Design of an Automated Dam Shutter Control System: Case Study

Ignatio Madanhire and Munyaradzi Madaka
Department of Mechanical Engineering
University of Zimbabwe
Mt Pleasant, Harare, Zimbabwe
imadanhire@eng.uz.ac.zw

Charles Mbohwa
Department of Quality Management and Operations Management
University of Johannesburg
Auckland Park 2006, South Africa
cmbohwa@uj.ac.za

Abstract

This work study was done to come up with an optimised design of an automated dam shutter system to monitor the level of water, pressure and flow of water at the case study dam site. The failure to monitor the opening and closing of dam gates has resulted in insufficient supply of water, water wastages and a lot of human errors associated with manual gate control mechanism. The designed control system was intended to reduce these shortcomings. The design incorporated servo- motors, mechanical hoist system and the electronic control to monitor the flow of water according to water level at any given time.

1. Introduction

Mostly water outlets for dams are manually operated, resulting in failure to effectively supply water from the dams for the purpose of irrigation, to control floods, as well as improve industrial uses such as hydro-electric power generation resulting in unwanted water wastages (Muhammad et al 2012). The importance of water in our daily life cannot be over emphasised, hence its distribution and usage water is of utmost consideration. The initiative to introduce automation and monitoring control system to manage dam water enables reliability and the same system helps monitor vibrations of the dam structure to ensure safety and detects early wall collapse warning collapse signs to avert any disaster. It is also robust for use in remote, confined and dangerous locations (Anon n.d.). Such installations will prove to be much economical in the long run although the initial cost of implementing the system could be high.

2. Dam outlet works

2.1 Mechanical dam outlet works

Basically a dam is a physical barrier constructed across flowing water course; to control, direct, hold or raise level of water. Non-corrosive materials such as concrete, wood and steel are used in its construction(Muhammad et al. 2012). There are many ways of preserving water through providing dams with spillway or gates systems to safely pass a broad range of flows over or through the dam(Bhardwaj et al. 2014). The configuration of gates used to block or pass a broad range of flow of water is dependent on the operation, application, purpose and location. The most common type is the outlet head regulator gates.

These gates move within a vertical groove incised between two piers. The vertical lift gates are used for controlling flow over the crest of a hydraulic structure and usually fitted with wheels (Diversion n.d.). Low head gates installed on the crest of dams, barrages or weirs which fall at a predetermined water level. Generally these are fully closed or fully open, that is, fallen flat, which are shown to operate using a hoist. However, in some weirs, falling shutters have been provided earlier that are manually operated. In many of the older weir installations constructed during the pre-independence period were equipped with falling shutters, some of which are still in use today(Diversion n.d.). Commonly used hoists for gate operation according to are the mechanical arrangements such as hoists, in form of the rope-drum type like winches, chain-pulley block, monorail crane, gantry crane, etc. Some are the screw operated type, while there is also the chain and sprocket type (Diversion n.d.).

2.2 Control systems

A control system can be considered to be an arrangement of physical components connected in such a manner as to command, direct, or regulate itself or another system. It consists of subsystems and processes assembled for the purpose of obtaining a desired output and performance (Anon n.d.). It can also be used to compensate human disabilities and in remote and dangerous areas. It can compensate the disturbances of the system.

2.2.1 Closed loop feedback system

The closed loop system has information feedback which is compared with the desired output and corrects the output automatically if there are deviations. The closed-loop control system has got a link feedback from the output to the input of the system. To obtain more accurate control, the controlled signal is fed back and compared with the desired output, and an actuating signal proportional to the difference of the input and output must be sent through the system to correct the error. A closed-loop control system is therefore an automatic control system which does not require manual intervention to correct for output deviations.

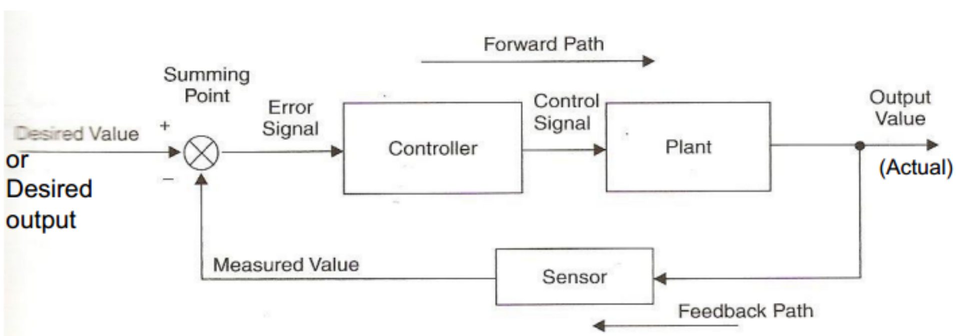


Figure 1. Closed loop system.

The closed-loop system compensates for disturbances by measuring the output response, feeding that measurement back through a feedback path, and comparing that response to the input at the summing.

2.2.2 Servomechanism

This is an automatic device that uses error-sensing feedback to correct the performance of a mechanism. It is unique among control systems in that it controls a parameter by commanding the time-based derivative of that parameter with typical applications widely found in automatic machine tools, satellite-tracking antennas, remote control airplanes, automatic navigation systems on boats and planes, and antiaircraft-gun control systems (Pen & Ball n.d.). Servo control is also referred to as motion control and it is mainly used in industrial processes to move a specific load in a controlled fashion. It uses different actuation technologies such as pneumatic, hydraulic, or electromechanical. Electromechanical systems are typically used in high precision, low to medium power, and high-speed applications and these systems are flexible, efficient, and cost-effective. Motors are the actuators used in electromechanical systems and are used to provide either rotary or linear motion.

2.2.3 Programmable logic controllers - PLCs
A controller is the "brains" of a servo system, and it is also responsible for generating the motion paths and for reacting to changes in the outside environment; as it sends a signal to the drive; the drive provides power to the motor; and the feedback from the motor is sent back to the controller and drive. Feedback from the load is also routed to the controller. The controller analyses the feedback signal and sends a new signal to the amplifier to correct errors. The controller is considered to be the intelligent part of the servo, closing the velocity position loops while the amplifier closes the current loop (Pen & Ball n.d.). Following from the above a PLC is a digitally operating electronic apparatus which uses a programming memory for the internal storage of instructions for implementing specific functions such as logic, sequencing, timing, counting and arithmetic to control through digital or analogue modules, various types of machines or process (Anon n.d.). Thus PLCs have a processor and memory to allow for commands to be programmed, saved and executed. It also has a rack and I/O slots so that I/O modules may be added to the PLC as needed. The modules may add such features as high-speed counters, real-time clocks, or servo control capabilities(Pen & Ball n.d.).

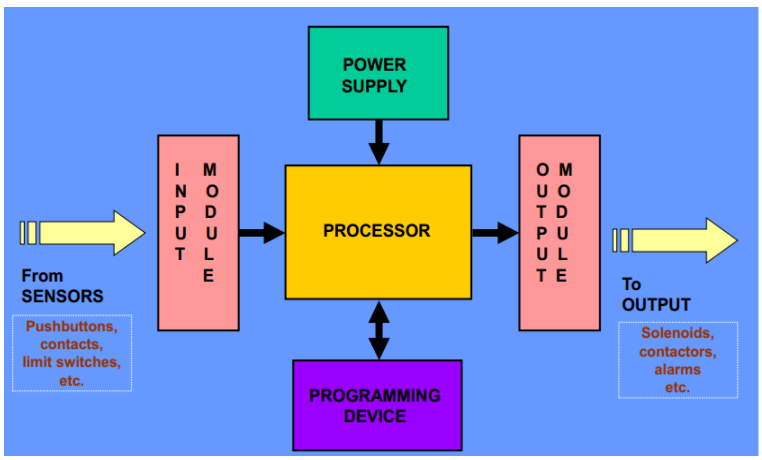


Figure 2. Major components of the PLCs

As shown in Figure 2 the processor is the central component as it provides intelligence to command and govern the activities of the entire PLC systems (Anon n.d.). PLC components allow for easier and faster changes, and its reliability will ensure operations for years before failure even in severely harsh environments.

2.2.4 Motion Controllers.
Motion controllers are built specifically for the control of motion. A motion controller, in general, is more user friendly than PLC because it has additional features and hence more expensive (Pen & Ball n.d.). Typically the servo drive is the link between the controller and motor. Also referred to as servo amplifiers, their job is to translate the low energy reference signals from the controller into high energy power signals to the motor. The motor would then convert the current and voltage that comes from the drive into mechanical motion. Most motors are rotary types but linear motors are also available. There are many types of motors that can be used in servo applications (Pen & Ball n.d.). A DC servo motor generally includes a built-in gearbox for speed reduction and is capable of delivering high torques directly. The output shaft of a servo motor does not rotate freely as do the shafts of DC motors because of the gearbox and feedback devices attached.

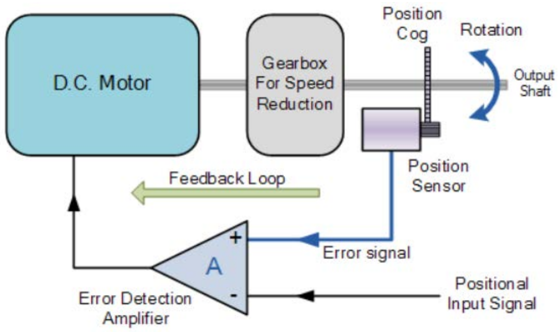


Figure 3. DC servo motor

A servo motor consists of several devices in one package, the motor, gearbox, feedback device and error correction for controlling position, direction or speed. They are widely used in robotics and small models as they are easily controlled using just three wires, Power, Ground and Signal Control (Storr, 1999). The motor starter can be used to adjust the speed of the gate if it's moving too fast, timers are put on the starter relays. The limit switches prevents the gate from continuous travel once it reaches the limit of moving either up or down. The limit switch is required to prevent damage to the actuator or the gate caused by continuing to force the gate open or closed when the limit of travel has been reached (Training 2000).

3. Case study

The case study dam was commissioned in 1970 and is located in a rural setting, it has a water holding capacity of 10.6 mega cubic metres (2 800 million gallons). This dam supplies water to the surrounding villagers for domestic purposes, a nearby irrigation scheme and a gold mine in its vicinity. The dam consisted of a control tower built at the deepest depth of the dam, it has four penstocks (inlets) that takes water to the irrigation schemes and the nearby mine. The mechanism used to control the flow of water is manual. Thus system has failed to sustain the community and the mine sufficiently with water as the water level varies.

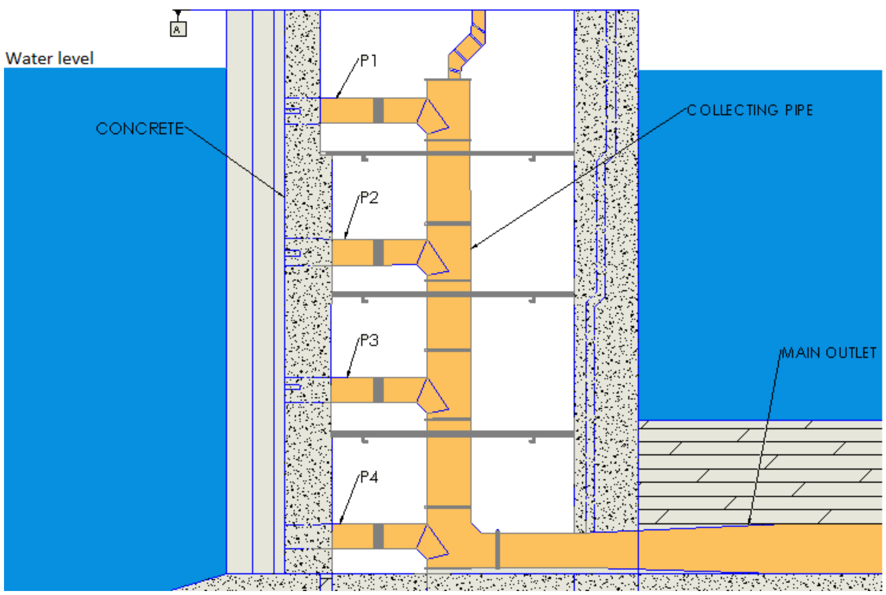


Figure 4. Penstock tower layout (Madaka 2016)

Monitoring the level of water in the case of floods might be impossible in a very short period of time with the manual system.

4. Automated dam shutter gate design

The generated design concepts were evaluated for suitability by considering parameters such as functionality, efficiency, quality, reliability and cost before settling for screw stem design mechanism.

4.1 Screw stem design mechanism

The sluice gate consists of four rollers that enable the gate to move up and down in its guides according to the dam water level. The gate is attached to a long threaded shaft and it is a rising stem thus the threaded shaft does not rotate but rather moves up and down as the lifting nut attached to the gate frame rotates. The lifting nut is driven by the chain sprockets assembly which is also driven by the reduction gearbox coupled to the motor as shown in the schematic diagram in Figure 5 below.

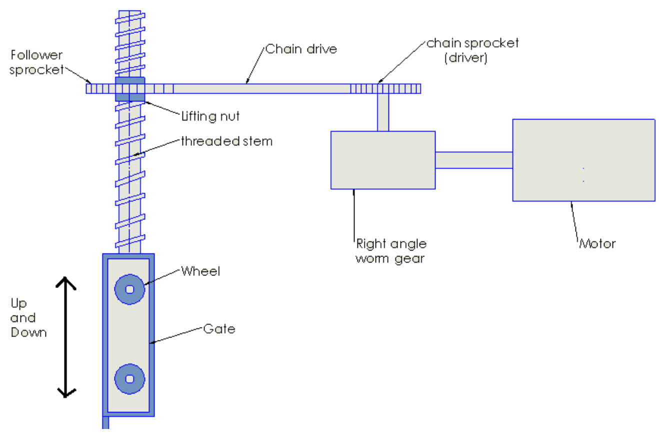


Figure 5.Chosen design concept - schematic diagram

The threaded stem moves the gate up and down as it is the rising stem (which is non-rotational) while the lifting nut rotates (Figure 6). The lifting nut is seated on top of the roller thrust bearing and the thrust washer as shown by the sectioned view below in Figure 6. The motor and the gearbox act as the actuators of the system. The motor is coupled to the speed reduction gearbox (right angle worm gear) which drives the chain drives allowing rotation of the lifting nut. The rotation of the lifting nut allows the stem to move up and down depending on the direction of which the motor is rotating.

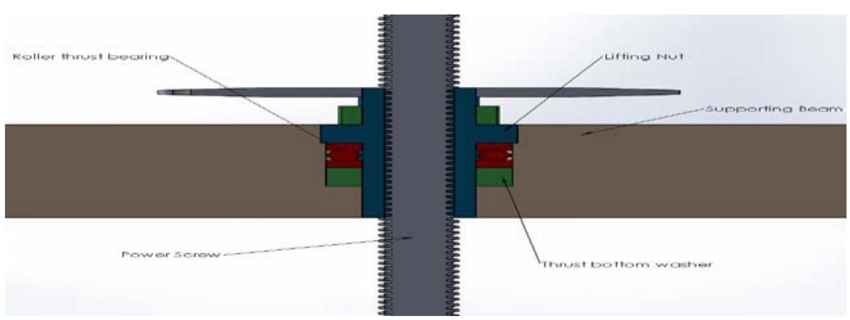


Figure 6. Power screw mechanism (lifting mechanism)

The screw stem hoist would provides the positive force both for up and downward movements of the gate (Sehgal & Ala, 1987). It also ensures complete seal of the gate when closed such that no water leakage is allowed. Chain drives gives a positive drive as no slip takes place during chain drive, hence perfect velocity ratio is obtained. It gives a high transmission efficiency of up to 98 percent and it transmits more power than belts**.**

4.2 Major components

The detailed design consist of the following components flat vertical gate, power screw, chain drives, shafts and its keys; as well as sizing of the servo-motor and the reduction gear box (Figure 7).

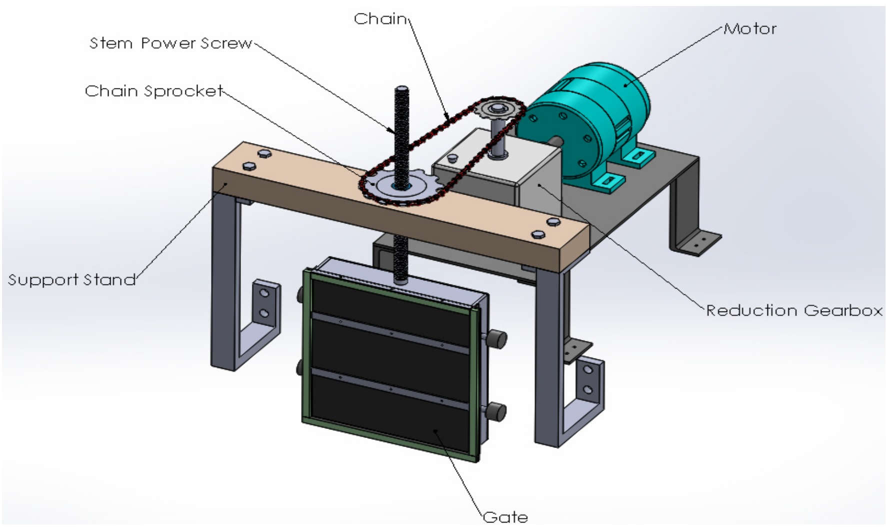


Figure 7. Major components solid works (Madaka 2016)

4.2.1 Design of a flat vertical sluice gate

The gate consists of four wheels that will enable the gate to move vertically up and down in the concrete guides. The material for the wheels is Cast steel as specified by IS NO 1030, 1998. The front face is coated thin layer of rubber (PVC) to prevent direct corrosion (pitting) of the steel sheet of the gate. It also consist of rubber (PVC) seal that prevent water leakages, the resilient rubber seal shall be mounted on the slide and shall be held securely in place with a retainer bar bolted to the side. The gate is reinforced with the high water resistance stainless steel to prevent rusting. The wheel axles are made of chrome nickel steel which is corrosion resistance steel according to IS 2004, 1994.

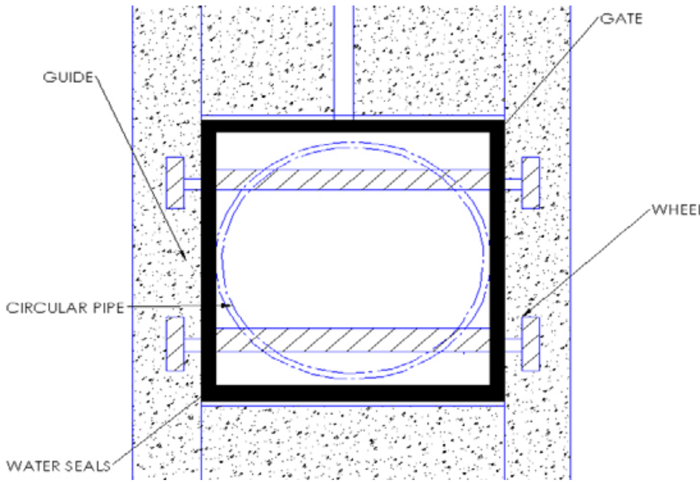


Figure 8. Gate closing the penstock diameter

Force acting on the vertical gate:

Figure gives a view of how the gate is laid out in the tower. The design considers the force acting on the gate closing the fourth penstock (the bottom penstock where greater pressure is exerted).

Considering a vertical area submerged below the surface of the water as shown above.

Total force (F_t) = 145 413.63N

The design specification of the gate are that, it should not exceed 60kgs

When the mass of the gate is 60 kg then its weight is given by:

Weight of the gate = **mg = (60 x 9.81) = 588.6 N**

Force due to friction on the wheel and the concrete guide F =μN ,

Where $\mu = 0.33$ friction coefficient between the steel wheels and the concrete and **N** is the normal force action perpendicular to the gate face.

F = 0.33 x145413.63 = **47986.29N** (in this case the frictional force due to seals is neglected).

4.2.2 Design of the power screw.

The length of the stem for which the threads maybe provided shall be the sum of: total lift of the gate, length of the nut in contact with the stem, and extra allowance of 300mm. The stem should be able to provide power transmission in either direction. The square threads are chosen over acme and buttress threads. Below it shows the square threads profile.

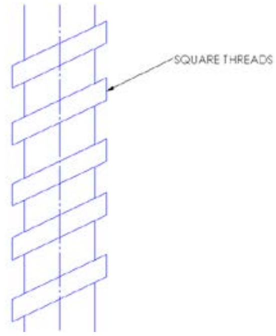


Figure 9. Square threaded power screw stem

4.2.2.1 Considering a case of raising the gate

Since the frictional resistance acting in the opposite direction to the motion of screw is neglected.

Total load acting on the screw W = 588.6 N

Total torque required to overcome friction $T = T_1 + T_2 = 2114.8 + 2648.7$ = **4 763.5Nmm**

4.2.2.2 In the case of lowering the gate

The frictional resistance will act upwards when lowering the gate but in this case it is assumed to zero

Total load acting on the screw $W =$ 588.6N

Total torque required to overcome friction $T = T_1 + T_2 =$ **3249.84 Nmm**

4.2.2.3 Efficiency of the Square threads.

Since it is assumed that there is no frictional resistance between the screw and the nut, the angle of friction becomes zero. The efficiency of the square threads becomes;

Efficiency of the square threads is 0.354 or 35%

4.2.2.4 Number of threads and height of the nut

The material used on the lifting nut is **Cast iron or bronze** while on the screw is **Steel.** From Tables on hoisting Screw the bearing pressure is **4.2N/mm^2** and t **= 4mm**

Length of the stem is the sum of 600mm required to raise and lower the gate and 40 mm in contact with the stem and the extra allowance of 300 mm as per specification.

Total stem length is 940mm.

4.2.2.5 Stresses in the screw stem

Maximum compressive stress in the screw is given as = $\mathbf{0.39 N/mm^2}$

4.2.2.6 Power required to drive the lifting nut.

$Power = 4.7635 \times \frac{2\pi \times \frac{6000}{8}}{60}$ = **374.12 W or 0.374 kW**

4.3 Sizing of the electric motor and gearbox

4.3.1 Selection of electric motor

The motor should be able to transmit the required power and torque by the lifting nut. It should also be able to overcome all the frictional between the gate and the gate guides, forces due to weight of the gate and internal friction in the reduction gearbox. The motor should be able to rotate in both directions to enable the movement of the screw up and down, a medium starting torque is required. It should be a 3 phase ac motor as per IS325 and insulated according to class B of IS1271. Parameters to be considered on the selection of the motor:

Power of half horse power (0.5hp or 0.37kw)
Torque of 4.763kNm
Application of uniform load, shock and vibration
Running hours per day and suitable to work under wet conditions (corrosive areas)

3-Phase AC induction motors are classified in two that is the squirrel cage and slip ring induction motor. In this case the squirrel cage type is going to be used because it has several advantages over the slip ring type. The motor torque should be always higher than the load torque for the load to be accelerated to the rated power. The motor selected in the catalogue is the Squirrel cage induction motor which uses Ac current in 3 phase with 0.5 Horse power at the speed of 1750 rpm.

Table 1. Specifications of the electric motor.

Ratings	0.37KW (0.5hp) at 1750 rpm 50hz 3ph
Power factor	0.74
Voltage	230V or 400V
Full load current	1.90A at 230V ,1.11A at 400V
Efficiency	65%
Physical properties	Weight 6kg 132mm wide x 255mm long x 188mm high

4.3.2 Selection of the gearbox.

The gearbox should be able to produce the required target output speed or output torque (5kNm). Parameters considered in selection of the reduction gearbox:

Input speed 1750 rpm
Target output speed 30 rpm (at gear ratio)
Service factor
Orientation
The gearbox should be designed for 15% more than the torque of the screw/lifting nut

Since the gearbox will be operating after a period of time (not 24 hours) and driving a moderate load the service factor of 1.25 is considered from Tables. Service factor is multiplied by (K) = 1 since it is driven by the electric motor or hydraulic motor and the class of service for this gear is 2. For the target output speed of 30 rpm the 60:1 gear ratio is selected from the appendix 3 to give the output speed of 29 rpm. The orientation of the gearbox should be right-angle worm gearbox. The efficiency of a gear reducer 60 of size 718-15 is 0.90 shown in the Tables for the specifications are shown below:

Table 2.Gear reducer specifications

Type	Right angle worm gear

Output speed	29 rpm
Input speed	1750rpm
Gear reducer	60:1
Size	718-15
Efficiency	0.90

.

4.4 Bearing Selection

The speed of the selected bearing would be a very low speed of 15 rpm thus it has less speed to that of the speed specified (high speeds). The load on the bearing is moderate compared to heavy loads. This system will be used for a short periods and its breakdown would not have serious consequence (Khumi & Gupta, 2005). Material to be used should be according to IS NO 305:1998 which is phosphor bronze, self-lubricating and of high strength brass castings. Therefore the roller contact thrust bearing was selected (roller thrust ball bearing) size 51212 with a bore of 60mm and 95mm outside diameter. The capacity of the roller thrust bearing is 68KN with the reliability of 90%. The total load on the bearing is 600N at a speed of 14.5 rpm that give the life of the bearing in hours or in revolution.

The life of the bearing is $1456622.112652 \times 10^6\ revs\ or\ 1674278290.404765\ hours$ according to the Solidworks15 bearing calculator.

4.5 Material selection for the support frame

The frame should be able to support all the weight exerted by the gate and the stem all in total being 600N.The material should be water resistance and resistance to corrosion since it will be working under wet conditions. It should be coated or painted to reduce corrosion and pitting. The legs should be able to withstand the load of the gate and that of the top support beam. **Stainless steel** is used on the support since it can be used in a corrosive environment, high strength to mass and no rusting which mean no paint is necessary. It has a wet abrasion resistance and it can also prevent catalytic reaction due to contamination (no contamination).

4.6 Design of chain drives

The following data is given:

Rated power = 0.5 hp (0.37kW) $N_1 = 29\ rpm$ $, N_2 = 14.5\ rpm$

Selection of the number of tooth on the smaller sprocket, T_1.The number of teeth on the smaller sprocket plays an important role in deciding the performance of a chain drive. A small number of teeth tends to make the drive noisy. A large number of teeth makes chain pitch smaller which is favourable for keeping the drive silent and reducing shock, centrifugal force as well as the frictional force (Khumi & Gupta, 2005).

Hence from Tables, the number of teeth on smaller sprocket is 27 using **roller chain**. $\mathbf{T_1}$ **= 27**

The number of teeth on the larger sprocket, $T_2 = V.R \times T_1$ = 2 x 27

$$\mathbf{T_2 = 54}$$

Table 3. List of chain specification requirements

Chain type	08B roller chain
Chain length × 1 strands	1.41m
Pitch circle diameters	

Gearbox (pinoin) sprocket (d_1)	109.4 mm
Stem (follower) sprocket (d_2)	218.4 mm

4.7 Design of shafts.

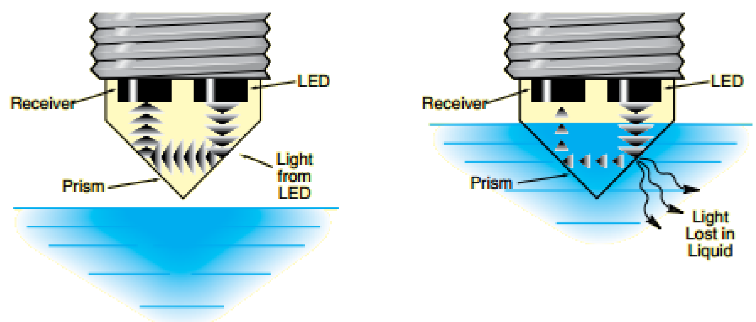
The shaft is the transmission type that transmits power from the electric motor to the reduction gear box subjected to twisting .**Carbon steel / alloy steel** can be used in this case. The carbon steel has good mechanical properties 40 C 8 with the ultimate tensile strength of 560 – 670 Mpa and yield strength of 320 MPa . It has high strength, high wear resistance, good machinability and good heat treatment properties. The power transmitted is 0.374Kw at the speed of 1750 rpm. The ultimate shear stress of 360MPa with a safety factor of 8.

Table 4. Design parameters of the muff

Rigid coupling type	Sleeve or muff coupling
Length (L)	140mm
Diameter of muff (D)	93mm
Diameter of the shaft (d)	40mm
Length of the key	70mm

4.8 Electronic control system design

The control system would get the mechanical system above automated using water level sensors to detect the presence or un-presence of water at required predetermined levels. The sensors to be selected should be a point-level sensors that can detect the level of water above or below a set point as shown in Figure 10. The sensor should be capable of being immersed in water, thus for robustness the optic sensors are chosen. An optical sensor is used because there are reliable and dependently since there are not affected by vapour and can be easily removed and cleaned.



(a) (b)

Figure 10. (a) Liquid below the sensing prism (b) Liquid immersing the sensing prism.

The contact optical sensor (LV171 wet probe) contains an infrared LED and the light receiver. The continuous light produced from the LED is focused into a tip of the optic sensor which forms the prism as shown above. In the absence ofthe liquid, the continuous light from the infrared LED is reflected backward to the receiver within the prism. When the sensor prism is immersed in a liquid, the light is refracted out from the prism into the liquid and very little light or none reaches the receiver. All the sensing changes that happens with the prism is feedback to the receiver which in turn actuates the electronic switching. When the sensors immersed in water in this case thus the continuous light from the Infrared LED is refracted out from the prism to the water, no light is reflected back to the receiver. When the

tip of the prism is no longer sensing water (contact of water) the light is reflected back to the receiver. When the water level is rising it does the opposite.
The sensors would be arranged in such a way that there at midpoint of the penstock diameter to accommodate the time interval of opening each gate which is 160 seconds to fully open thus (continuous supply of water is required). There are four sensors that senses water level with each penstock having one sensor as per Figure 4 showing the penstock levels. The sequence of control system operations will be as follows:

- ✓ ***when the dam is draining***
  - When the water level is at the marked point above penstock 1 then the gate 1 is open
  - When water level passes the sensor 1, gate 2 opens while gate 1 closes
  - When water level passes the sensor 2, gate 3 opens while gate 2 closes

- ✓ ***when water level is rising in the dam***
  - When water level rise it passes sensor 3, then when sensor 2 sense water level gate 2 opens while gate 3 closes.
  - Water level passes sensor 2, then when sensor 1 sense water level gate 1 opens while gate 2 closes.

5. Recommendations.

Power screw mechanism can be further designed to improve the efficiency of the system of the power screw which is 35% as there is room to increase this to 81%. The material selection is also to be looked at for every component and change can be made depending on the rate of wearing of material due to rust, loads and frictional resistances.
The installation of the electric motor should allow easy of access to inspection and maintenance. Also adequate protection should be considered since the environment will be wet and dust at most of the time. The motor should be kept clean from the dust, debris and oil. It should also be lubricated at regular intervals and checked for proper alignment of the shafts. All the internal parts of the motor should be painted to avoid corrosion and the windings shall be impregnated to render then non hydroscopic. The thermostat should be used for temperature protection.

On the reduction gear box, the shaft connection and alignment should be checked in four places around the shaft at 90°. The correct gap must also be maintained and the gear drive must be level and secure before alignment of shafting begins. A sufficient amount of clean lubricant is required for long service life (Cleveland, 1999). It should be checked for leaks on the seals and lose bolts. Tooth profile should be checked periodically to ensure maximum transmission. The gear unit should be enclosed with an oil bath lubricated type and it should be able to move the stem screw up and down under different operating pressure differential. The lifting nut should be properly aligned to the stem rod prevent damage of the threads. The used on the design is bronze or cast iron. Selection of another material would be necessary if the lifting nut wore out fast. In order to achieve maximum transmission it should be changed regularly and lubrication should be done each time maintenance is done. The sluice gate does not need periodic maintenance, but checking of crack and wearing out due to corrosion and pitting. Rust may cause weak points on the gate which cause water sipping through. The steel sheet must be cleaned and painted to avoid rusting. The groove where the gate seals seat must be cleaned to make sure that there is positive thrust and complete water tight.

6. Conclusion

The study came up a design to incorporate an automated dam sluice gate control system to handle floods risks and unnecessary water wastages the outlet penstocks. The design entailed the electric motor selection rated at 1750 rpm connected to the right angle worm gear of 60:1 speed reduction. The chain drive would provide speed reduction of 2:1 to the driven sprocket that drives the lifting nut. The overall speed reduction of the system is 120:1 from the motor. The rotational speed of the lifting nut is 14.5 rpm that enable the stem to move up and down. The stem moves 8mm in one revolution of the lifting nut. Considering the safety factor of 1.3 between the rotation of the steel screw and the bronze nut. As the diameter of the penstock pipe is 400mm it takes 2.65 minutes (2minutes and 40sec) to fully open the full diameter pipe. This operation being enabled by electronic optic sensor control unit at each dam penstock water level.

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Biography

Ignatio Madanhire graduated with a PhD in Engineering Management at the University of Johannesburg, South Africa, where is also a Senior Research Associate. He is also a Senior Lecturer with the Department of Mechanical Engineering at the University of Zimbabwe. He is a professional member of Zimbabwe Institution of Engineers (ZIE) and he is also registered with Engineering Council of Zimbabwe (ECZ). He has research interests in engineering management and has published works on cleaner production in renowned journals.

Charles Mbohwa is a Professor of Sustainability Engineering and currently Vice Dean Postgraduate Studies, Research and Innovation with the University of Johannesburg, SA. He is a keen researcher with interest in logistics, supply chain management, life cycle assessment and sustainability, operations management, project management and engineering/manufacturing systems management. He is a professional member of Zimbabwe Institution of Engineers (ZIE) and a fellow of American Society of Mechanical Engineers (ASME).