International Conference on Systems, Science, Control, Communication, Engineering and Technology 2016 [ICSSCCET 2016]

ISBN	978-81-929866-6-1
Website	icssccet.org
Received	25 – February – 2016
Article ID	ICSSCCET114

VOL	02
eMail	icssccet@asdf.res.in
Accepted	10 - March – 2016
eAID	ICSSCCET.2016.114

Design of a Controller for Single Phase Stand-Alone Tidal Power Plant

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Abstract- *With the permanent increase in energy consumption, the use of renewable energy sources such as ocean, wind, photovoltaic, and hydropower plants for electricity generation has been given great attention. The proposed system consists of a hybrid power generation system with tidal turbine driving the permanent magnet synchronous generator. The stator windings of the tidal generator are connected to the load through an ac to dc converter, boost converter, dc-to- ac inverter, a step-up transformer and the system for energy storage during random and seasonal nature of the energy resource and load variations. The power absorbed by the connected loads can be effectively delivered and supplied by the proposed system. The main objective is to supply 230-V/50-Hz domestic appliances through a single-phase inverter. Simulation results show that the proposed system can effectively provide reliable and good quality power to the customers in the autonomous power system.*

Index Terms- *Energy storage, real-time control, stand-alone generator, variable-speed generation, tidal power.*

I. INTRODUCTION

Over the past few years, research into the use of renewable energy sources (RESs), such as an ocean, wind, photovoltaic, and hydropower plant [1]–[3], for electricity generation has been the subject of increased attention. In the case of tidal en-ergy conversion systems (TECSs), the interest is also focused on small units, used to provide electricity supply in remote areas that are beyond the reach of an electric power grid or cannot be economically connected to a grid.

Several electrical machines can be used to implement the electromechanical energy conversion and control, each of which presents different advantages and disadvantages [4] – [6]. For small-power tidal systems operating in remote and isolated areas, the study of permanent-magnet synchronous generators (PMSGs) has been the subject of much research. PMSGs are particularly interesting in low-power tidal energy applications, due to their small size and high power density. The primary advantage of PMSGs is that they do not require any external excitation current. A major cost benefit in using the PMSG is the fact that a diode bridge rectifier may be used at the generator terminals since no external excitation current is needed. The system topology used in this paper is based on a PMSG connected through a diode bridge rectifier and a boost converter to the dc link for small- and medium-power ranges [6]–[9].

Maximum power capture through variable speed generation is a field that has gained attention in the wind power industry, however, MPPT in tidal in-stream systems remain a rather less documented field. Moreover, this relatively new field of study also requires addressing of other critical aspects such as maintaining the power quality and avoiding voltage fluctuations while injecting variable amounts of high active power into the network. A prototype marine-current generator based on a permanent-magnet synchronous generator (PMSG) for extracting energy from a free-flow marine current using a vertical-axis fixed-pitch turbine was designed and

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constructed in [10]. The turbine gave maximum power capture for a fixed tip speed ratio and was evaluated under variable speeds and different loading conditions [10]. A variable-speed constant-frequency tidal-current generation system based on a PMSG and its control strategy were proposed in [11] while the maximum power point tracking (MPPT) control method and the maximum energy capture from tidal current were also achieved. The authors in [12] initially identified the tidal resource around Ireland and then utilized the most appropriate and developed tidal energy technology to provide a potential magnitude and output profile. Ireland was found to have a resource available to the first generation of tidal energy devices (TEDs) of 374 MW of turbine capacity, giving an average power of 72 MW with no down-rating [12]. An innovative renewable energy conversion system called

"Hybrid Offshore-wind and Tidal Turbine" (HOTT) was proposed in [13]. The HOTT consisted of four tidal turbines (TTs) and one offshore wind turbine. A 6-pulse GTO rectifier and an inverter were used in the arrangement to deliver the combined generated energy from tidal and wind to the local load and the power system [13]. A hybrid system proposed in [14]–[15] contained an offshore wind energy conversion system and a tidal energy conversion system.

Due to the highly variable nature of the tides, the utilization of an energy storage device such as a battery can significantly

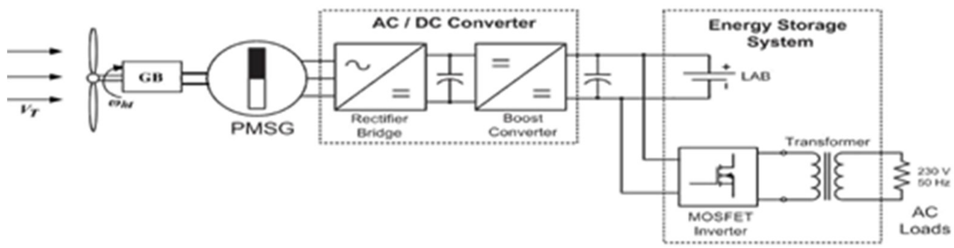

Fig. 1. Tidal turbine configuration.

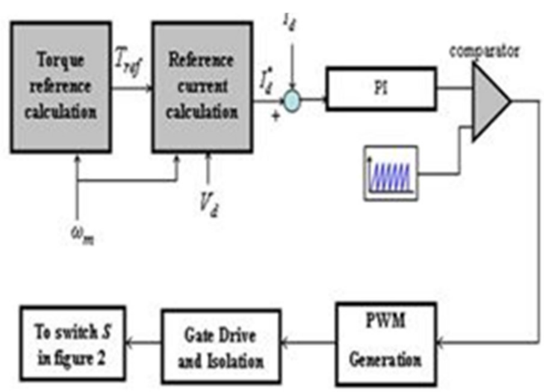

Fig. 2. Control strategy of the switched-mode rectifier.

enhance the reliability of a small stand-alone tidal system. Integrating an appropriate energy storage system in conjunction with a tidal generator removes the fluctuations and can maximize the reliability of the power supplied to the loads [16]–[18]. In the autonomous system, the tidal power converter may be operated to maximize the tidal energy converted into electricity. The captured energy is supplied to the load directly, the difference between the tidal power generation and user consumption being directed to or supplied by the battery energy storage device connected via the power electronic interface [2].

The lead–acid batteries (LABs) are the dominant energy storage technology, with their advantages of low price, high unit voltage, stable performance, and a wide range of operating temperature [19], [20]. This paper is organized as follows. In Section II, the stand-alone tidal turbine system configuration and associated control methods are presented; then, Section III describes the control strategy for switched-mode rectifier. Section IV describes the simulation and experimental results, while conclusions are provided in Section V.

II. Stand-Alone Wind Turbine System Configuration

The proposed stand-alone tidal power system supplies single-phase consumers at 230 V/50 Hz. It is designed for a residential location, and it is based on a 2-kW tidal turbine (Fig. 1), equipped with the following: 1) a direct-driven PMSG; 2) an ac/dc converter (diode rectifier bridge+ boost converter) for the tracking of the maximum power from the available wind resource; 3) a LAB storage device; 4) an inverter; 5) a transformer; and 6) resistive loads. The tidal power is converted into the mechanical rotational energy of the tidal

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turbine rotor. A tidal turbine cannot "completely" extract the power from the tides. Theoretically, only 59% of the tidal power could be utilized by a tidal turbine [19], but for the 2-kW tidal turbine system analyzed in this paper, the real power coefficient is 39%.

The tidal turbine rotor is connected to the generator, thus converting the mechanical energy into electrical energy. The generator's ac voltage is converted into dc voltage through an ac/dc converter. The rectifier is matching the generator's ac voltage to the dc voltage, while the boost converter provides the required level of constant dc voltage. The dc output voltage is fed to the battery bank and through an inverter further to the load. The voltage should stay constant for various tide speeds. When the tide speed is too high, the excess power supplied by the tidal turbine is stored in the battery. When the tide speed is low, the generator, together with the battery bank, can provide sufficient energy to the loads. The dc loads are supplied directly from the dc circuit. At high speeds, the turbine control system stops the energy production. The same protection is activated also in the case when the battery is fully charged and energy production exceeds consumption. At low tide speeds, load shedding is used to keep the frequency at the rated value.

The storage system is composed of a LAB and a full-bridge single-phase inverter that converts the dc voltage of the battery to ac voltage. Furthermore, this voltage is applied to a single-phase transformer, which boosts up the voltage to 230 V. The inverter controls the power transfer.

III. Control of Switched-Mode Rectifier with Maximum Power Extraction

The structure of the proposed control strategy of the switched-mode rectifier is shown in Fig. 2. The control objective is to control the duty cycle of the switch S in Fig. 2 to extract maximum power from the variable-speed tidal turbine and transfer the power to the load. The control algorithm includes the following steps.

1. Measure generator speed ωg.
2. Determine the reference torque (Fig. 2) using the following equation:

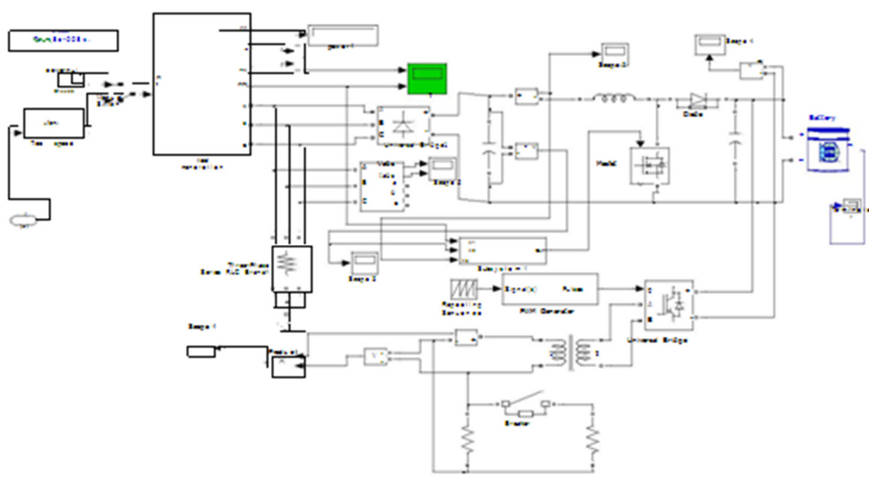

Fig. 3. Proposed Simulink block diagram

3. This torque reference is then used to calculate the dc current reference by measuring the rectifier output voltage Vd as given
4. The error between the reference dc current and measured dc current is used to vary the duty cycle of the switch to regulate the output of the switch-mode rectifier and the generator torque through a Proportional–Integral (PI) controller.

The generator torque is controlled in the optimum torque curve according to the generator speed. The acceleration or deceleration of the generator is determined by the difference of the turbine torque Tm and generator torque Tg. If the generator speed is less than the optimal speed, the turbine torque is larger than the generator torque, and the generator will be accelerated. The generator will be decelerated if the generator speed is higher than the optimal speed. Therefore, the turbine and generator torques settle down to the optimum torque point Tm_opt at any tide speed, and the tidal turbine is operated at the maximum power point.

IV. Simulation and Experimental Results

The proposed system has been modeled and simulated using the Matlab/Simulink/SimPowerSystems environment. Fig. 3 shows the block diagrams for simulation. In order to investigate the system's operation, the following simulations and experiments were carried out:

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A. Variation of the tide Speed, while the Load is Constant

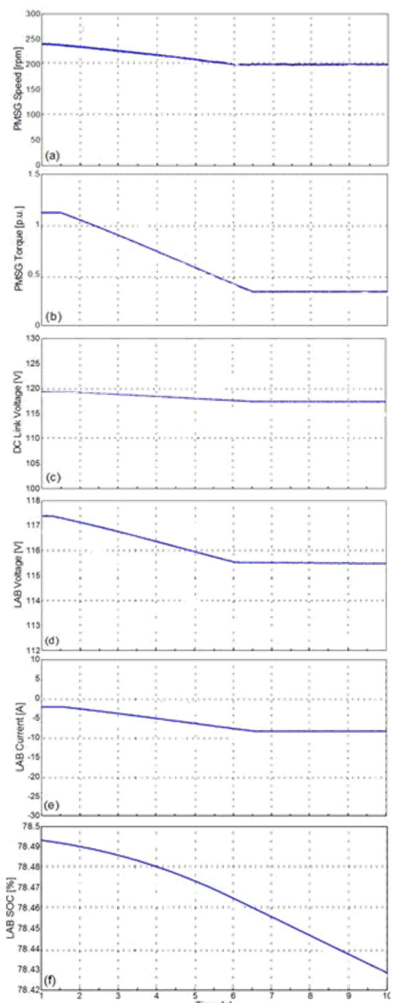
Case 1) Decreasing variation of the tide speed, while the load is constant (P=1kW).

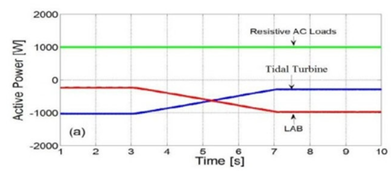
In Case 1), the entire energy load demand is considered to be 1 kW. The simulation results for the tidal generator are summarized in Fig. 4(a)–(c). During this process, the LAB voltage decreases by about 3 V [Fig. 4(d)]. The simulation and experimental test results for the LAB current are shown in Fig. 4(e). When the LAB is discharging, the battery SOC decreases in order to ensure a stable supply for the loads. The results can be seen in Fig. 4(f). When the tide speed is 5 m/s, the tidal turbine cannot supply the entire energy demand of the load (1 kW); therefore, the battery is supplying the difference. The active power balance of the system is shown in Fig. 5, experimental tests confirming the simulation results.

B. Load Switching, at Fixed Tide Speed (Two Case Studies)

Case 1) 2-kW load switching at 9 m/s; Case 2) 1-kW load switching at 0 m/s.

In Case 1), the tidal speed is maintained constant at 9 m/s. A 2-kW load is connected at t = 3 s and disconnected at t = 7 s. The simulation results for the tidal turbine are summarized in Fig. 6(a) and (b). The dc-link bridge voltage variation is shown in Fig. 6(c). Furthermore, Fig. 6(d) and (e) shows that the LAB's operating mode changes from charge to discharge





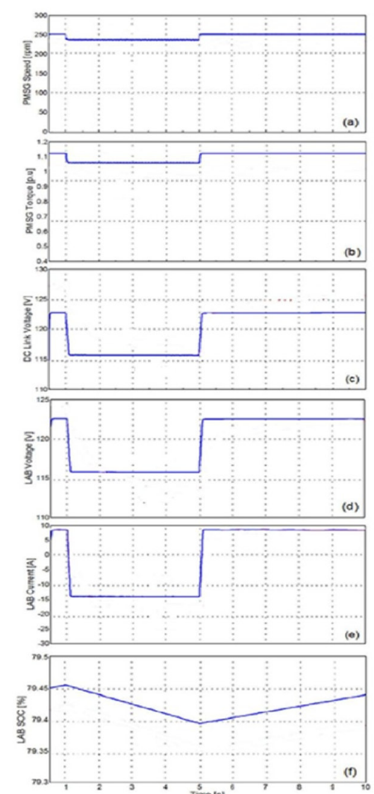


Fig. 4. (a) PMSG rotor speed variation. (b) PMSG electromagnetic torque. (c) DC-link rectifier bridge voltage variation. (d) LAB voltage variation. (e) LAB current variation. (f) LAB-SOC variation.

Fig. 5. Active power balance of the system.

Fig. 6. (a) PMSG rotor speed variation. (b) PMSG electromagnetic torque. (c) DC-link rectifier bridge voltage variation. (d) LAB voltage variation. (e) LAB current variation. (f) LAB-SOC variation.

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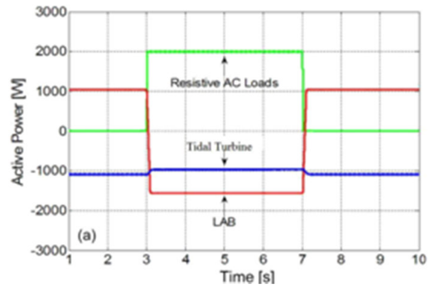

Fig. 7. Active power balance of the system.

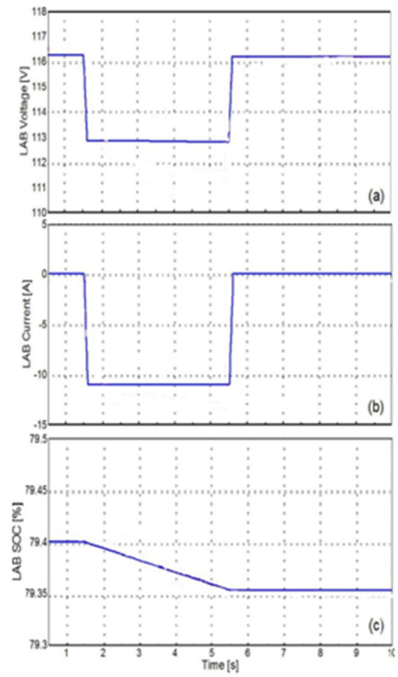

Fig. 8. (a) LAB voltage variation. (b) LAB current variation. (c) LAB-SOC variation.

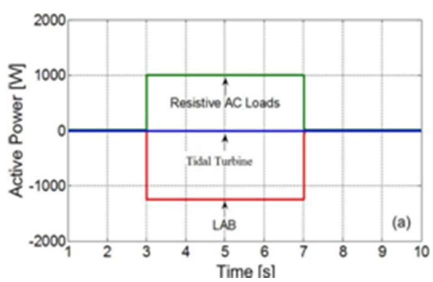

Fig. 9. Active power balance of the system.

during the transient event. As no load is connected initially, the power difference supplied by the wind turbine is stored in the battery and is then released when the 2-kW load is connected, thus ensuring continuous supply of the load. The SOC slope changes when the load is switched on and off, as shown in Fig. 6(f), which means that the battery is switching from the charging to the discharging modes. Consequently, the system maintains its active power balance (Fig. 7).

In Case 2), the tidal turbine does not rotate (v=0m/s). A 1 kW load is connected at t = 3s, and then, it is disconnected at t = 7s. During the transient event, the LAB voltage decreases [Fig. 8(a)], and the negative current implies that the LAB has entered into the discharge mode, in order to ensure stable supply for the loads [Fig. 8 (b) and (c)]. Fig. 9 shows that the active power balance of the system is maintained, regardless of the load change.

Small changes in the battery voltage and current waveforms can be observed on the experimental results, compared with the simulation curves, taken as reference. The explanation for these differences is that the real system is more complex than the model used in the simulation, and its performance can be affected by many parameters which are not considered in the simulation.

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V. Conclusion

A control structure for single-phase stand-alone tide-based energy sources have been analyzed in this paper. This includes an associated energy storage system, with the role to stabilize the output voltage in autonomous applications. The MPPT algorithm, which controls the power electronic interface, will ensure a maximum extraction of energy from the available tide. The LAB always ensures the safe supply of the loads (households), regardless of the problems caused by tide speed or load variations, by switching between the charging and the discharging modes.

Simulation and experimental test results show that the active power balance of the system proves to be satisfied during transient loads and variable tide speed conditions. The configuration can operate with inductive loads, but there is no effect of the L component on the dc-side power circulation, so the specific study of the RL case is of no interest. However, the inverter has to be oversized to bear the reactive component. Thus, the analysis performed and the case studies considered lead to the conclusion that the proposed system can effectively provide reliable and good quality power to the customers in the autonomous power system. This paper highlights the functionality and efficiency of the control system developed and offers perspectives for future research on autonomous tidal energy system control strategies.

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