Design and selection of a belt drive for an electric generator

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Abstract. The issue of the selection of mechanical drive for medium size power generators was raised in the work. The issue begins with the analysis of the propulsion system in the hydroelectric power plant, in which the turbines were selected for the amount of water flowing and for these turbines electric generators. An overview of the available drive solutions pointed to belt transmissions, which must meet the task of transferring torque from the turbine to the generator. The solution must be durable, which is why the authors conducted a deep analysis of material issues and pointed to modern polymer strips that can meet the challenges posed.

1. Introduction

Low-power electric generators are widely used in solutions used in renewable, “clean” energy sources. Many watercourses are dammed, and turbines are built to power electric generators. Depending on the height of the backwater and the size of the water stream, the first challenge is to choose the right type of turbine, so that the rotational speed of the active shaft drive is optimal and ensures a constant frequency of the electric current and that the power is generated with optimal efficiency. The efficiency of the system for converting mechanical energy into electricity is largely related to the design of the belt mechanical transmission. To obtain an average generator speed of about 1500 rpm, the speed of the turbine must be multiplied. In such cases, belt transmissions are used. They make it possible to increase the rotational speed several times while maintaining high efficiency. The operating parameters of the belt transmission are influenced by the appropriate selection of the mechanics of the drive system: the active shaft and the passive shaft, as a function of water flow velocity through the Kaplan turbine rotor [1].

The value of mass moments of inertia on the axis of the active shaft - the largest, and the smallest on the idle shaft, determine belt selection for the design of the driven mechanism. You can choose from a wide variety of drive belt types. In the case of medium power generators, this choice is limited. Belts are characterized by a number of material and construction parameters. A belt with “large” overall dimensions should be used in the transmission, which is resistant to typical rheological phenomena occurring in polymer belts [4,7]. The design of the generator drive requires the use of a belt with a special load-bearing layer structure, made of steel or Kevlar cord. Its height should be minimal due to the work of internal friction when bending on the arc of contact. Based on many years of professional experience in the design of belt drives and many studies on the mechanics of frictional coupling, the authors selected the appropriate type and dimensions of belts for the assumed mechanics and geometry of the drive [5]. The work was implemented at a power plant on the Odra River. The gearbox has been in operation for 8 years without the need to correct the preload force and elongation symptoms. It is
resistant to the effects of cyclically changing rheological phenomena, such as progressive and transverse creep, stress relaxation and the values of elastic and inelastic strains.

2. The problem of torque transmission from a water turbine onto an electric current generator. The geological and hydrological conditions described in previous works resulted in the Kaplan turbines being selected for the planned hydropower plant. As a result of literature analyzes and the indicated conditions, they constitute a solution that most effectively uses the energy of water flow through the constructed supply channels (Fig. 1).

![Figure 1. Suggested generator drive system](image)

Various types of mechanical transmissions are used in the drives of wind and water electric generators. The basic parameters that the transmissions must meet, in addition to the transmission of high torques, are operating in the multiplier mode, high efficiency, and the ability to not self-lock. Moreover, wind turbines, due to their compact design of the head, also use various types of helical gears. On the other hand, hydroelectric power plants and combustion generators more often use belt transmissions, which simultaneously operate as a clutch of the system. The constantly appearing new solutions of belt transmissions require a new approach to be taken when looking at this group of transmissions (Fig. 2).
When analyzing the design of modern drive belts, one should pay attention to the modern materials used in their construction. The plethora of materials used in the load-bearing layer has significantly developed over the years, as well as the types of materials are used in the construction of the belt on the running and dorsal side. This allowed for a new approach to the selection of belts for the structure and the method of calculating the transmission to emerge [2].

### 3. Properties of materials used in the construction of timing belts

Non-classical construction materials with a high molecular structure, homogeneous or composite, such as elastomers, differ significantly from metals, that are most commonly used in construction, due to their mechanical and rheological properties. These materials are characterized by the following features:

- strong internal friction and energy dissipation,
- nonlinear elastic properties and large deformations,
- strong influence of van der Waals forces,
- developed rheological properties, such as: undergoing the process of structure orientation and mechanical stabilization; creep; stress relaxation and chemical relaxation; reverse creep; material memory for load and deformation history; change of mechanical and rheological properties because of positive or negative temperature changes [3].

For uniaxial constant and step-changing loads, the strain law can be presented in the form of a differential equation

\[
\frac{d^2 \epsilon_y}{dt^2} = -\mu^{-1}(\sigma, h_i) \left[ \frac{d \epsilon}{dt} - \chi(\sigma, h_i) \right]^\eta
\]

where: \( \mu(\sigma, h_i) \) and \( \chi(\sigma, h_i) \) - are functions of tension \( \sigma \), temperature and the history of material deformation \( \eta \) - material constant.

For spatial, variable loads:

\[
\frac{d^2 \epsilon_{ij}}{dt^2} = \mu_{ij} \left( \frac{d \epsilon_{ij}}{dt} - \chi \right)^\eta
\]

![Figure 2. Classification of belt transmissions due to the design of the tendon](image-url)
\[ \frac{d\varepsilon_y}{dt} \bigg|_{t=0} = V_0 \quad \varepsilon_y \bigg|_{t=0} = \varepsilon_0 \]  

(3)

where \( \mu_{ij} \) is a function of the external tension tensor and the parameters describing the internal tension causing the deformation.

\[ \mu^{-1} = \frac{E_c}{V_0} \]  

(4)

Ultimately, the creep law takes the form of a nonlinear differential equation:

\[ \frac{d^2\varepsilon}{dt^2} = -\mu^{-1} \left( \frac{d\varepsilon}{dt} \right)^2 \]  

(5)

Solving the equation after adopting the following initial conditions for \( t = 0 \)

\[ \varepsilon \bigg|_{t=0} = \varepsilon_0 \quad \frac{d\varepsilon}{dt} \bigg|_{t=0} = V_0 \]

Leads to the determination of the deformation function

\[ \varepsilon^c = \varepsilon_o + \frac{1}{E_c} a \sigma^b \ln(E_c t + 1) \]  

(6)

The initial rate of deformation should be determined by preforming experimental creep tests under constant loads. The results of this experiment, after the least squares approximation, are described by the function:

\[ V_o (\sigma) = a \sigma^b \]  

(7)

\[ e_N = e_c - e_w \]

deformation in the creep process \( e_c \) can be obtained by:

\[ \frac{d^2e_c}{dt^2} = -\mu^{-1}(t_p) \left( \frac{de_c}{dt} \right)^2 \]  

(8)

\[ e \bigg|_{t=0} = \varepsilon_0 \quad \frac{de}{dt} \bigg|_{t=0} = V_o(\sigma) = a \sigma^b \cdot t_p \]

(9)

Where: \( \mu^{-1}(t_p) = \frac{E_c}{V_o(t_p)} \)  

- \( E_c \) - material constant, \( V_o \) - initial velocity of deformation, \( t_p \) - material hardening parameter.

Backcrow process for the described conditions:

\[ \frac{d^2e_w}{dt^2} = -\mu^{-1}(t_w) \left( \frac{de_w}{dt} \right)^2 \]  

(10)

Where:

\[ \mu^{-1}(t_w) = \frac{E_c}{V_o(t_w)} \]

(11)
Creep speed (E - variable modulus of elasticity)

Tension relaxation

\[
\frac{d}{dt} \left( \frac{1}{E(\sigma)} \frac{d\sigma}{dt} \right) = \mu^{-1} \left( - \frac{1}{E(\sigma)} \frac{d\sigma}{dt} \right)^\eta
\]  

(12)

\[
\frac{d\sigma}{dt} \Big|_{t=0} = -V_0 E(\sigma_0)
\]

(13)

After the introduction the function: \( \mu^{-1} = \frac{E_c}{V_0} = \frac{E_c}{a_\sigma b} \)

For linearly elastic materials, we get the law of relaxation

\[
\frac{d^2\sigma}{dt^2} = \mu^{-1} \frac{1}{E} \left( \frac{d\sigma}{dt} \right)^\eta \frac{d\sigma}{dt^2} = \sigma^{-b} K \left( \frac{d\sigma}{dt} \right)^2
\]  

(14)

Where: \( K = \frac{E_c}{E(\sigma)^a} \)

**Figure 3.** Graph of tension changes over time in non-classical materials

In drive belts, you can find homogeneous structures and solutions in which the foot layer is made of elastic or nonlinear-elastic materials, while the rest is made of non-classical materials [2, 8]. For the quality of the belt operation, the thickness of the running side layer is reduced, and the structure is selected in such a way that the section 0A in Fig. 3 is as short as possible.

**4. The choice of belt for construction**

Due to the geometrical dimensions of the gears and the amount of the torque transmitted, it was only possible to use joined flat belts. In other types of belts, there were no belts of such length and width that could transfer such large circumferential forces [6]. At the same time, modern flat belts are characterized by high durability and efficiency, and additionally they are very resistant to environmental conditions (i.e. high humidity).
Baseline data for belt selection:
Turbine rotor diameter $\varnothing 2100$,
Turbine type TW2100, $u = 6.41$
Belt width $B = 450$ mm
Wheel width $B_k = 450$ mm
Power = 280 kW

As it results from previous analyzes, the basic parameter of belt selection was low belt deformability during power transmission and passing of the elementary section of the belt between the passive active sides. In earlier designs, 2 to 5% deformation was allowed under the influence of the circumferential force. However, 1% and below this value is recommended in modern belts. The belt selected in such a way is not subject to visible rheological changes, and its wear in operation mainly concerns the abrasive wear of the running side or material aging after many years.
5. Summary
The full implementation of the power plant propulsion took place at the end of 2014. The operational power obtained is $4 \times 250 \text{ kW} = 1000 \text{ kW}$. Among the many solutions of belt transmissions, it was not possible to find suitable V-belts and toothed belts that could meet the parameters of the drive. Similarly, in the case of Poli-V belts, only one company in the world produced such a belt, however, had no experience in a similar application. Therefore, a flat belt was selected for construction, as previously described to be used in such drives. Flat belts for such power loads are produced by some of the largest producers in the world: NITTA in Japan, FORBO in Germany, HABASIT in Switzerland, and the Dutch - Italian concern AMMEGA. By means of a tender evaluation, a HABASIT product was selected, the TF75TE belt, with a cross-section of 4,450 mm, with a supporting layer made of aramid fibers embedded in high-quality TPU. The running and dorsal side of the belt is covered with high-quality rubber. Belts of this design are the most modern solution in heavy drives and are becoming the new standard offered by the largest manufacturers in the world.
Figure 6. Eclectic generators in the “Dolna Odra” hydroelectric power plant

The presented drive (Fig. 6.) includes a belt $L = 11074$ mm long and $450$ mm wide, connected by thermoplastic welding of the belt ends, on which fine triangular teeth with dimensions $200 \times 10$ mm were made. A connection of this type in the manufacturer’s nomenclature is called Flexproof, and the execution at an angle of 30 degrees to the edge and not perpendicularly is marked with the letters EF.

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