INVESTIGATION OF THE POSSIBILITIES FOR DEVELOPMENT OF A VARIABLE SPEED HYDRAULIC TURBINE

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Abstract:

The need of hydropower, as a renewable energy resource, nowadays is increasing more and more. The goal is to obtain more efficient and more reliable power generating equipment for rational and long-term harnessing energy from the water. Following the Horizon 2020 goals in the field of renewable energy, the need for development of a variable speed hydraulic turbine was exploited. The potential benefits of developing such a hydraulic generation unit with variable speed are described in this paper along with the theoretical background used as a starting condition to be taken into account for the further development processes. The "Ss. Cyril and Methodius" University is a partner in a project called HydroFlex, with the aim of developing a variable speed high pressure Francis Turbine, with particular goal to develop the stay/guide vanes cascade to be suitable for such hydraulic turbines.

Keywords: Hydropower, Variable Speed Turbine, Fluid Structure Interaction, Guide Vanes

1.INTRODUCTION

Interest in hydropower generation as a sustainable energy system is continuously increasing nowadays, while the focus of attention is energy efficiency and savings. Hydropower is considered to be the largest and most cost effective renewable energy source for power generation in the world and tends to remain a competitive and most increasingly growing renewable technology due to the existence of large technically feasible hydropower potential to be developed. High efficiency and reliability became significant objectives for the hydropower industry to achieve, as a result of the rapid development of hydropower generation, which lead to the appearance of variable speed operation of hydropower plants [1,2,3].

A hydroelectric unit is compound of a turbine coupled with a generator. In the turbine, the water's energy is converted into the mechanical energy of the rotating shaft. The shaft rotates the rotor of the electric generator, where the mechanical energy is converted into electricity that is supplied to consumers via high-voltage transmission lines [4]. In general, the generators used are synchronous machines due to their great advantages producing voltage and frequency of the grid and providing reactive power for consumers and network [5].

The biggest constraint of current hydraulic turbines is the fixed speed operation, which is imposed by the use of synchronous generators. The synchronous generators used in conventional hydropower plants are operated to match the frequency of integrated AC grid. The speed of the hydropower generating unit must remain constant in order to provide energy to the electric grid with constant frequency (50 or 60 Hz) [6].

$$n = 60 \cdot f/z$$

where f [Hz]- grid frequency; z- number of generator poles and n[rpm]- rotational speed of the runner.

Conventional turbines are designed to run at the speed specified by the frequency [1,7,8]. The magnetic field of the stator and the magnetic field of the rotor always rotate with the same speed and the two are coupled [9,10]. The constant rotary speed is maintained by the use of a speed controller [11,12].

2.THEORETICAL BACKGROUND

Hydraulic turbines operate at optimal value of head and discharge which can only vary limited so as not to cause major efficiency decrease.

If the rotational speed of hydraulic turbine can be adjusted, the efficiency of hydropower generation would be significantly increased [7]. In variable speed turbines, larger variation of the operating conditions is possible, giving rise to significant advantages in plant operation [11].The main idea of this technique is allowance of change in turbine speed in accordance with hydraulic conditions, thus improving the overall unit efficiency [1].

The hydraulic efficiency is defined by the relation of the useful energy absorbed by the turbine to the available hydraulic energy at the turbine inlet. Both water discharge and net head significantly affect the hydraulic efficiency, which can be represented in a turbine hill diagram (Fig.1) [1]. From this chart, the efficiency drop due to head and discharge deviations from their nominal values, can be determined.

The idea of introducing variable speed operation is the following: in case of change in head or discharge, the rotary speed can be adjusted accordingly to maintain high efficiencies. This is shown on Fig.1. For fixed speed operation at certain head, when the water flow decreases from Q_a to Q_b, the efficiency will decrease from a to b'. In order to operate at better efficiency point (b), equivalent to the efficiency point a, it is more convenient to run the unit at speed n_b rather than n_a [6,10]. It can be concluded that a variable speed turbine permits maximum efficiency tracking for a given power demand.

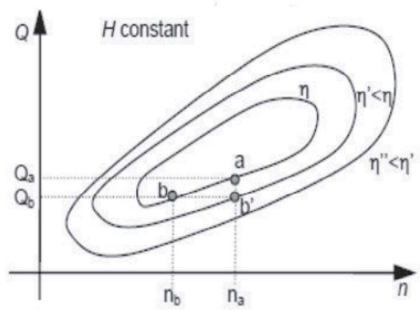

Fig.1. Hill diagram of a hydraulic turbine [6]

So far, variable speed turbines are implemented in the Small Hydropower Plants and tested for constant heads and variable gates (moving guide vanes). The following chart presents that the efficiency curve for small amounts of flow through the turbine for a variable speed turbine, has greater values than the constant speed turbine (Fig.2.).

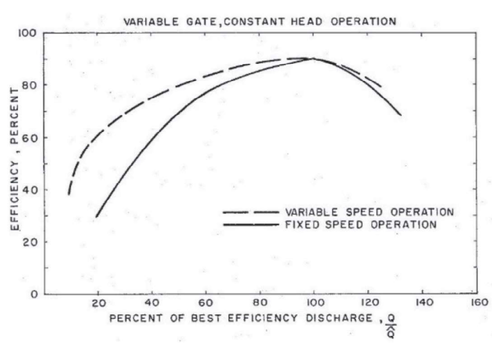

Fig.2. Efficiency curves of variable and constant speed hydraulic turbine [13]

3. BENEFITS OF VARIABLE SPEED OPERATION

Problems that are common for fixed speed turbine operation are higher possibility of cavitation appearance when turbines operate with higher heads than nominal and draft tube pressure oscillations when operating with lower heads and/or lower discharges [1].

Adjustable speed hydropower plants may alleviate draft tube surging and cavitation problems. Moreover, variable speed technology offers additional network flexibility by enabling power regulation so it could provide additional means for enhancement of electric grid stability [14,15].

Possible variable speed turbine benefits depend on the mode of plant operation, but in general, variable speed operation of hydropower plants results in a substantial improvement in system efficiency and performance. Besides the energy efficiency increase, major operational benefits can be obtained by means of adjustable speed operation. On one hand, this technique allows, in hydro plants with certain regulating capacity, to generate the same amount of energy with a reduced flooded area, thus giving rise to environmental benefits.

On the other hand, increased efficiency operation tends to extend equipment life and to reduce long term maintenance requirements. Reduced noise, vibration and cavitation problems give advantage of a longer hydraulic turbine service time.

Other benefits that can be obtained from using variable speed turbines are additional control flexibility and more flexible selection of site location and hydro generating units size [1,2,7,13].

Potential cost benefits require definition and analyses of operation scenarios.

4. SOLUTIONS KNOWN FOR THE ELECTRIC GENERATION UNITS

In a variable speed machine, the stator and the magnetic field of the rotor are decoupled. There are two ways for achieving this [6]:

-the stator can be decoupled from the grid by using a frequency converter between the grid and the stator winding

-the rotor field can be decoupled by a multiphase rotor winding fed from a frequency converter connected to the rotor.

The adjustable speed technology requires an electronic power conversion system, a high performance control equipment and a special design of the generator and the turbine [16]. A typical variable speed hydroelectric scheme consists of a turbine, a generator, a rectifier for the generator output, an inverter at the powerhouse and AC or DC transmission, and an inverter at the substation [1,13].

Basically, there are three technical solutions applied for variable speed hydropower generation, previously used for wind power plants:

Doubly Fed Induction Generator (DFIG) – The stator is directly connected to the grid. The rotor is connected to the terminals of the machine through an electronic power converter. Therefore, the power converter can control the voltage, current and frequency in the rotor circuit. The converter introduces a slip frequency AC field current, allowing the rotor to spin faster or slower than the grid frequency. The DFIG rotor is directly connected by the shaft to the turbine runner, thus enabling turbine speed change.

Full Power Converter (FPC) - The generator is fully decoupled from the frequency of the AC grid and additional negative sequence component during grid fault is not needed. Reduction of the nominal power of the generator can be obtained. In addition, the grid side converter has the decoupled control of active and reactive power that leads to improvement of the whole system performance.

High Voltage Direct Current (HVDC) - enables unit speed variations of ±25%.

5. HYDROFLEX PROJECT

The European Commission and the Innovation and Networks Executive Agency (INEA) recognized the potential for integration of variable speed operation of hydropower systems and decided to finance a project that will develop a variable speed Francis turbine-HydroFlex project. Its aim is to make hydro power available in a time as short as possible by performing well-focused research and innovation actions on the key bottlenecks of hydro power plants that restrict their flexibility. The focus of the project is on enabling hydropower to operate with very high flexibility in order to utilize the power and storage capability, aiming to create the environmental and technical basis for successful future industrial development. The idea was born from the extensive experience that the lead institution, the Norwegian University of Science and Technology, Norway has in the field of hydropower. Hence, the operating conditions of hydro power plants in the future energy system will be identified. Taking into account that Francis turbine is the most common turbine type in Europe, the emphasis on the research is on the flexibility of Francis turbines and the configuration of synchronous generators and frequency converters that allow for variable speed operation.

The main task of the Faculty of Mechanical Engineering in Skopje is the development of a parametric design tool for variable speed Francis turbines, which will focus on the geometry of the stay and guide vanes.The main goal of the designing tool is to provide various logical geometries for the stay/guide vanes cascade, which later those geometries will be exported to the solver ANSYS, where a coupled numerical simulations are planned to be made – Fluid Flow and Structural Simulations (FSI - Fluid Structure Interaction), to provide a hydraulic optimal design of the stay/guide vanes cascade system, and also to provide a structural integrity of the developed solution design.

The stay/guide vanes system shall be designed to provide efficiency by various energy and structural parameters, such as:

-Minimal pressure drop through the stay/guide vanes cascade

-Defining operating ranges for the guide vanes

-Flow coefficient curve distribution

-Developing a shock-free flow conditions for the runner

-Structural integrity of the cascade

The criteria for optimization will include the hydraulic turbine efficiency and its characteristic hill chart geometry. The task includes the development of a robust mesh process and an FSI-analysis that will result in a solution-space for the parametric design.

An evaluation/ verification of results from the multi-parametric design will be carried out based on results from the experimental study. It is important to see that the change of speed gives a change of power output at a higher efficiency than of constant speed turbines.

6. THEORETICAL BACKGROUND BEHIND THE PLAUSABLE SOLUTION FOR THE VARIABLE SPEED HYDRAULIC TURBINE STAY/GUIDE VANES SYSTEM

In theory, it is known that the water flow in front of the runner is formed by the wicket gate, which represents an annular cascade of guide vanes. This cascade is characterized by the form of the profiles and the chord spacing in the cascade. The blade profile is said to be symmetric when the middle line of the profile is straight, and asymmetric when the middle line is curved.

For a radial-flow wicket gate, commonly used with reaction turbines, the vector may be represented as a sum of two components – the radial component and the peripheral component:

$$v_0 = v_{0r} + v_{0u}$$

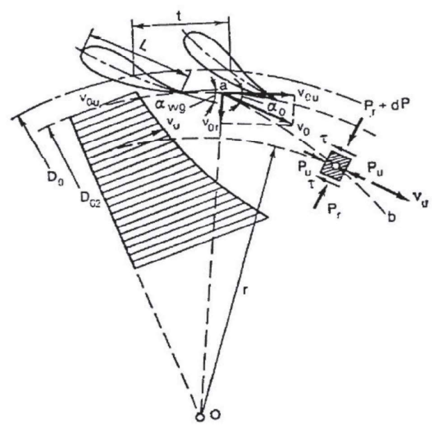

Fig.3. Flow created by the guide vanes

From Fig.3 it can be concluded that the guide vanes flow is created from the two vectors, which can be defined easily from the defined amount of flow through the runner. The peripheral component indicates that the flow is rotated about the "0" axes downstream of the vanes, where this phenomenon is generally expressed as a cascade circulation . The circulation created in the space between the guide vanes and the runner blades remains constant.

The water flow in the runner, on the other hand, is investigated and considered as a compound of two motions: relative and circumferential. The relative motion **'w'** is "fixed" by an observer that is positioned on the runner, and the circumferential motion **'u'** is the rotational motion in the turbines. The sum **'v'** is called absolute motion.

The operating conditions of the turbine are presented by two parameters: the flow rate 'Q' and the rotational speed 'n'. These parameters affect the flow.

In the theory, which can later be taken into account for the development of a variable speed turbine, is to assume first a constant flow rate Q, constant head H, varying rotational speed 'n' and non-whirlpool flow condition at the runner outlet. The absolute velocity at the runner inlet edges will not change, only the circumferential and relative components will change, where the relative component changes the direction too.

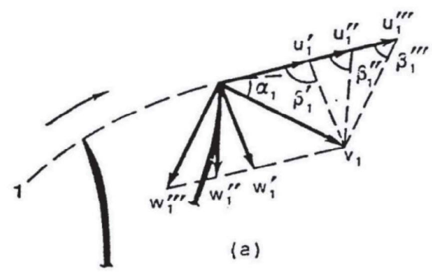

Fig.4. a) Flow at the inlet edges of the runner

For low rotational speeds, the vector $\mathbf{w_1}$ deflects in the direction of rotation, and for high speeds, the vector $\mathbf{w_1}$ deflects in the opposite direction. The effect obtained from the vector direction changes is given on Fig.5.

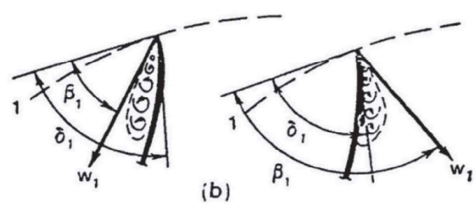

Fig.5. Relative motion vector on the runner inlet edges
for various rotational speeds

The angle between the transportation and relative motion components is and the incidence (inlet blade angle) is noted with , so for different rotational speeds, the angle between the vector changes. From Fig.5 we can see that for very high and very low rotational speeds, a creation of vorticity regions is obtained and it causes additional losses of energy, i.e. shock-loss. So, the most favorable case is when .

The guide vanes have the task to deliver the water flow efficiently in the runner for the optimal working condition of the turbine. Our task lies somewhere here, to develop, as it was said, guide vanes with the most favorable blade geometry to provide a minor pressure drop, a shock free entry for the optimal conditions of working, to provide a constancy of the flow etc.

7. CONCLUSIONS

Conclusions cannot be carried out in this stage, but a major guidelines and some expected improvements can be set in order to provide solutions about this problematics. First of all, from an energy view point, the project goals are plausible, the effect of having a variable speed turbine makes sense in a way to have an efficient energy conversion in the runner for small amounts of flow, i.e. to produce more power for small amounts of flow, and by that, saving the equipment and giving the equipment a longer operating lifetime.

Also it may lead to solving the cavitation problem and submerging the turbine, which is known that hydraulic turbines cavitation conditions changes with the rotational speed.

The electrical connectivity solutions and the generator (stator/rotor interaction etc.) are more or less known, which are already used in the wind power generation systems, where the wind turbines are operating with variable rotational speeds.

Our goal is developing the stay/guide vanes system, i.e. the distribution system of water to the runner, and the main goal is to be as much more efficient to satisfy the needs of the variable speed turbine.

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HydroFlex