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Novel approach for hydrokinetic turbine applications

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ABSTRACT

By 2017, Egypt is expected to finish its sixth hydropower plant which is associated with the new Assiut barrage. Based on any hydraulic structure's design, there is enormous kinetic energy created downstream of the gates. This super power water jet generated under dams/barrage gates creates a destructive scouring effect downstream of the gates. In this work, a novel approach for hydrokinetic energy application is presented. The new approach proposes installing a farm of hydrokinetic turbines on the stilling basin of the spillways of the barrage's gate. This approach does not only magnify the total electric energy which was untapped in the past but also dissipates the enormous kinetic energy downstream of the gates. The total expected captured electric power from the barrage reaches 14.88 MW compared to 32 MW rated value of the existing hydropower plant.

Introduction

Hydro power is considered one of the economical and uncontaminated sources of power generation in Egypt, the hydropower generation in Egypt started firstly with the construction of Aswan dam to control the Nile water flow for irrigation, navigation and industrial purposes. In 1967, the high dam hydropower plant with total capacity of 2.1 GW was commissioned, followed by the startup of Aswan 2 power plant in 1985. Meanwhile, the Ministry of Water Resources and Irrigation constructed new barrages along the Nile River such as: new Esna barrage and its hydropower plant was constructed and completed in 1994, new Naga-Hammadi barrage and its hydropower plant was constructed and completed in year 2008 and finally the new Assiut barrage. Recently, the hydropower plant of the new Assiut barrage is under construction and expected to be completed in 2017. The total power that is generated from the hydropower of new Esna, Naga-Hammadi and Assiut barrages are 90, 64 and 32 MW respectively (Hydraulics Research Institute, 1991, 1997, 2014). According to the Ministry of Electricity & Energy (2012), the total share of hydropower generation in Egypt to the total generation represents about 8.9% in 2012/2013.

Several research papers have introduced schemes to increase the energy extracted downstream (far away) powerhouses of dams with different principals, criteria of applied approach and expected harnessed energy (Yue and Daniel, 2014; Arango, 2011). The main objective of this paper is to present a novel development for the conventional dams/barrages design to increase the total harnessed energy from them. The proposed approach suggests the utilization of the super power water jet downstream dams/barrage gates by means of installing a hydrokinetic turbines farm downstream the gates on the stilling basin of the spillways. Such power is not only an untapped power, but also it is a problematic issue for civil engineers/designers since dissipation of this power requires sometimes lengthening of the stilling basin and sometimes adding concrete structures to dissipate or at least deviate some amount of this power away from the river bed (Peterka, 1984).

The proposed approach may be an ambitious idea, notably if the recorded water velocities under gates may exceed 8–12 m/s for certain water discharge flow. The associated problems are mainly relevant to mechanical issues that if these ultra-speeds are suitable for installing hydrokinetic turbines or not. Another question primarily related to hydraulic engineers is raised: Is this proposal a real solution for super-jet water flow problem and is there any need of another way for energy dissipation? All these questions and others will be open for discussion with all involved fields of engineering.

In the succeeding sections, a brief comparison between hydrokinetic and conventional hydropower turbines is introduced; problem overview

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is fully presented in Problem overview, followed by methodology of investigation and case study description in Methodology and case study description. Results presents the achieved results. Challenges and potentials are fully described in Challenges and potentials, and conclusions are finally drawn.

Hydrokinetic turbines vs. conventional hydropower turbines

River streams, tidal waves, marine stream currents, and other artificial channels have potential for generating electric power through various hydrokinetic energy technologies. This nascent class of renewable energy technology is being strongly considered as an exclusive and unconventional solution falling within the area of both in-land water resource and marine energy.

The terminology of 'Hydrokinetic Turbine' has been alternately used with other terms such as: 'Marine Current Turbine' (MCT) (Verdant Power Canada, 2007; Garman, 1986), 'Ultra-low-head Hydro Turbine' (Radkey and Hibbs, 1981), 'Free Flow/Stream Turbine' (Geraldo and Tiago, 2003), or 'In-stream Hydro Turbine' (Dixon, 2007). Like wind energy, hydrokinetic turbines are employing both horizontal and vertical schemes and are currently being explored deeply. Such devices can be deployed in pre-selected water channels in a modular/array pattern without significantly disturbing the natural path of the stream (Khan et al., 2009). As inspired by wind energy conversion systems, the global scheme for a grid-connected hydrokinetic energy conversion system (HECS) is similar to wind energy conversion system (WECS) and given in Fig. 1. Same methodologies for modeling resource, turbine, and electric generators for WECS can be used for HECS (Khan et al., 2011; Lago et al., 2010). For HECS, water is the flowing fluid; however the total kinetic power in a MCT is governed by the following equation (Guney and Kaygusuz, 2010):

$$P_{HECS} = \frac{1}{2}\rho A V_{wr}^3 \tag{1}$$

where: P_{HECS} is the total hydro power that can be collected from the turbine, ρ is the water density (1000–1025 kg/m^3), A is the turbine swept area while V_{wr} is the water velocity. A hydrokinetic turbine can only yield a fraction of this power owing to hydrodynamic behavior and thus Eq. (1) is modified as follows:

$$P_{Mech} = \frac{1}{2}C_p \rho A V_{wr}^3 \tag{2}$$

where: P_{Mech} is the shaft power harnessed by hydrokinetic turbine, and C_p is the power coefficient that indicates to the power losses due to energy conversion through turbine shaft.

The aforementioned principle is different for conventional hydropower plants; *hydraulic turbines* derive the potential energy of the fluid into kinetic energy and convert into useful shaft torque. In another words, hydraulic turbines derive torque from the force exerted by a head of water coming from reservoir. These turbines are classified into two main classes: impulse turbines and reaction turbines (IEEE Std). A conventional hydro power plant depends mainly on natural topology of the site. So it requires huge infrastructure buildings and massive capital investment contrary to HECS. The mechanical power developed by the turbine is proportional to the product of the flow rate, the head and the efficiency. The power is controlled by adjusting the flow into the turbine by means of wicket gates on the reaction turbines and by a needle on the impulse turbine. The nominal power is given by the following equation (IEEE Std):

$$P_{hyd} = \rho g Q H \eta \tag{3}$$

where: P_{hyd} is the mechanical power developed by the turbine, Q is the flow rate, H is the head, g is the gravitational acceleration while η represents the actual utilization of the available potential energy of the system. The turbine efficiency is defined as the ratio of mechanical power transmitted by the turbine shaft to the absorbed power from fluid flow and depends on the water flow rate and the turbine operating characteristics.

Problem overview

Dams and barrages are structures created across a river or a natural water channel for diverting water into a canal for the purpose of irrigation or water supply, or into a channel or tunnel for generation of electricity. However, and despite their similarities, there are differences in these two structures. A barrage is considered as a type of dam consisting of a series of large gates (sluice gates or spillways) that can be closed or opened to control/manage the amount of water passing through it. These gates are mainly predestined for adjusting and stabilizing the water flow for irrigation, navigation and industrial purposes. One key difference between a dam and a barrage is that while a barrage is built for diverting water, a dam is constructed for storing water in a reservoir/basin to raise the water level significantly. A barrage is usually constructed where the surface is flat across rivers (Mott MacDonald, 2014).

Based on barrage design, flow over spillways or underneath gates has an enormous potential energy value, which is converted into kinetic energy downstream control structures. This phenomenon is called *hydraulic jump*; such terminology is a well-known term for hydraulic structure engineers. Hydraulic jumps are natural phenomena that occur owing to the flow discrepancy between the upstream and downstream regimes affecting the same reach of a channel (Abdelazim et al., 2010).

For example, as demonstrated in the sketch of the hydraulic jump shown in Fig. 2, if the upstream control causes supercritical flow, then a hydraulic jump is the only means to resolve this transition by forming significant turbulence and dissipating the energy (Abdelazim et al., 2010). Where V is the flow velocity, M is the velocity head in height of water column, P represents the pressure, h_L is the energy head loss and L_j is the length of the hydraulic jump. Subscript 1 refers to the upstream, while subscript 2 refers to the downstream of the gates. In

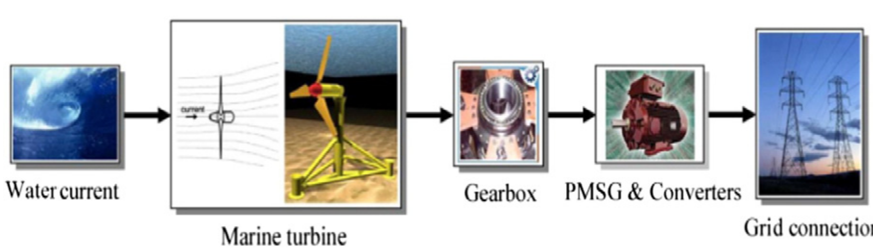

Fig. 1. HECS global block diagram.