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Design of an Autonomous Pumping System for the Water Supply of an Urban Dwelling

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Abstract

Since the 1980s, the city of Dakar has been facing a significant water supply deficit due to rapid population growth. To address this issue, certain communities have implemented autonomous water supply systems utilizing submerged pumps. However, these systems are plagued by a major drawback: frequent pump breakdowns. The objective of this study is to identify the causes behind these breakdowns and propose technical solutions to enhance the reliability of these systems. To achieve this goal, an analysis of the pumping systems utilized in Dakar was conducted, and user interviews were employed to gather insights into system performance. This research has enabled the development of a highly effective method for secure management during the operation of submerged pumps, which is outlined in this article.

Subject Areas

Engineering and Automation

Keywords

Dry Pumping, Regulation, Submersible Pimping, Sizing

1. Introduction

The issue of access to clean drinking water is a critical challenge for humanity as a whole, to the extent that international organizations have included it in the Millennium Development Goals (MDGs). In reality, there are millions of people worldwide who do not have direct access to water, and this phenomenon also affects Senegal. Despite all the efforts made by state authorities, the city of Dakar, facing spatial expansion and demographic pressure, is confronted with significant shortages of clean water. [1]

Since the 1980s, Dakar has experienced a significant deficit in providing water to its population. From 4% in 1984, this deficit surpassed the 30% threshold in 1991, reaching a record of 100,000 m^3/day in 1995 [2]. This situation is a result of the population's level of infrastructure but also the extremely rapid and partially uncontrolled growth of the urban area. The installation of water supply networks often lagged behind the development of certain neighborhoods. The low incomes of residents and the incomplete nature of the piped water network hinder better water distribution in the outskirts of Dakar.

Faced with this shortage of clean water, desperate populations have developed their own supply strategies. Some resort to technical means to ensure their own water supply, which is often completely separate from the public distribution network. Among these strategies, one has caught our attention, which is the water supply method using a submerged pump [3] [4] [5]. This type of installation is currently very common in certain areas of Dakar, especially in the suburbs. It utilizes a submerged pump, which is ideal for drawing water from deep sources. Having such an installation allows for water supply to one's home through a personal water reserve. The pumps used are electric and permanently submerged, making them completely silent and requiring minimal maintenance. However, these installations have a major drawback due to the frequent pump failures that often render them inoperable

As researchers and educators in this field, we have decided to investigate the root causes of these failures and propose solutions. The approach used in this research is to study an autonomous water supply system in urban areas to identify the underlying causes of the recurrent issues reported. At the end of this study, a technical solution that provides a viable resolution to this problem will be proposed.

2. Study of a Pumping Installation

The installation we have chosen to study is one that has been frequently reported to us for malfunctioning. It involves a submersible pump that fills two tanks. These tanks enable the independent water supply to the house, separate from the public water supply network.

2.1. Water Supply with Immersed Pump

This installation with a submerged pump is currently utilized in Dakar and is well-suited for extracting water from deep sources. The pumps employed are electric and remain permanently submerged, resulting in silent operation and minimal maintenance requirements. It comprises a motor that generates the necessary pumping power, a transmission system to transmit this power to the hydraulic component, and an upper section known as the "hydraulic" part, responsible for water circulation. **Figure 1** shows an installation with an immersed pump.

The system operates using a submerged pump that is controlled by a control box. This control and protection box is housed in an ABS IP54 enclosure and is

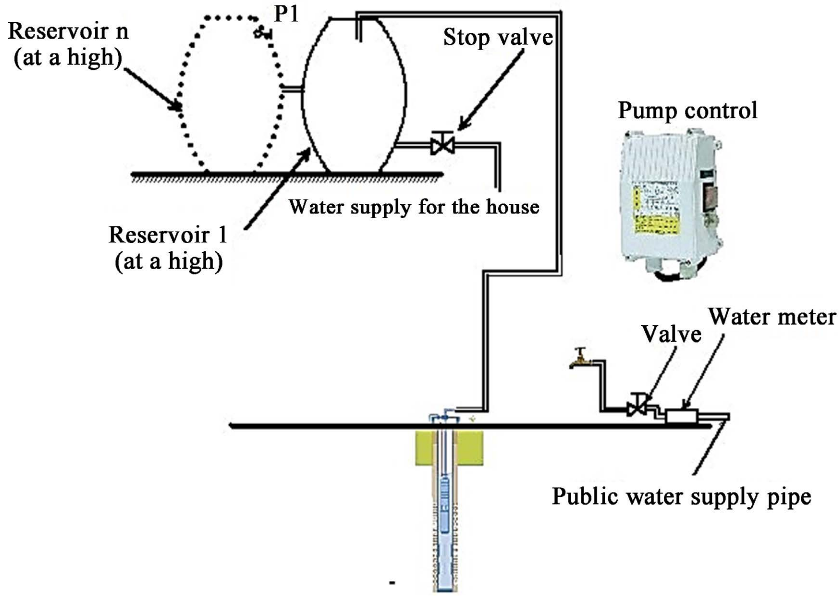

Figure 1. Schematic submerged pump.

designed to regulate a single-phase electric motor. It incorporates thermal protection to ensure that the motor shuts down in the event of overcurrent. The key features include:

- Pump control via a luminous bipolar switch;
- Motor protection through a manual reset thermal breaker;
- Standard provision of a capacitor.

For any single-phase submerged motor to function, it must be connected to a starting capacitor. A single-phase motor consists of a main winding and an auxiliary winding, with the auxiliary winding requiring connection to a capacitor. The capacitor's capacity depends on the motor power and cannot be substituted with a more or less powerful model.

The starting control box needs to be powered by 230 V. The motor of the pump should be connected to the control box using a 4-conductor cable, with the cable size chosen appropriately based on the current intensity and length of the cable between the control box and the motor. It is essential to connect the control box following the color codes depicted in the diagram. Incorrect connections can lead to motor overheating and irreparable damage. Figure 2 illustrates the connection diagram provided by the manufacturer.

The system incorporates a float/level regulator system that is installed in one of the tanks. This float acts as a level regulator and enables automatic operation of the submerged pump by turning it on and off. It is crucial to adjust this system accurately, as improper settings can result in the pump running dry and sustaining damage. Figure 3 illustrates an electric float switch.

2.2. Characteristics of the Installation

The specific installation under consideration provides water to a two-story house accommodating approximately fifteen individuals. The equipment utilized

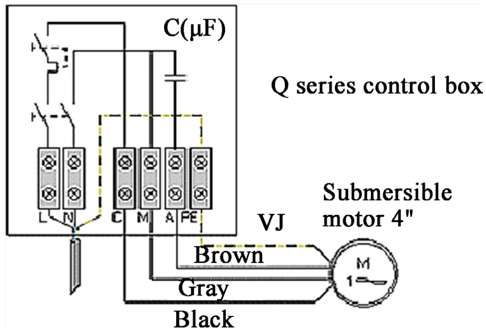

Figure 2. Control box of the pump.

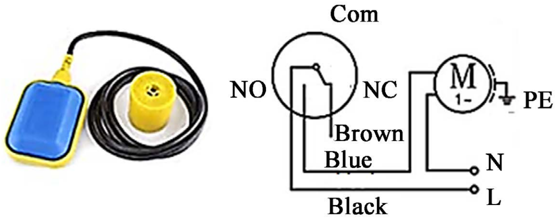

Figure 3. Float switch.

consists of a submerged pump with its control mechanism, two tanks, and connecting pipes. The well is situated outside the house, and the pump is powered by the public energy distribution network

The installed electric pump is of the SPE 100 type, designed for deep wells with a diameter of 4" (DN 100 mm). These pumps are versatile and suitable for various applications, including water jet and fountain supply, fire protection systems, general irrigation, and clean water distribution. They are supplied complete with a power cord, nylon rope, control box, and built-in check valve, ready for installation. However, it is important to adhere to local laws and regulations regarding the pump's use for garden irrigation, vegetable plots, and domestic or residential purposes.

The electric pump is delivered in sturdy cardboard packaging, accompanied by an instruction manual, and is equipped with a power cord, ready for seamless installation.

2.3. The Command

The pump control system in the installation comprises a manufacturer-provided control box and a float/level regulator system. Figure 4 displays the reproduced control diagram of the installation.

2.4. The Problem Posed

The owner of the installation contacted the expert multiple times for inspections due to recurring breakdowns. The pump would stop working several times a day. It was discovered that the pump failures were caused by thermal faults detected by the thermal relay in the control cabinet. The expert attempted to identify the reasons behind the thermal relay tripping.

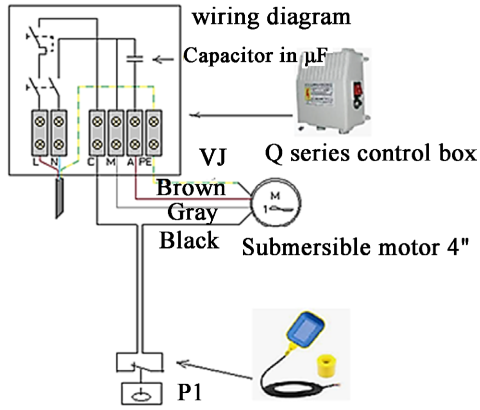

Figure 4. Control diagram of the installation.

After the system was delivered, neighboring houses started receiving water supply from the installation, leading to continuous operation of the pump and frequent depletion of the water table. As per the manufacturer's guidelines, the thermal relay should shut down the pump if it detects dry pumping to prevent permanent damage. The expert also examined the operation of the float installed in the second tank. This float is responsible for correctly stopping the pump when the water level in the tank is sufficient.

The issue with this type of installation lies in the frequent filling of the tanks and the misuse of the tanks by neighboring houses, resulting in the water level never being sufficient for the float to halt the pump. Additionally, the expert decided to assess the sizing of the pump to verify if the installed pump meets the necessary specifications.

3. Pump Sizing

The sizing method we will employ is outlined in [6] and involves several steps. The initial step entails assessing the water requirements. Subsequently, we proceed to calculate the flow rate, the tank volume, and the required hydraulic energy.

3.1. Evaluating Water Needs

The calculation of water needs for a specific household depends on its lifestyle. The capacity of the tank is determined based on the daily water requirements, which corresponds to the flow rate that the pump needs to deliver at the end of the process. A detailed calculation will be utilized to determine the daily water needs for this particular house. This calculation involves summing the base flow rates of appliances and multiplying them by the simultaneity coefficient. In the case of this installation, the full-open flow rate is equal to $Q_{0T} = 1.76$ l/s.

3.2. Power of Pump

The manometer head (H_{mt}) of a pump is given by:

$$H_{mt} = H_g + J_a + J_r + P_r \tag{1}$$

$$H_a \pm H_r \quad (2)$$

H_a: Geometric suction height in meters (m);

H_r: Geometric discharge height in meters (m);

H_g: Geometric height in meters (m);

P_r: Residual pressure at the tap in meters (m);

J_r: Total head losses at the discharge;

J_a: Total head losses at the suction.

The flow is calculated using the following formula:

$$Q_V = Q_T = Q_{0T} \cdot y \quad (3)$$

y: simultaneity coefficient;

Q_T: Total volumetric flow pumped by the pump in L/s.

The simultaneity coefficient can be calculated using the following formula:

$$y = 0.8(x-1)^{-0.5} \quad (4)$$

With x being the number of simultaneously operating appliances ($x = 10$), the simultaneity coefficient can be calculated as follows:

The pressure losses are calculated using the following formula:

$$J_l = \frac{L}{D} y \frac{V^2}{2g} \quad (5)$$

J_l: Linear pressure losses;

γ: Linear pressure loss coefficient;

V: Liquid flow speed in the conduit in m/s;

L: Length of the conduit in m;

D: Diameter of the conduit;

g: Gravitational acceleration 9.81 N/kg (or in m/s²).

The γ coefficient depends on the type of flow regime defined by the Reynolds number.

$$R_e = \frac{VD}{v} \quad (6)$$

R_e: Reynolds number;

V: Average flow velocity in m/s;

D: Diameter of the conduit in m;

v: Kinematic viscosity of the fluid in m^2/s.

With this sizing method and the data collected on the installation site, we have found the following results:

$$Q_T = 0.5 \text{ l/s soit } 1.8 \text{ m}^3/\text{h} \sim 2 \text{ m}^3/\text{h} \quad (7)$$

$$H_{mt} = 12.39 \text{ m} \quad (8)$$

According to the manufacturer's curves (**Figure 5**), we have determined that a pump with a power of 550 W or 0.55 kW is suitable for the installation. However, the pump installed by the technician has a power of 600 W, which is within the acceptable range. Therefore, the power of the installed pump is not the cause

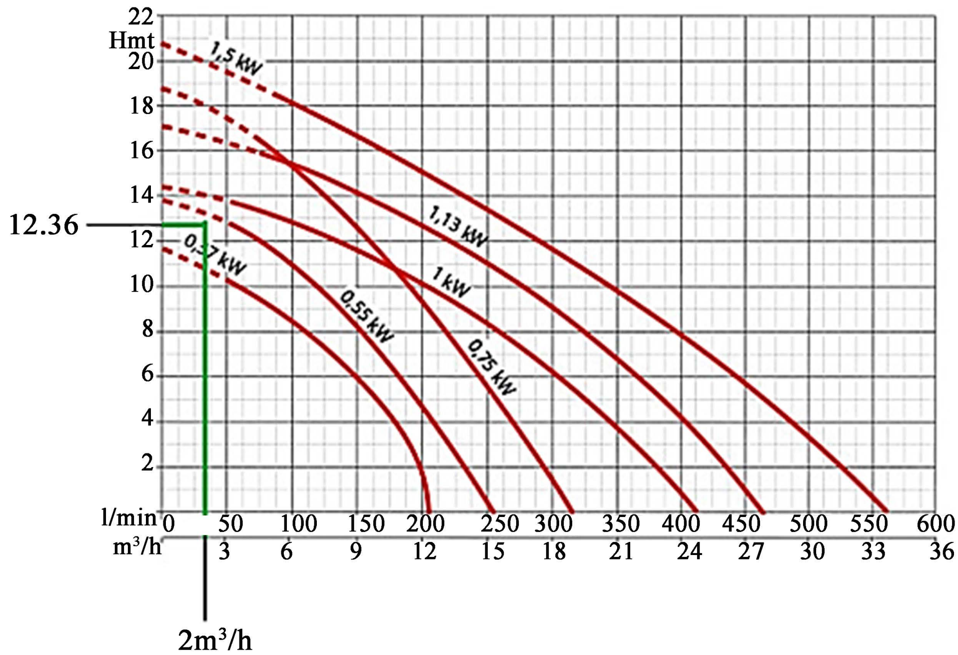

Figure 5. Pump power determination curve.

of the malfunctions that required our intervention.

4. Proposed Solution

We have proposed a solution to address the problem at hand. The proposed solution, which we have implemented, involves operating the pump intermittently. This approach is based on a comprehensive and experimentally validated model outlined in [7], which considers various factors. Of particular interest is the response of the groundwater aquifer to water pumping. Through extensive testing of the aquifer's water level in the area, we have discovered that, on average, the pump stops due to thermal issues if it runs continuously for 15 minutes without the float cutting off the power supply. This occurs when the aquifer reaches its lowest level after approximately 15 minutes of pumping.

Table 1 presents the test results that enabled us to assess the aquifer's level between January and May. Throughout this period, we recorded the following values twice a week.

- T1: Pumping duration before the pump ceases operation due to thermal issues;
- Q1: Volume of water pumped;
- T2: Duration of pump downtime before resuming pumping.

After conducting the test, we considered installing a float to detect the low level of the aquifer and stop the pump to prevent dry pumping. However, due to the limited diameter of the installed pipe, this option was not feasible. As a result, we opted for a solution based on the test results, which involves operating the pump for 10 minutes and then stopping it for 30 minutes. The proposed algorithm for managing the operation of the system is shown below (see **Figure 6**):

Table 1. Test results for groundwater level.

	January	February	March	April	May
T1 (mn)	16	16	16	15	15
Q1 (liter)	80	80	80	78	77
T2 (mn)	20	20	20	23	23

Note: The values presented in the table are average values.

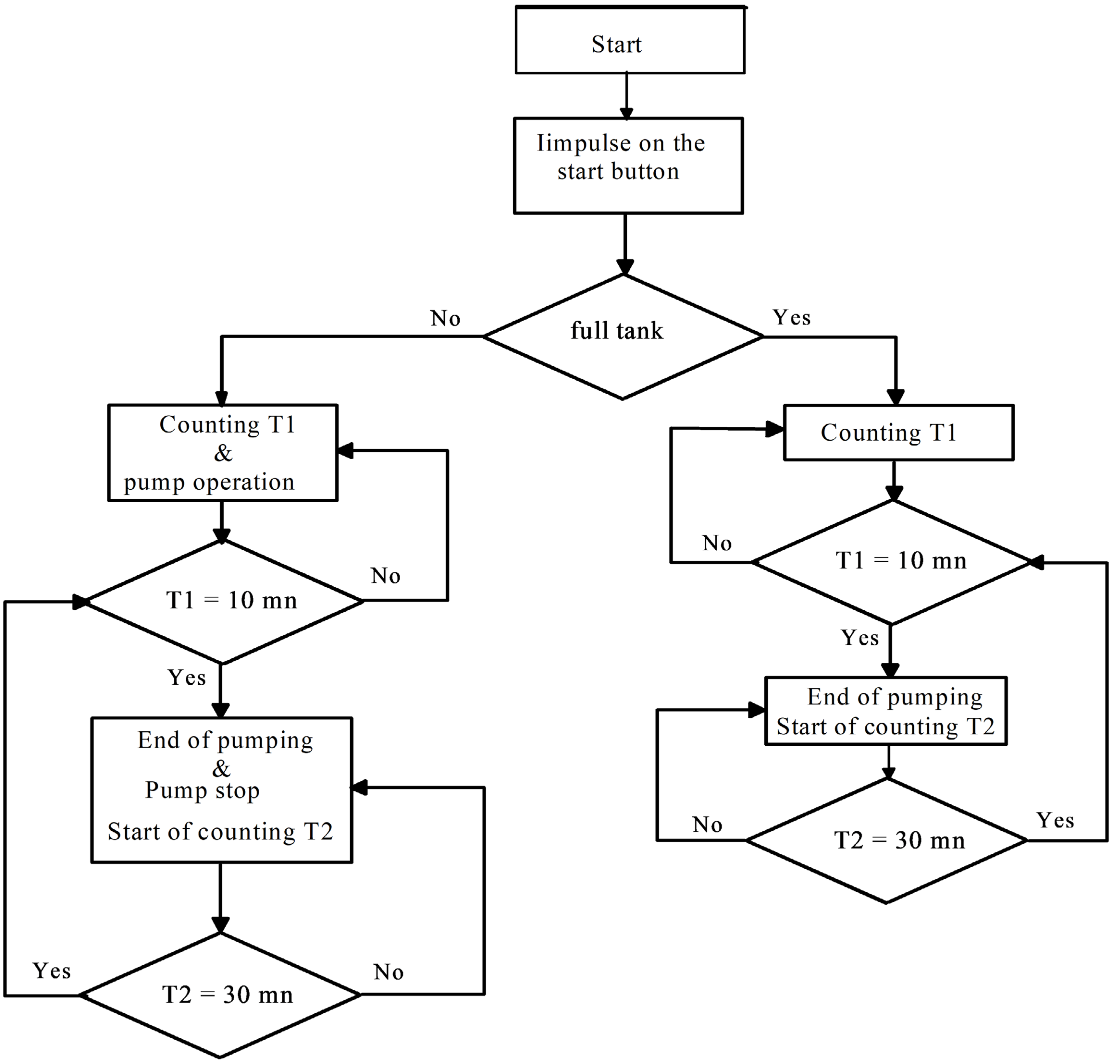

Figure 6. Proposed algorithm for managing the operation of the system.

1) The system starts when the impulse is applied to S1;

2) Upon pressing S1, the pump operates for 10 minutes and then stops;

3) The pump remains idle for 30 minutes;

4) After 30 minutes, the pump restarts and operates for another 10 minutes;

5) This cycle of operation and rest is repeated indefinitely until the operator decides to stop the pump by pressing button S2;

6) In the event of a power failure, the pump does not start immediately when

the power is restored. To restart the pump, the S1 button must be pressed.

Additionally, considering the integration of humans into complex systems resulting from technological advancements, such as man-machine systems and remote control, it brings forth a transformation of human activity and presents various challenges for psychologists [3].

In this particular system, where human intervention is involved in the regulation loop and direct participation in system control, activity planning becomes crucial. Therefore, we have also decided to incorporate human involvement in this regulation loop. This intervention includes restarting the pump when power is restored after a power outage and regularly checking the pump level every six months. The organization of this intervention is illustrated in Figure 7.

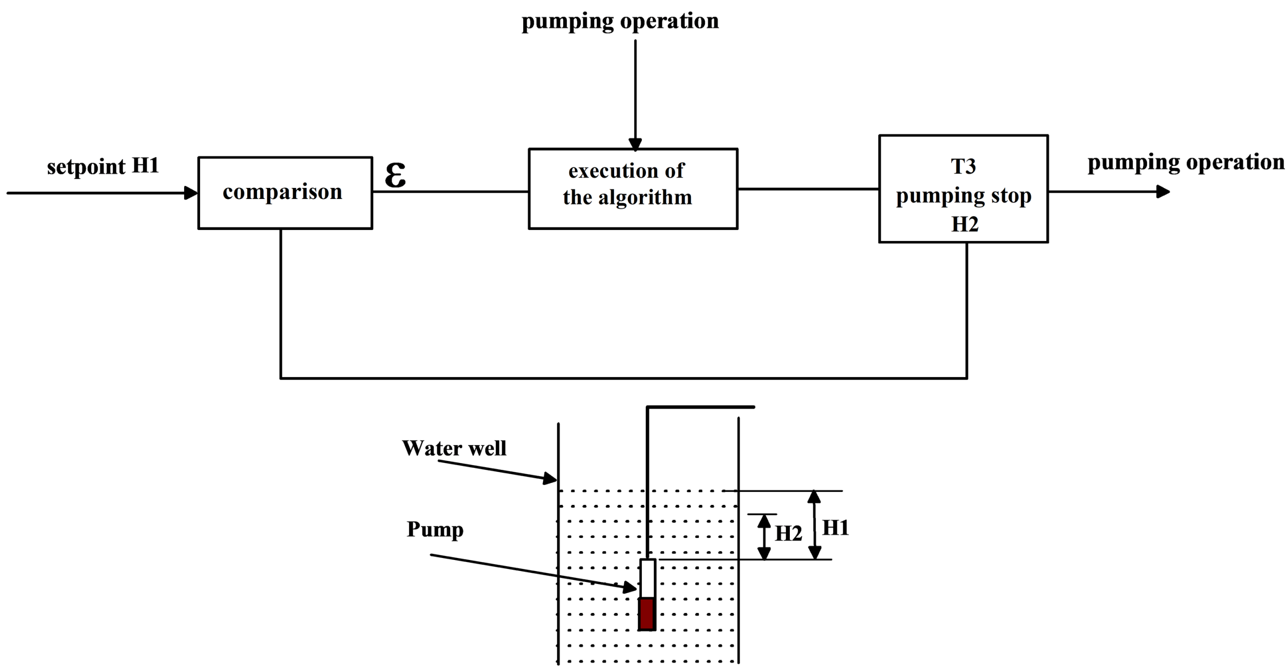

Figure 7. Regulation system diagram with human intervention.

Every six months (T3), we propose human intervention in the regulation loop of the pumping system's operation. The intervention includes the following steps:

- Stop the pump for a duration T4 ≥ T2;
- Probe the aquifer to measure the water level H2;
- If H2 is less than the desired setpoint H1:
  - Lower the pump into the aquifer until it reaches the desired setpoint H1;
  - Start the pump.
- If H2 is equal to or greater than the desired setpoint H1, indicating a sufficient water level in the aquifer:
  - Start the pump.

5. Conclusion

The objective of this research was to investigate a pumping system designed to supply water to a residential house in an urban area. Specifically, our aim was to analyze the installation to identify the exact causes of frequent pump stops and propose an effective solution. As a result, we proposed the implementation of an intermittent water pumping system, with 10 minutes of pumping followed by a 30-minute stop, to fill the water tanks. This solution successfully prevented a drop in the aquifer level and eliminated the issue of dry pumping.

To gain a better understanding of the problem, we conducted tests over an extended period to assess the aquifer level in the area. Additionally, we thoroughly examined the dimensioning of the installed pump to comprehend the underlying causes of the malfunctions observed in the studied installation. Based on our findings, we proposed a new installation approach to ensure the pump operates without encountering issues related to dry pumping.

Since the implementation of the new installation, the owner has reported no pump shutdowns caused by thermal failures, which are a consequence of dry pumping. These positive results validate the effectiveness of our proposed solution.

However, it is important to note that our pumping system relies on electricity from the SENELEC network, and in the event of a power outage, the system remains non-functional even when the power is restored. To address this concern, we recommend including human intervention in the pump operation loop for two specific situations. First, re-energizing the system after power is restored following an outage on the distribution electrical network. Second, testing the water table level in the event of decreased pumping pressure and adjusting the pump's position if a drop in the water level is detected.

To further enhance the system, we propose the integration of an independent power source, such as solar or wind energy, to ensure continuous electrical supply to the pumping system. Additionally, we plan to implement an automatic system for injecting water disinfectant products into the tanks to enhance water quality.

In conclusion, our research has successfully addressed the challenges associated with frequent pump stops in the studied pumping system. The intermittent water pumping system, along with the inclusion of human intervention, has proven effective in preventing dry pumping. Our work contributes to the field of urban water supply and pumping system optimization [References in the field of urban water supply and pumping system optimization]. Future improvements, such as integrating alternative power sources and implementing automated disinfection systems, will further enhance the efficiency and reliability of the pumping system.

Conflicts of Interest

The authors declare no conflicts of interest.

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