bad impact on the lifespan of the shaft system.

Instead of harvesting the maximum power, we tried to extend the lifespan of the generation system to harness more energy in the long run.

This strategy was realized with the PI control of the rectifier and the inverter. The rectifier controlled the rotating speed and the inverter controlled the DC-link voltage.

A. Rectifier Control

The rectifier mainly controlled the rotating speed of the turbine. The control diagram is shown in Fig. 3. The d-axis current reference is 0 to ensure a linear relation between electromagnetic torque and q-axis current [14]. The rotating speed is controlled by regulation of the q-axis current.

B. Inverter Control

The inverter is controlled to keep the DC-link voltage stable. A phase lock loop is used to obtain the angle of the grid voltage and to perform the park transformation. q-axis reference current is set to zero to eliminate the reactive power. The control diagram is shown in Fig. 4.

IV. Simulation Techniques

In this research, real time simulator was used to perform simulations. This simulator, with multiple CPUs and huge memory, is able to run simulations in real time and store large amounts of data in it. The software interface is RT-Lab. RT-Lab is responsible for generating C code from the modified SimPowerSystem model, for transferring the C code to the simulator, for receiving the compiled files, for sending out compiled files to execute, for interaction with the simulator during simulations, and for receiving simulation results. The simulator is controlled by RT-Lab, and is responsible for compilation, simulation, and results extraction. This process is shown in Fig. 5.

Speed and accuracy are the most important indices for simulation. Generally, accuracy is dependent on the time step, and time step determines simulation speed. The reason is as follows.

An electrical system is described with differential and algebra equations (DAEs). To solve the differential equations with computers, numerical integrations must be performed in all types of solvers, which introduce errors. One approach to

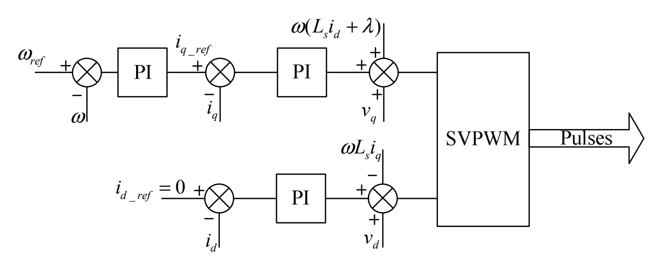

Fig. 3. Control diagram of the rectifier

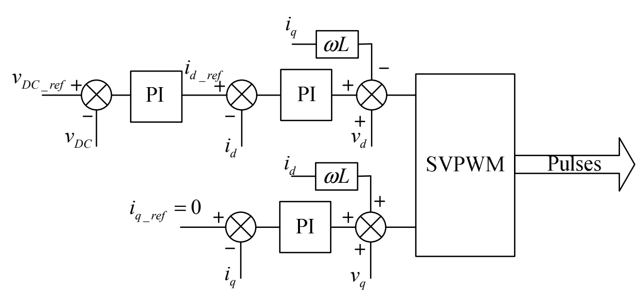

Fig. 4. Control diagram of the inverter

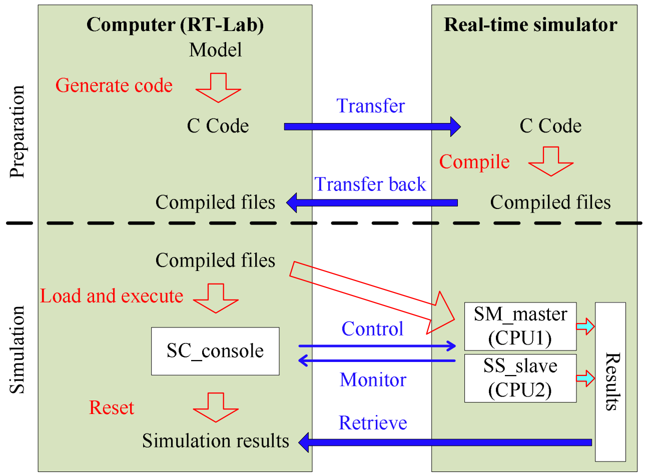

Fig. 5. Operation Scheme of the real time simulator

reduce integration error is using a small time step. In real-time simulations, fixed-step is required due to synchronization with real time. Using a small time step in the whole simulation makes it slow. In PSCAD, trapezoidal integration method is used, which is 2nd order. In our research, Artemis (Advanced real-time electromechanical simulator), a simulator with 5th order integration method is used. It is able to get as accurate results as 2nd order integration with 10-µs time step, with 100-µs time step. The comparison is found in [15]. Thus the simulation speed is improved considerably without losing intolerable accuracy.

The top level of the simulation model is shown in Fig. 6. SM_system and SS_control are two subsystems that will be assigned to two CPUs in the simulator. A 12-hour simulation was carried out with real data as input. The advantage of real-time simulation is obvious in this case. Simulation in Simulink would become prohibitively slow as data accumulate in the memory.

There are still other issues when simulations are performed. The tidal current speed is recorded every 6 minutes, but the simulation time step is 20 microseconds. The solution to this issue is interpolation.

The simulation results include 2.16×10^9 double data per variable. If five variables are monitored, the results will take up 80 GB. The real time simulator is able to store such data with its huge memory. But it is very difficult to deal with these data with Matlab. Still, it is unnecessary. Our method is to sample one point every 1000 points.

V. Simulation Results

Simulation was carried out using real data. Both maximum power point control and the proposed hybrid control are simulated. The results are shown in Fig. 7. Under low tidal current speed conditions, the maximum power point control and the proposed strategy are exactly the same. When tidal current speed is high, the system performs differently

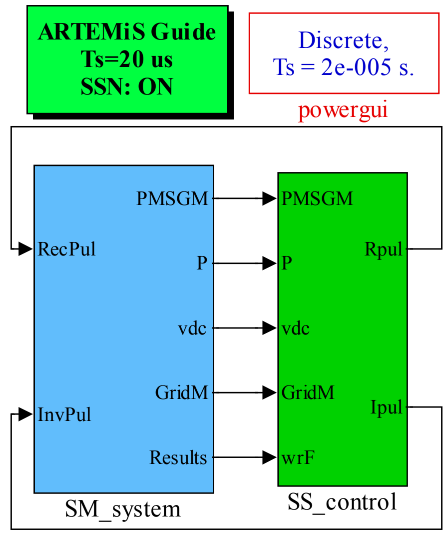

Fig. 6. RT-Lab top level model

under the two strategies.

Under the proposed strategy, the rotating speed is higher than that under maximum power point strategy, as is shown in trace (b). From Fig. 2, less power will be captured. Then the mechanical torque will be reduced according to (6), which is also shown in trace (c). As the rotating speed of the turbine changes very slow, the electromagnetic torque is almost equal to the mechanical torque, with slight fluctuation, as is shown in trace (d). In this way, both mechanical torque and electromagnetic torque are reduced significantly, with only a little cost of power in trace (e).

As noted in Section II, the torque applied on the shaft is mainly electromagnetic torque. Reduction of electromagnetic torque means mitigation of the torsional stress. This leads to longer life of the shaft between the turbine and the generator.

From Table I, it is seen that the proposed control strategy is able to reduce the torque to 77.63%, leading to 39.8 times of lifespan extension, with 1.5% less energy captured. Note that this is an optimistic result because factors like chemical corrosion also have bad impacts on the lifespan of the shaft, which is not considered.

In the design process, the designer must consider the power rating, the strength of the shaft, and the conditions of the site where the tidal generator will be installed. In reality, there will be abnormal conditions like extremely high tidal current speed. This may destroy the system. In 2009, the 1MW tidal turbine installed at the Bay of Fundy was destroyed by high speed currents after 20 days of installation. To handle this situation, the controller must be carefully designed. This paper provides a potential solution to this particular challenge.

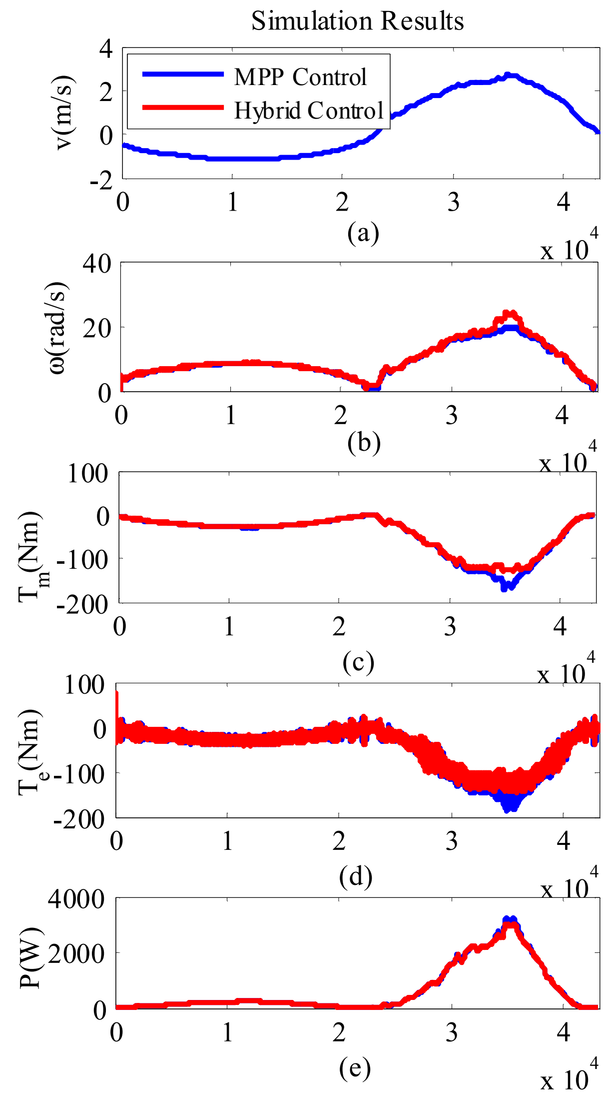

Fig. 7. Simution results.

TABLE I
SIMULATION RESULTS

	Electromagnetic Torque Max(Nm)	Electromagnetic Torque Lifespan (day)	Energy Captured (kWh)
MPP Control	188.54	132.5	7.724
Proposed Control	146.37	5275.1	7.606
%	77.63%	**39.8**	98.47%

VI. CONCLUSIONS

This paper proposed a hybrid control strategy to extend the life span of the shaft in the tidal turbine-generator system. By smoothing the torque on the shaft, the pulsating torque magnitude is reduced to 78%. Simulation shows that under the proposed control, the life cycle of the shaft can be extended to 39.8 times if other factors are omitted.

Simulations indicate that design parameters and control parameters have impacts on the lifespan of the system. Studies on the lifespan sensitivity to these parameters will provide directions for designers.

To enhance the scale of tidal system, interconnection of tidal generators is a trend. Tidal generators are sequentially and spatially correlated because tidal current flows from one generator to another. How to coordinate the generators to extend lifespan of the whole system will also become a research direction.

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