Numerical Simulation and Experimental Validation of Planetary gearbox System Design to Govern Constant Generator Speed in Hydro Power Plant

Bhargav1, M. A. Parameshwaran2, Sivaraj S2. & Nithin Venkataram1

1Dept. of MME, Ramaiah University of Applied Sciences Bangalore, India
2MAGTORQ Pvt. Ltd., Hosur, Tamil Nadu, India
E-mail: nithin31@gmail.com

Abstract. Micro Hydro Power Plant (MHPP) is a clean and renewable source of harnessing power ranging between 5kW-100kW. The reservoirs are avoided in MHPP and power house is directly placed in the path of the water stream. In India, there exists an abundant resources unutilized due to technical constraints. As the flow of the water stream varies, the input velocity of turbine also varies and so does the generator speed. Hence, the challenge lies in arriving at a gear arrangement to maintain constant generator speed. In the present paper, an auxiliary gearbox with planetary gearbox is designed to maintain constant generator speed for various input turbine speed. Based on these specifications, the planetary gear and auxiliary gearbox is designed through analytical calculations. The complete system is modelled to carry out Multi Body Dynamic simulation to verify kinematic analysis (analytical method) and FEA to analyse stresses developed in planetary gearbox system. The auxiliary unit and planetary gearbox is fabricated and tested for no load condition to maintain the constant generator speed. The test results are found to be close agreement when validated with the analytical method and multi body dynamic simulation results. Hence the designed system is practically feasible for maintaining constant generator speed for fluctuation turbine speed.

1. Introduction

Hydro power is a clean, renewable and non-polluting energy source utilized by more than 150 countries around the world. India produces about 26% of its electricity from Hydro Power Plants. Hydro power plants can be of large and small in size. Usually power plants up to 100 kW is called as Micro Hydro Power plant [1]. India has round 6474 potential small hydro sites out of which 1251 sites are operational. India generates 21134 MW of power from small hydro power plant, which accounts for only 2% of total potential for renewable power generation. In India 0.8% of the villages are still not electrified [2]. One of the emerging solutions for village electrification is Micro Hydro Power Plant (MHPP). MHPP are located near small rivers, open canals and streams. MHPP requires little or no reservoir and is generally built on run way of water streams with little arrangement to direct water towards the turbine. Hence it has a very little impact on local ecosystem. In MHPP hydro governors and reservoirs are avoided based on power generation capacity to reduce the overall size and cost. Hence MHPP requires good control system to keep the constant generator speed for fluctuating flow of water in the stream. One of the means to maintain constant generator speed is by modifying the transmission system.
The transmission system used in MHPP is generally a speed multiplier, since the turbine speed is less than the generator speed. Various types of transmission systems in MHPP are belt drive, chain drive, spur/helical drive, and planetary gear drive. A planetary chain transmission is developed for MHPP to increase efficiency. Since the system is complex, it is developed for lower transmission ratios. The planetary chain drive is tested for Turgo turbine with a speed ratio of 1:4.8. Such a system gives an efficiency of about 67% for speed ranges of 150-500 rpm. This type of drive is used for lower transmission ratios only. Spur and helical gear drives are used for lower speed ratios. For higher speed ratios, multiple stages are required, which will increase overall dimension and cost. In order to have good efficiency, higher speed ratios, and compact size, planetary gearboxes are used for MHPP. In planetary gear drives, the turbine shaft is connected to the carrier, and the ring gear is fixed. The output is drawn from the sun gear. The planetary gearbox works as a speed multiplier but fails to control the generator speed. Hence, a conceptual design of a planetary gearbox system is developed by fixing an auxiliary unit to the ring gear. The feasibility study of this conceptual design concludes that planetary gearbox systems can be used to maintain constant speed. The present paper focuses on multi-body dynamic simulation, FEA, and testing of planetary gearbox systems for governing constant generator speed for variable turbine speeds.

2. Design Requirements

The conceptual design includes planetary gearboxes placed between the turbine and generator for speed amplification. The turbine shaft is connected to the carrier of the gearbox, and the generator shaft is connected to the sun gear. The auxiliary gearbox unit is attached to the ring gear of the planetary gearbox as shown in Fig. 1.

The specifications arrived from field surveys for designing planetary gearbox systems for MHPP are shown in Table 1. Based on the specifications from the survey, the planetary gearbox and auxiliary units are analytically designed.

| Sl. No | Particulars                          | Specifications       |
|--------|-------------------------------------|----------------------|
| 1      | Turbine speed variation             | 10%                  |
| 2      | Generator specification             | 1500rpm, 50Hz        |
| 3      | MHPP power generation capacity      | 5kW                  |

3. Simulations of Planetary Gearbox System

The designed planetary gearbox system for maintaining constant generator speed is shown in Fig. 2. The developed model is simulated for Multi Body Dynamic simulation and flexible body simulation. The Multi Body Dynamic simulation is performed for kinematic analysis to verify the analytical design and flexible body analysis (FEA) for determining the stresses developed in the gearbox.

3.1. Multi Body Dynamic Simulations

The developed CAD model is imported to Multi Body Dynamic Simulation environment. The required material properties and boundary conditions are assigned to the components of the imported model and simulated for three conditions based on the working condition of MHPP. When the flow of water (turbine speed) is equal to the operation speed, the auxiliary unit will be in fixed condition. Here the gearbox system works as a conventional speed amplifier. This condition is considered as the operating condition. During simulation, the input shaft to the carrier is provided with turbine speed. The auxiliary unit is fixed by fixing the ring gear. From simulation result
shown in Fig. 3, it is observed that the planetary gearbox system acts as convention gearbox by amplifying speed by 9.9 times. The generalized equation is arrived given by Eqn.1

\[ \text{outputspeed} = \text{inputspeed} \times 9.9 \quad (1) \]

Second condition, where the turbine speed is more than the operating speed, the auxiliary unit will start to rotate the ring gear and planet gear opposite to each other. This condition leads to speed reduction in the generator shaft (sun gear), is considered as braking condition. During this process the auxiliary unit acts as generator and stores power. While carrying out simulation, the input shaft to the carriage is provided with minimum turbine speed which is less 10% less than operational speed. The auxiliary unit is run at -31.83 rad/s based on analytical design calculations. Negative sign indicates rotation in opposite direction. Simulation output is plotted in Fig. 4, which shows that output speed was equal to generator speed. The generalized equation arrived from simulation result is given by Eqn.2

\[ \text{outputspeed} = \langle \text{turbinespeed} \times 9.9 \rangle - \langle \frac{\text{auxiliaryunitspeed}}{2.03} \rangle \quad (2) \]

In third condition, turbine speed is considered less than the operation speed. The stored energy during braking condition is utilized by the auxiliary motor to run auxiliary unit such that ring gear and the planet gear run in the same direction. When the planetary gear and ring gear both run in same direction, extra speed is added to the output (generator shaft) to maintain constant speed. Hence this condition is considered as speed amplification condition.
During simulation the input shaft to the carriage is provided with maximum of turbine speed which is 10% more than operating speed. The auxiliary unit is run at 31.83 rad/s based on analytical design calculations. Simulation output is plotted in Fig. 5, which shows that output speed was equal to generator speed. The generalized equation is arrived from simulation result is given by Eqn. 3

\[
\text{output speed} = \langle \text{turbine speed } \times 9.9 \rangle + \left\langle \frac{\text{auxiliary units speed}}{2.03} \right\rangle
\]  (3)

3.2. Finite Element Analysis

The results of multi body dynamic simulations are in close agreement with the designed planetary gearbox system. During working of the planetary gearbox, both ring gear and planet gears are in motion, may have higher stresses for the designed load. Hence Finite element Analysis is carried out to analyse the induced stresses. 2D static analysis is carried out instead of 3D Dynamic analysis due to high computation time and memory. Mesh convergence study is carried out to arrive at proper element size. Structured mesh is developed in HYPERMESH and imported in FEA simulation software for simulation and post processing. 4-noded linear quad element with 3 degrees of freedom is used to develop FE model. Table 1, shows the material property assigned during simulation.

The shaft of each gear is modelled as a rigid node to reduce the computation time. The rigid nodes are created at the centre of the each gear and kinematically coupled to provide the boundary condition for the respective gears. Gear contact property is defined between the meshing gears with coefficient of friction as 0.3. Finally, the required boundary condition and loads are applied on the gears for simulating all three conditions.

During FE simulation for operating condition 1280 N-mm and 12720 N-mm are applied.
Table 2. Specification for designing planetary gearbox system for MHPP

| Sl. No | Material Properties | Particulars       |
|--------|---------------------|-------------------|
| 1      | Material Density    | $7.85 \times 10^{-9}$ tonne/mm$^3$ |
| 2      | Elastic Modulus     | $210 \times 10^3$ MPa   |
| 3      | Poisson's ratio     | 0.3               |

on sun gear and carriage respectively. Maximum stress of 307 MPa is observed on all planet gears. Fig. 6 and 7 shows the stress distribution in planetary gear drive for operating condition respectively. 1420 N-mm, -12720 N-mm and 1414 N-mm are applied on sun gear, ring gear and carrier to simulate braking condition. Maximum stress of 475 MPa is observed on planetary gear. Similarly 1160 N-mm, 10410 N-mm and 11570 N-mm are applied on sun gear, ring gear and carrier to simulate speed amplification condition. During simulation maximum stress of 430 MPa is observed on the planetary gear. From the simulation results it is be observed that the maximum stress is induced in braking condition, which is less than the allowable stress of 510 MPa. These simulation results show that the developed system is safe for fabricating and testing.

**Figure 6.** FEA of planetary gearbox

**Figure 7.** Stress distribution in gears

4. Experimentation

The results from multi body dynamic simulation and FE simulation indicates that the planetary gearbox can be used for maintaining constant generator speed in MHPP. The planetary gearbox system is fabricated and tested for no load condition. The Fig. 8. shows the experimental setup of planetary gearbox system.

The experimental setup is developed to replicate the working conditions. It consists of two variable frequency drives (VFD), planetary gearbox, auxiliary gearbox, dynamometer, electromagnetic brakes and connecting shafts. A 37kW capacity VFD is connected to carrier, which acts as hydro turbine. A 3.7kW capacity VFD is connected to the auxiliary unit to compensate speed during speed amplification and braking condition. Testing are carried out for all the three operating condition with no load at the output shaft. Experiment results found are satisfying the requirement of constant speed. Table 3. shows the testing result for all the three operating conditions. It is observed that the experimental results and analytical results are in close agreement with insignificant error. From the experimental result the compensating speed for auxiliary unit is arrived for fluctuating turbine speed. This compensating speed will be used for automatic control, which is the future scope of work.
5. Conclusion
The planetary gearbox system for maintaining constant generator speed is designed using analytical method for 1:9.9 speed ratio and validated using multi body dynamic simulation. Finite element analysis is carried out for all the three operating condition to analyse induced stresses. From simulation it is observed that breaking condition is the worst condition which has maximum stress of 475 MPa in all planet gears. The maximum stresses developed are less than the allowable stress. Later the system is fabricated and tested for no load condition. The testing results were in close agreement with analytical and multi body dynamic simulation result having insignificant error. Hence the design is practically feasible for maintaining constant speed in MHPP.

6. References
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