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Dynamic Braking System of a Tidal Generator

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***Abstract*——Renewable energy generation has experienced significant cost reductions during the past decades, and it has become more accepted by the global population. In the beginning, wind generation dominated the development and deployment of renewable energy; however, during recent decades, photovoltaic (PV) generation has grown at a very significant pace due to the tremendous decrease in the cost of PV modules. The focus on renewable energy generation has now expanded to include new types with promising future applications, such as river and tidal generation. The input water flow to these types of resources is more predictable than wind or solar generation.**

The data used in this paper is representative of a typical river or tidal generator. The analysis is based on a generator with a power rating of 40 kW. The tidal generator under consideration is driven by two sets of helical turbines connected to each side of the generator located in between the turbines. The generator is operated in variable speed, and it is controlled to maximize the energy harvested as well as the operation of the turbine generator. The electrical system consists of a three-phase permanent magnet generator connected to a three-phase passive rectifier. The output of the rectifier is connected to a DC-DC converter to match the rectifier output to the DC bus voltage of the DC-AC inverter. The three-phase inverter is connected to the grid, and it is controlled to provide a good interface with the grid.

One important aspect of river and tidal generation is the braking mechanism. In a tidal generator, the braking mechanism is important to avoid a runaway condition in case the connection to the grid is lost when there is a fault in the lines. A runaway condition may lead to an overspeed condition and cause extreme stresses on the turbine blade structure and eventual disintegration of the mechanical structure. In this paper, the concept of the dynamic braking system is developed and investigated for normal and abnormal operations. The main objective is to optimize the performance under emergency braking while designing the system to be as simple as possible to avoid overdesigning the power electronics or exceeding the target budget.

***Index Terms*—braking, dynamic model, marine, hydrokinetic, permanent magnet, power plant, river, tidal, synchronous generator, turbine.**

I. Introduction

DURING the past few decades, a significant body of work has been dedicated to wind generation, and as such the nature of the resource is generally well understood. Tidal generation has characteristics similar to wind generation; thus, the knowledge we have acquired about wind generation can be readily transferred to a certain degree to tidal generation. The tidal generator we consider in this paper is very similar to a direct-drive wind generator with full power conversion, also known as a Type 4 wind turbine generator. An overview of marine hydrokinetic generation is given in [1], [2]. Resource assessment of tidal generation can be found in [3]–[5], while the control to maximize energy capture is discussed in [6], [7].

The hydrokinetic prime mover in the power generation is a series of Gorlov hydro turbines connected together as shown in Fig. 1. The two sets of turbines drive the permanent magnet generator in the middle. The generator is controlled by a complete set of power electronics that convert the hydrodynamic power into electrical power. A simplified diagram of the electrical power conversion is shown in Fig. 2. The generator is a direct-drive permanent magnet synchronous generator [8], and a discussion on electro-mechanical braking for a transportation system can be found in [9], [10].

Figure 1. Example tidal generator consisting of a series of connected Gorlov turbines. Image from Wikipedia

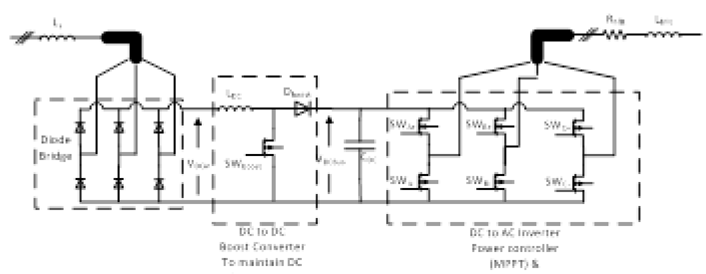

Fig. 2. Simplified diagram of the electrical power conversion

The sequence of this paper will be arranged as follows: Section II presents the concept of the balance of power, Section III discusses the implementation of dynamic braking, and Section IV presents the conclusion.

II. BALANCE OF POWER

The balance of power between the energy source generating the hydrodynamic power and the energy sink absorbing energy in the form of electrical energy (power entering the grid) must be maintained at all times to achieve multiple goals, such as maximizing energy capture, maintaining the mechanical integrity of the structure and components of the generation, and producing good power quality while providing ancillary services to the grid.

In this paper, we focus on the specific task of designing and operating the dynamic braking system of the turbine to avoid a runaway problem.

A. Hydrodynamic Representation

The available hydrodynamic power of a water turbine can be computed from the water flow and the turbine dimension. The tip speed ratio (TSR) is defined as the ratio of the linear speed of the tip of the blade to the flow speed

$$P_{turbine} = 0.5\,\rho\, A C_p C_p\, V^3 \quad (1)$$

$$TSR = \frac{\omega R}{V} \quad (2)$$

where A is the cross sectional area of the turbine [m], ρ is the water density [kg/m^3], V is the speed of the water flow [m/s], and C_p is the performance coefficient of the turbine. The C_p of the typical turbine of a tidal generator under consideration is available. The rotational speed, ω, is the rotational speed of the blade. The maximum operating C_p (C_{pmax}) is 0.32 for this turbine and corresponds to $TSR_{cp\_max} = 1.9$.

The equation used to control the generation can be further simplified as shown in (3):

$$P_{gen} = K_{Cpmax}\,\omega^3 \quad (3)$$

where $K_{Cpmax} = 0.5\,\rho\, AC_{pmax}\left(\frac{R}{TSR_{Cpmax}}\right)^3$

B. Torque Equations

The balance of electromechanical power allows the speed to be controlled. The equation governing the speed can be simply expressed as follows:

$$\omega_m = \frac{1}{J}\int (T_m - T_e)\, dt \quad (4)$$

And:

$$T_m = \frac{P_{Turbine}}{\omega_m} \quad (5)$$

$$T_e = \frac{P_{gen}}{\omega_m} \quad (6)$$

where ω_m is the rotational speed in mechanical radian/second, T_m is the mechanical torque driving the generator (N.m.), and T_e is the electrical torque of the generator (N.m.). Under normal conditions, the electrical torque is controlled to maximize energy capture, thus maximizing the performance coefficient, C_p. On the other hand, to avoid a runaway condition, a sufficient braking torque must be applied to control the rotational speed below the allowable rotational speed limit. Cross flow turbines "runaway condition" is limited to the hydrodynamic maximum TSR for a given flow speed, so as long as the electrical system is rated to allow for this condition, which it should be, then this freewheel state is not a short term issue.

C. Electrical Generator Representation

The permanent magnet generator is basically a voltage source directly proportional to the rotational speed. The terminal of the generator is connected to the DC rectifier; thus, in a per-phase AC equivalent circuit, the DC rectifier can be considered variable resistance, and the size of the effective resistance can be controlled by the power electronic devices.

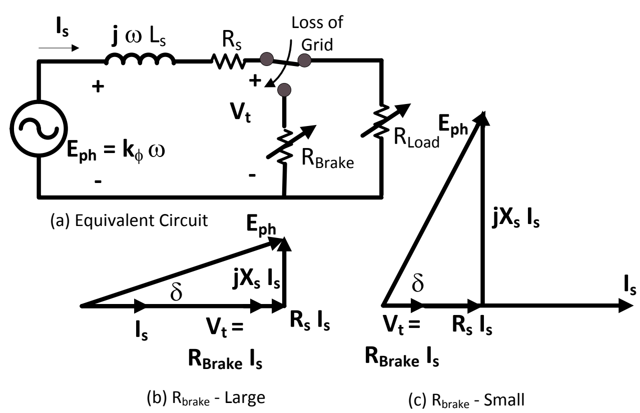

Fig. 3. Per-phase equivalent circuit and phasor diagrams

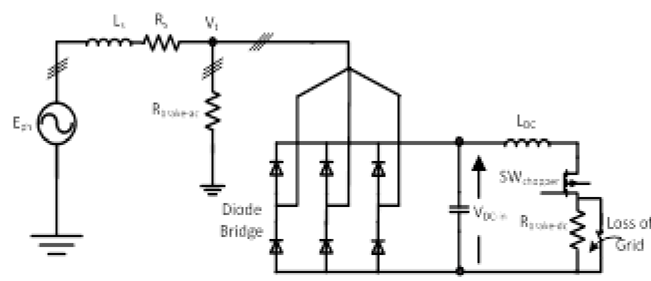

Fig. 4. Implementation of R_{brake} with AC and/or DC resistors

The internal emf E of the permanent magnet synchronous generator connected to a diode rectifier can be expressed as:

$$E_{ph} = k_\Phi\, \omega \quad (7)$$

The frequency of the generator can be expressed as a function of the rotational speed, ω_m and the number of poles, *pole*.

$$\omega = \frac{pole}{2}\,\omega_m \quad (8)$$

The terminal voltage can be expressed as in (9). Note that in order to ensure that the electrical current is to flow in the circuit, the magnitude of the internal emf E must be higher than the magnitude of the voltage V_t ($E > V_t$):

$$V_t = R_{Load}\, I_s \tag{9}$$

And:

$$R_{Load} = \frac{P}{3\, I_s^2} \tag{10}$$

$$E_{ph} = V_t + R_s I_s + j\omega L_s I_s \tag{11}$$

where

E_{ph} = per-phase internal emf of the permanent magnet synchronous generator

ω = electrical frequency in electrical radian/sec

R_{Load} = variable resistance representing variable output power P into a diode bridge and the grid

V_t = AC equivalent of the per-phase terminal voltage connected to a rectifier (not drawn)

I_s = the stator current feeding the rectifier bridge at unity power factor

L_s = the stator inductance

R_s = the stator resistance

By controlling the power converter, the output power delivered to the grid can be adjusted. The variable load resistance represents the output power delivered to the grid. Under normal conditions, the stator current is within the normal range (up to the rated current); and the voltage drop across the stator resistance, R_s, can be neglected ($I_s\ R_s \simeq 0$). Thus, the output power $P = P_{gen}$, as shown in (6).

III. Dynamic Braking Implementation

Dynamic braking is applied during an emergency to avoid overspeeding—for example, when the connection to the grid is lost during a fault because the system protection disconnects the generator from the grid to protect the generator. When this happens, the balance of power is no longer maintained; thus, the torque equation shown in (4) will be driven by the mechanical torque from the hydrodynamic turbine, and there is no generator torque to counteract and keep the balance in check. Overspeeding can occur in a short time, so either a mechanical brake or electrical dynamic braking must be applied. Dynamic braking has the advantage of having no mechanical contact between a disc brake and brake pad, which for a tidal generator would need to be sealed in a waterproof container, adding to the capital cost and periodic maintenance cost. The implementation of the dynamic braking can be accomplished in several ways. Another advantage of dynamic braking is in the form of an additional protective feature for a power converter of a hydrokinetic generator. Absorbing short-term power imbalances allows avoiding dangerous overvoltage in the converter DC bus.

A. Braking Resistance (R_{brake})

The equivalent resistance, R_{brake}, can be used to illustrate the impact of the size of the braking resistance because the size of the AC resistance determines the effectiveness of the dynamic braking.

The value of the braking resistance that maximizes the braking power can be derived from the Thevenin equivalent from the terminal of the generator:

$$R_{brake} = \omega L_s - R_s \tag{12}$$

The stator current and the maximum braking power can be computed as follows:

$$I_s = \frac{E_{ph}}{R_s + R_{brake} + j\omega L_s} \tag{13}$$

$$P_{\max\_brake} = 3\,|I_s|^2\,(R_s + R_{brake}) = \frac{3\,k_\varphi^2\,\varphi^2}{2L_s}\omega \tag{14}$$

As shown from the equation above, the maximum braking power (P_{max_brake}) varies linearly with the rotational speed or frequency. Note that it is common for permanent magnet generators to short circuit its stator windings when parked; however, short-circuiting the terminals of the generator does not produce significant braking power (or torque) when the generator is rotating. In fact, the braking power at short circuit is approximately 16 kW (losses are converted into heat inside the winding, a major risk for winding insulation failure). In comparison, the P_{max_brake} = 110 kW at 21 Hz, corresponding to R_{brake} = 0.74 ohm; and at 14 Hz the P_{max_brake} = 73 kW, corresponding to R_{brake} = 0.47 ohm.

B. Implementation of the Braking Resistance

1) Implementation on the AC Side

Three-phase resistors can be used to implement AC dynamic braking at the AC side (also known as a crow-bar solution); however, to make the dynamic braking resistors adjustable, a resistor bank must be used to allow for an adjustable resistance. The implementation on the AC side is shown in Fig. 4, wherein the three-phase resistance is labeled "$R_{brake\text{-}ac}$." The advantage of using resistors with a connection to the AC side is that the device rating (voltage and current) of the diode bridge does not need to be oversized.

2) Implementation on the DC Side

The implementation on the DC side is shown in Fig. 4, wherein the single resistance is labeled "$R_{brake\text{-}dc}$." The implementation on the DC side takes advantage of the available DC-DC boost converter currently used to match the generator voltage to the DC bus voltage of the DC-AC inverter. With this arrangement, the $R_{brake\text{-}dc}$ is varied by adjusting the duty ratio of the pulse-width modulation switch. Note that the resistor must be bypassed during normal operation, thus allowing the power electronics switch, $SW_{chopper}$, to function as a DC-DC boost converter. With the DC-side implementation, the device rating of the DC-DC boost converter and the diode bridge must be oversized to allow for overload operation during dynamic braking.

3) Implementation on Both the DC and AC Sides

If both the AC-side and DC-side implementations are enabled, the system becomes much simpler, with the AC-side resistance chosen to carry the minimum braking requirement and the DC-side resistance chosen to adjust the braking torque according to the need and thus ensure successful braking. Another advantage is that the device ratings of the diode bridge and the DC-DC boost converter do not need to be oversized to perform the braking operation.

C. Braking Performance under Variable Speed

Because the generator is operated in a variable-speed mode, it is convenient to find the braking power at different frequencies. Note that for a permanent magnet generator, the output frequency is proportional to the rotational speed.

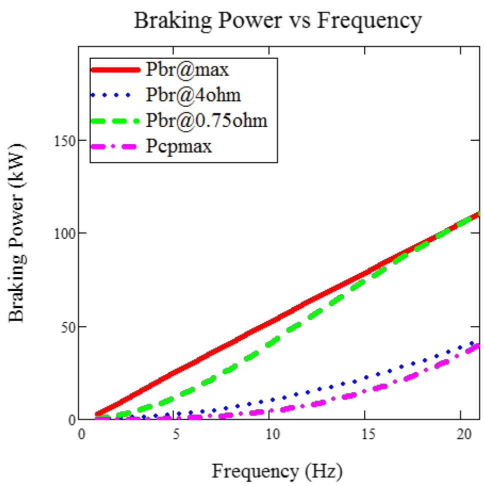

Fig. 5. Braking power vs. R_{brake} in variable frequency

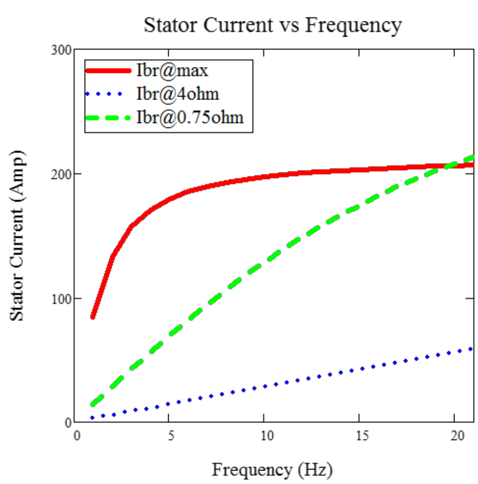

Fig. 6. Stator current magnitude vs. R_{brake} at variable frequency

Fig. 5 shows the characteristics of the braking power as a function of the frequency. The corresponding stator current is given in Fig. 6. The output power during normal operation (C_{pmax} operation) is also given in Fig. 6. Note that for a permanent magnet generator, the output frequency is proportional to the rotational speed. As shown here, the maximum braking power is linearly proportional to the frequency of the generator. To operate in maximum braking power, it is necessary to control the R_{brake}. This means that with the braking resistance on the AC side, it is not possible to operate in maximum braking power all the time. On the other hand, by controlling the maximum power on the DC side, it is possible to operate more precisely.

As we compare the maximum braking power to the output power for different modes of operation, as shown in Fig. 5, several observations are worth noting:

- The maximum braking power is very high compared to normal output power (maximum C_p operation; refer to the dashed-dotted pink line in Fig. 5), and several observations should be considered here.
- Operation close to the maximum braking power can also be achieved by applying R_{brake} = 0.75 ohm (refer to the dashed green line in Fig. 5). This single-value resistance can be implemented on the AC side with minimal control.
- Operation slightly higher than normal operation (C_{pmax} operation; refer to the dotted blue line in Fig. 5) can also be achieved by applying R_{brake} = 4.0 ohm. This single-value resistance can be implemented on the AC side with minimal control.
- As shown in Fig. 6, operating at maximum braking power or operating at R_{brake} = 0.75 ohm produces a very large stator current (much higher than the rated current of 60 A), thus overheating of the winding may result if the process of dynamic braking takes longer than expected.
- Based on the above observations, we propose applying a single-value R_{brake} = 4.0 ohm implemented as a three-phase constant resistance on the AC side as the braking mechanism. In this way, we can guarantee that at any rotational speed, the braking output power will be larger than the C_{pmax} operation, thus ensuring that the speed control slows down the rotational speed until the generator is reconnected to the grid. As a precaution, we can include additional dynamic braking on the DC side with minimal additional braking resistance, which does not require oversizing the power electronics devices.

IV. Conclusion

This paper explored the dynamic braking of a tidal generator. Basic operation under normal conditions is presented to give the baseline of the fully loaded or rated condition of the tidal generator. The balance of power between the source (turbine) and the sink (generated power to the grid) is an important aspect of the speed control. Understanding this balance of power is the key to designing a successful dynamic braking system. The maximum braking power is derived as a function of the rotational speed to explore the possible electrical output power that can be extracted from the generator. Similarly, the maximum performance coefficient of the turbine is used during normal operation; thus, the maximum turbine hydrodynamic output power is also derived as a function of the rotational speed. Knowing the envelope of the operating ranges of both the turbine and the generator, we can design the control strategy so that the generator will be controlled to maximize the efficiency of the turbine (C_{pmax} operation) during normal conditions. It will be operated in the dynamic braking mode during emergencies when the generator is disconnected from the grid because of a fault or other disturbance.

From our investigation, we proposed a simple dynamic braking system with AC-side dynamic braking implemented using a single-step, three-phase braking resistor. The size of the braking resistor is computed so that the generator will slightly generate electrical output power above C_{pmax} operation. This control method will force the turbine to stall, and the rotational speed will decrease to zero. As a backup and to ensure successful dynamic braking, DC dynamic braking is also included to provide additional power. This DC dynamic braking can be implemented by utilizing the existing DC-DC boost converter with a small modification.

V. ACKNOWLEDGMENT

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