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Dynamic Modelling of a Water Distribution Laboratory set-up System with SCADA Capabilities

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Abstract: Level control systems are widely implemented in various processes in the process industries, water distribution system (WDS) in particular. An efficient WDS is represented by a system which is able to transfer a desired amount of water automatically, within a specified time. In current practice, the distribution of water is done manually. Although the system has proven sufficient so far, the current increase in general population has resulted in increasing demand of clean water, hence the need for a more efficient water distribution system has become the priority in the water industry. One method to resolve this is through automation of the distribution system. Hence, in this research, an automated WDS is set-up in the laboratory, which dynamically represents a real system. The laboratory set-up is utilized to design a control algorithm by obtaining the mathematical model of the system, i.e. the highlight of this paper. Since the laboratory set-up is part of a supervisory, control and data acquisition (SCADA) system of the WDS, the mathematical model of the system is obtained from the logged data, utilizing system identification technique, prediction error method (PEM) in MATLAB. Band pass filter is used to remove electrical noises. From the results obtained, a mathematical model of 6^{th} order is obtained with best fits of 99.9998% and a mean square error of 0.00000000388. The mathematical model obtained represents the relationship between the reservoir tank level and the incoming motor speed.

Keywords: Water distribution system, supervisory control and data acquisition, system modeling, automation, human machine interface, prediction error minimization

1. Introduction

The rapid growth of Malaysian population has made managing and controlling water usage efficiently, a significant priority. In the local water utility industry, water distribution system or WDS is a system where treated water is distributed by means of pumps through the distribution pumping networks to customers i.e., from the clear water tank from the water

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treatment plant to the reservoir tanks at the customers' side. The main priority in the water industry is meeting the treated water demand through transferring sufficient treated water volume (m3) to customers. This demand can be represented by the level of the reservoir tanks. In the usual practice, levels of the reservoir tanks are monitored manually, i.e. when a set-point tank level is not met, a trigger from that tank is sent to an operator who will be responsible to switch the pumps in the water pump house ON hence increasing the level of the reservoir tank, thus increasing the volume to meet the desired demand, and once the desired height is achieved, another trigger will be sent to this operator to turn the pump OFF. Since the piping network from the pump house to the reservoir tanks can stretch up to several kilometers away, the change in volume may take quite sometimes to accomplish.

Utilizing the conventional technique, the transfer time takes exceptionally long due to the distance, including the response time of the operator, hence the intended required volume transferred is difficult to achieve hence achieving customers' demand will be exceedingly slow. A more efficient water transference process system is thus, highly desirable. Therefore, taking all these into consideration, in this research, an automated level control for the WDS is proposed. The automated WDS run using PLC OMRON whereby a desired level can be automatically achieved using the preprogrammed ladder diagram. The system is also equipped with a supervisory control and data acquisition (SCADA) system which makes the monitoring of the system and controlling the pumps ON and OFF, easy to perform. In addition, from the SCADA system, the data from the system is logged and displayed for the convenience of the operator. The logged data is the key to obtaining a mathematical model of the system, hence designing an optimized level control of the system.

Focusing on the efficiency of the system, an optimized level for achieving the desired volume of water to be transferred, is thus required. To achieve this, a mathematical model of the system needs to be obtained first, i.e., the focus of this research. Therefore, from the logged data of the automated water distribution process in the WDS, run in a time duration with a fixed interval time, provides sufficient information for the system to be modelled. In this research prediction error minimization (PEM) is utilized in MATLAB to obtain the coveted mathematical model. When modeling a system, electrical noise occurs will then be filtered using band-pass filter. An accurate mathematical model will provide a good foundation for a robust and optimized control algorithm [1]. The work presented is a proof of concept to be applied in the real system in collaboration with Ranhill SAJ Sdn. Bhd. The installation, fabrication and industrial-related advice of the laboratory set-up is a continuous work with ZEC Sdn. Bhd.

2. Water Distribution System

In water supply network of a local water utility services, water distribution system plays the role of delivering sufficient treated water from a water treatment plant to consumers, in residential areas, commercial areas, industrial areas and for fire-fighting requirements etc. From literature, the development of an efficient water distribution system is capable in overcoming water loss [2]. In [3] for example, the proposed system able to monitor water usage of consumers in the establishment, hence able to provide accurate billing, able to detect leakage by monitoring and sustaining the level of reservoir tanks in the system. Several research finding in the literature [4,5,6] has proven that with an efficient system, the amount of water use can be monitored, and any anomalies of the system can be instantly detected. Therefore, any irregularities to the system can be detected faster, hence rectified. However, it should be highlighted here, that the efficient developed system covers only a restricted area of residential areas, not the whole water distribution system, for example, the whole country. However though if the process of water digitalization [7,8] starts now, this is not impossible.

Speaking of an efficient water distribution system, equipped with both monitoring and control of the water transference, one can only establish that with the establishment of an accurate mathematical model of the system. A fully monitored system will be able to provide this through determining the mathematical model that represents the system. For this purpose, in this research, to show the real occurrence of the distribution process, a typical water distribution system is presented in terms of a laboratory set-up in the Instrumentation Laboratory in the School of Electrical Engineering, Universiti Teknologi Malaysia, Skudai, Johor. The laboratory set-up is elaborated in the next section.

2.1 Laboratory set-up

The laboratory set-up for the water distribution system, which is an upgrade to the system in [9] and [10] is given in Fig. 1. Meanwhile, the dimension of the laboratory set-up can be observed in the technical drawing of the system in Fig. 2. The laboratory set-up is fabricated to represent a real system. The proposed system able to control the distribution of water from the clear water tank to the reservoir tank, automatically utilizing PLC. An accurate design and fabrication of a dynamical process system is crucial in ensuring accurate results of the system [11]. The list of system apparatus of the Laboratory set-up and their specification is given in Table 1.

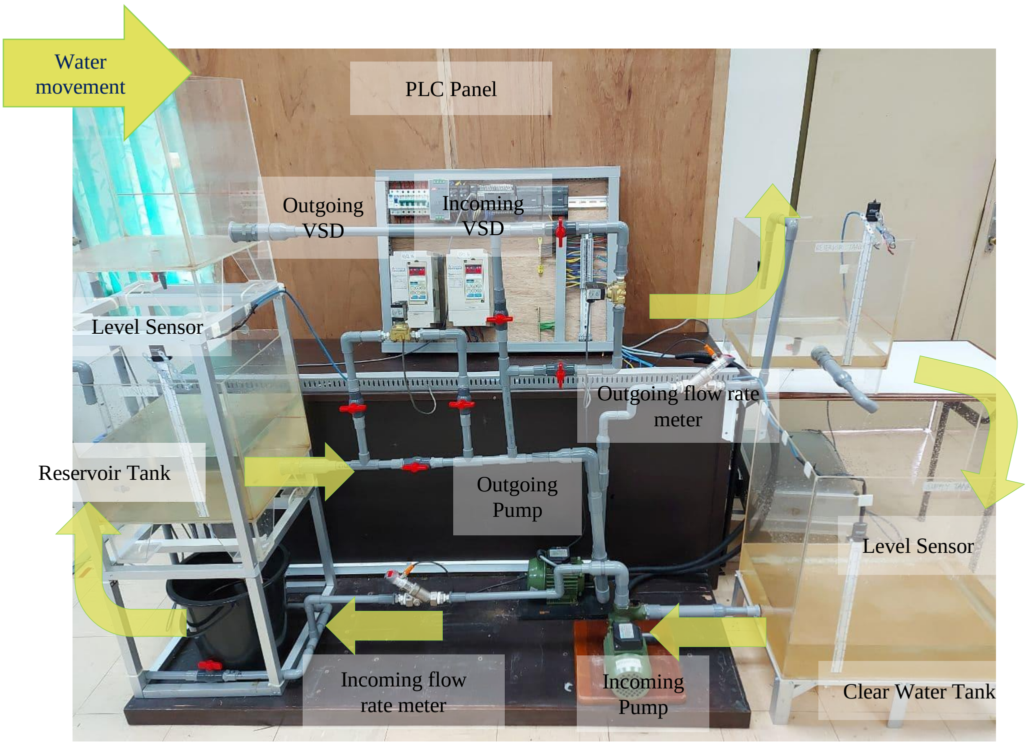


Fig. 1 - Laboratory set-up of the water distribution system

Table 1 - List of system apparatus of the Laboratory set-up and their specification

No	Item	Function	Specifications
1	OMRON SYSMAC CP1H-X40D	PLC Master controller	Number of inputs: 24 (DC) Voltage: 24V DC Program Capacity: 20000 Steps Communication Port: USB 1.1
2	VSD Speecon 7200M3	Variable speed drives - Regulating speed of motor	Voltage: 0 to 10 V/ Max Output freq Current: 4 to 20 mA / Max Output Freq Freq: 0 to 60 Hz
3	Water Pump SAER KF/1	Transferring water	Power: 370 W/ Single Phase Flow rate: 10 ~ 40 L/min Max working pressure 9 bar Manometer Suction lift: Max 8 meter
4	IFM SBY246	Flow meter sensor – to monitor water flow rate	Measuring range: 2 – 100 l/min Operating Voltage: 18-30 DC Current consumption: <50A Medium Temp: -10 ~ 100 C Pressure rating: 25 bar
5	Milonetech e-Tape	Liquid Level sensor	Voltage Output range: 0 – 5 V Current output range: 4-20 mA Length: 40 cm Temperature range: -40 ~ 257 F Power requirement: 6-30 VDC

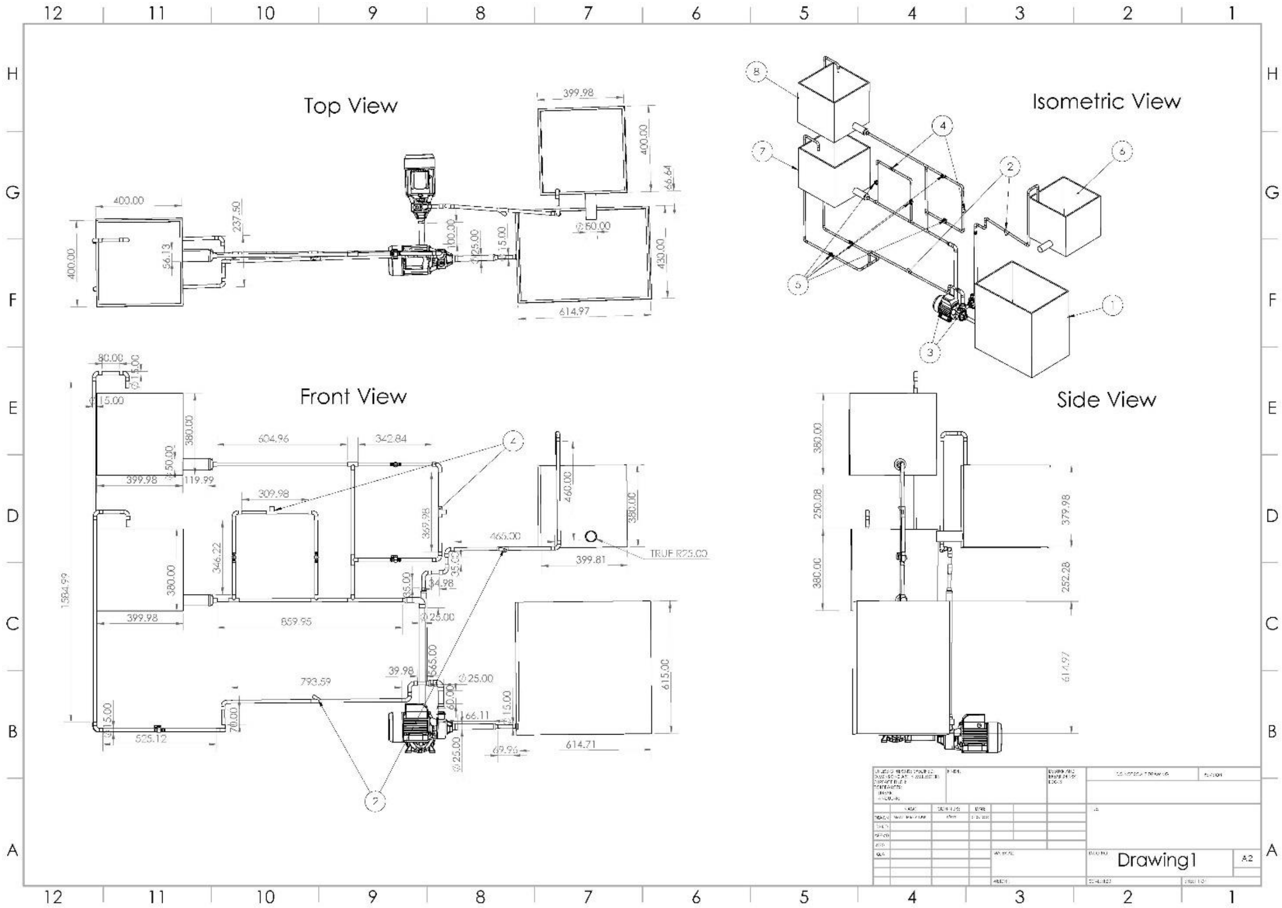
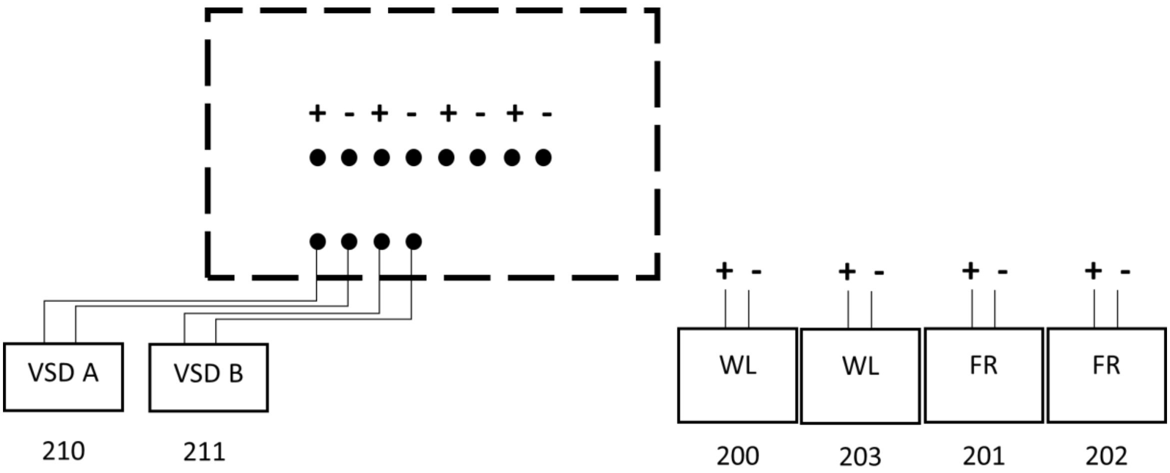


Fig. 2 - Technical drawing of laboratory set-up

2.2 System Automation

To maintain the desired level of the reservoir tank of the laboratory set-up, a programmable logic controller (PLC) is utilized. The PLC panel and the corresponding wiring diagram of the Laboratory set-up are given in Fig. 3(a) and 3(b) respectively. On the PLC panel, it can be clearly seen that there are PLC connected to the circuit breaker, power supply, expansion slot, as well as the incoming and outgoing variable speed drives.

Fig. 3 - (a) PLC Panel



WL: Water Level
FR: Flow Rate
VSD: Variable speed drive

Fig. 3(b) - PLC Panel - Wiring Diagram

The system automation of the system is programmed through PLC CX-programmer ladder diagram, where the process flow is presented in Fig. 4. The control algorithm is conveniently presented in *Algorithm.*

Algorithm 1

Step 1. Determine the set-point level L_A of the reservoir tank using trial and error.

Low level: $0cm \leq L_{A\_LL} \leq 10cm$

Medium level: $10cm \leq L_{A\_ML} \leq 25cm$

High Level: $25cm \leq L_{A\_HL} \leq 30cm$

High-High Level: $30cm \leq L_{A\_HL}$

Step 2. Determine the desired level for $L_A = L_D$ using trial and error.

$L_D = 25cm$

Step 3. Determine the incoming motor speed Hz_i according to the set-point level

At Low level, $Hz_i = 50Hz$

At Medium level, $Hz_i = 50Hz$

At High level, $Hz_i = 30Hz$

Step 4. Determine the outgoing motor speed Hz_o according to the set-point level

At Low level, $Hz_i = 0Hz$

At Medium level, $Hz_i = 30Hz$

At High level, $Hz_i = 50Hz$

Step 5. Trigger the overflow when L_A accidentally reaches High high Level

Hz_i = 0Hz

Hz_o = 50Hz

Step 6. Repeat the system to maintain L_D.

The automation of the system is designed through the ladder-diagram programming of the system (due to copyright issues, the ladder diagram is not provided here). The flow of the system utilizing PLC ladder diagram can be depicted in Fig. 4 below. Initially, the set-point level of the reservoir tank, which represents the customer demand, is determined. In this research, the desired volume is initially set as $0.04m^3$. Demand of clean water from customers can be represented by a set-point level in the reservoir tank, hence the demand is represented by the reservoir tank level at 25cm. Then, the speed of the pump is regulated automatically through configuring the variable speed drives (VSD) speed setting, i.e. when the reservoir tank reaches certain level, a certain speed of the VSD is set. From Figure 1, the clear water tank (CWT) represents the treated water from a water treatment plant (WTP).

From the control algorithm represented by Fig. 4, there are four design modes of tank level, which are the low level, the medium level, the high level, and the high-high level. Initially, at the low level, when the tank level of the reservoir tank is less than 10 cm, the incoming motor will be triggered to turn ON, at 50 Hz and water is pumped from the CWT to the reservoir tank, while the outgoing motor is OFF. The speed of the motor is varied depending on the current level of the reservoir tank. Once the reservoir tank level reaches the medium level between 10 cm and 25 cm, the outgoing motor is triggered and turned ON which runs at 30Hz, while the incoming motor remains at the maximum speed i.e., 50 Hz. Then, when the reservoir tank level reaches the high level between 25 cm and 30 cm, the incoming motor speed will reduce to 30 Hz while the outgoing motor speed will increase to 50 Hz. Lastly, at the high-high level, when then reservoir tank level exceeds 30 cm, the incoming motor will be turned OFF while the outgoing motor speed will be at the maximum speed of 50 Hz. A delay of 1 minute is used for the medium and high-level mode to ensure the desired level of 25 cm is achieved. The interval time for the process is set at 1 second.

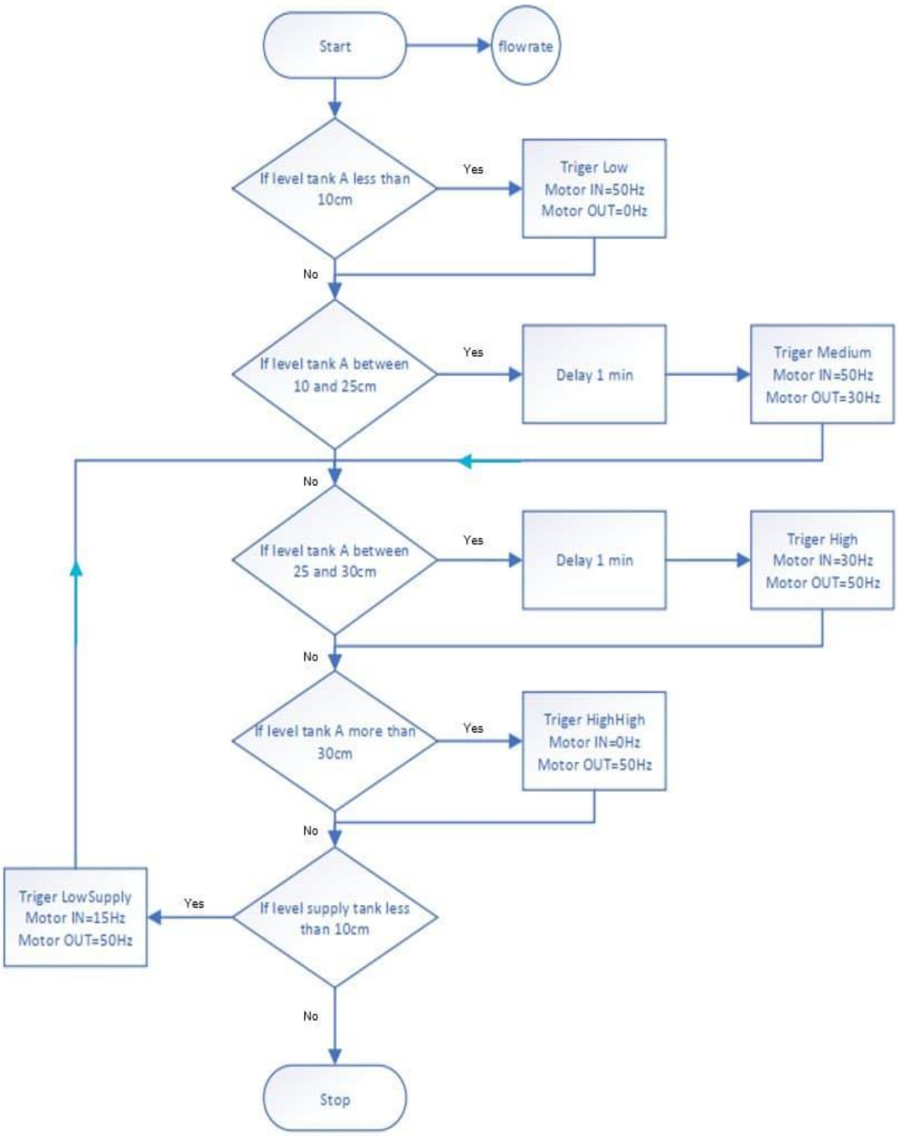


Fig. 4 - Process flow of the laboratory set-up using ladder diagram

2.3 Supervisory, Control and Data Acquisition (SCADA) of WDS

The SCADA interface for the laboratory set-up can be seen in Fig. 5. From Fig. 5, values for Tank A level, supply Tank level, incoming flow rate, incoming and outgoing motor speed, as well as the system turning ON and OFF are displayed in real time. The system is set to run either automatically or by triggering the START button on the interface. The human machine interface (HMI) designed can monitor the system in real time hence the current condition of the installed sensors can be observed. Monitoring the current condition of the system is crucial to detect any discrepancies in the reading hence detecting any faults that might occur while running the system [12]. The changes in sensors' reading are given in Fig. 6 and Fig. 7, with an interval time of 1 second.

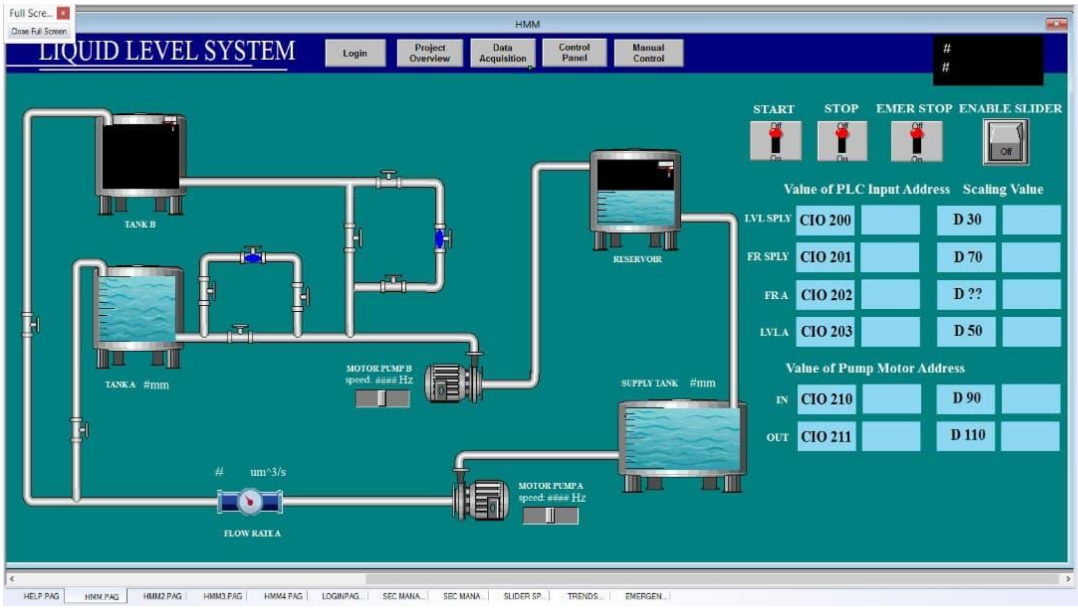


Fig. 5 - SCADA interface system of the Laboratory set-up

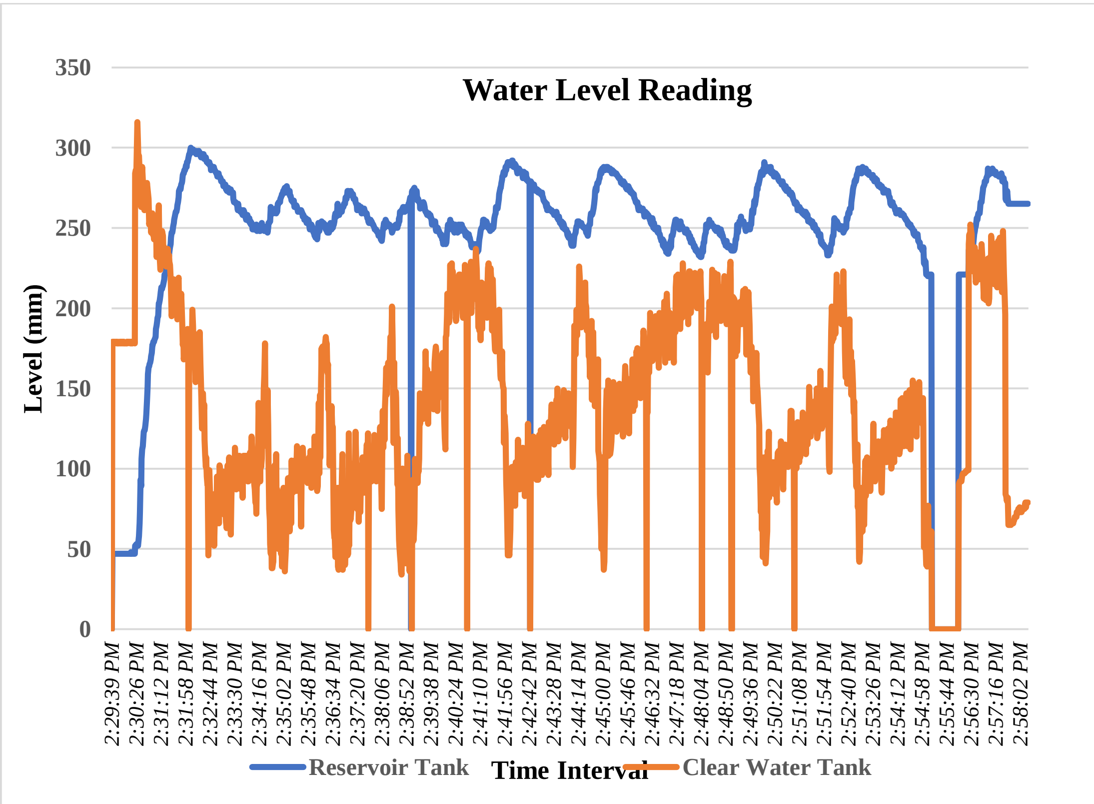


Fig. 6 - Level sensor reading

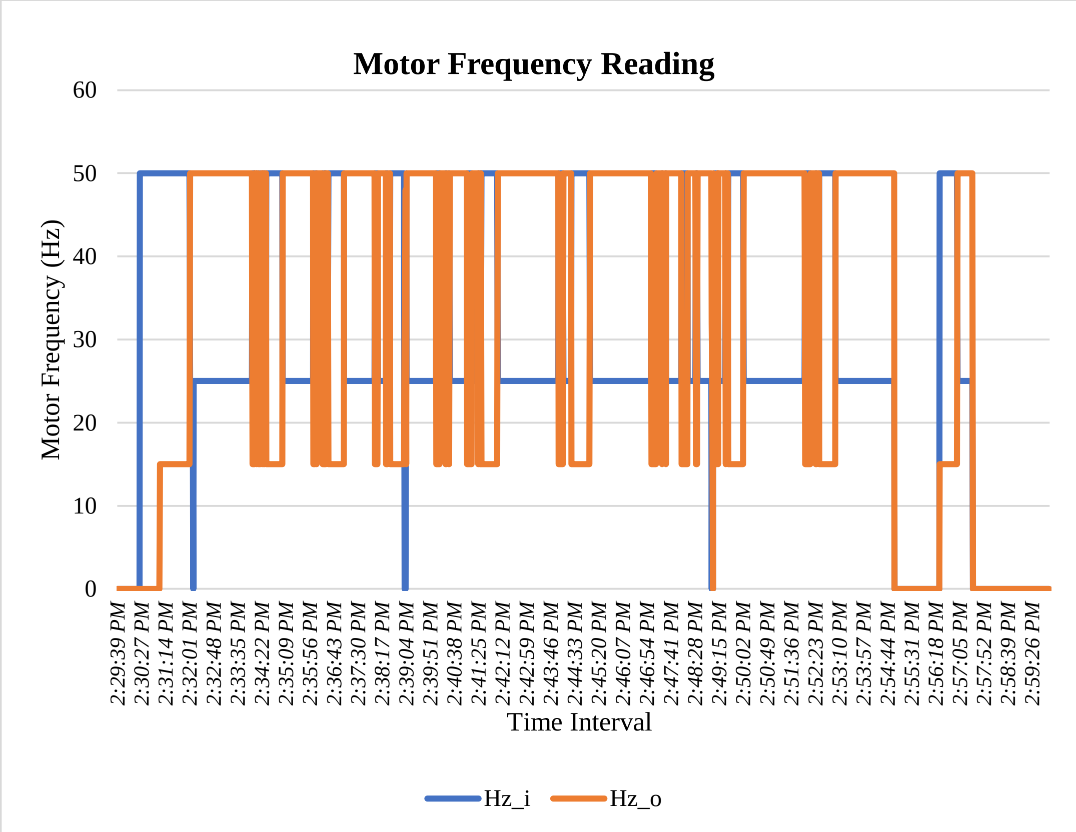


Fig. 7 - Motor frequency reading

From Fig. 6, can be observed that the desired level of the reservoir tank, i.e. 25 cm (250 mm) is achieved, although noise are apparent. The corresponding incoming motor frequency and outgoing motor frequency can be observed in Fig. 7. These two outputs trending of the system are crucial to show that the system is controllable, hence mathematical modelling of the system can be obtained.

3. Mathematical Modelling

For the existing laboratory set-up of the water distribution system, correlation between the water level of the reservoir tank and the input motor speed, and the incoming flow rate is established. Hence, a mathematical model obtained represents the WDS characteristic. In this research, to determine the system, the system identification technique of model prediction error minimization (PEM) is used. PEM is one of the techniques used for identifying dynamical model of a system based on recorded input and output data. Typically, unknown model parameters were estimated to obtain model prediction. Prediction error considers on the accuracy level of the predicted model parameter with least prediction error [14]. The accuracy of the prediction error minimization can be measured through validation correlation analysis, or the cost function, such as Mean Square Error (MSE) and Final Prediction Error (FPE). In addition, the quality of the predicted model can be determined by considering the best-fit criteria. The best-fit criteria are calculated by comparing the performance of the estimated models with the validation data. The higher value of best fit obtained, indicates a higher quality of the predicted model.

3.1 Prediction Error Minimization

Prediction error minimization is utilized to estimate a discrete-time state-space model using the subspace method, both for linear and nonlinear model. In PEM, the intended output is obtained from the time ($k+1$) to a future time by utilizing the input and output signals before the time, k. The prediction error model is shown in equation 1.

$$z(k) = f[z(k-1), \dots, z(1), z(0), u(k-1), \dots, u(1), \theta] + e(k,\theta) = f[z^{k-1}, u^{k-1}, \theta] + e(k,\theta) \quad (1)$$

Where $z(k-1)$ is the output of time $k-1$; $e(k,\theta)$ is the forecast or the ‘predicted’ error at time k. The parametric estimation of θ is called the prediction error estimation to a pre-selected cost function as the prediction error criterion.

Utilizing PEM, the state-space model obtained is refined hence increasing the accuracy of the system modelled. In this research PEM applied yields a good model fit of bigger than 90%, both with and without the pipe extension. The models obtained are tested for their stability, model order as well as their best fits, which are elaborated in the next section. The block diagram of the overall system is shown in Fig. 8. From Fig. 8, a mathematical model of L_A i.e. the water level of tank A or the reservoir tank as the output and H_{zi} the incoming frequency as the input needs to be determined. From the block diagram, the transfer function of G_c, G_{m_i}, G_{m_o} and G_b are assumed to be 1.

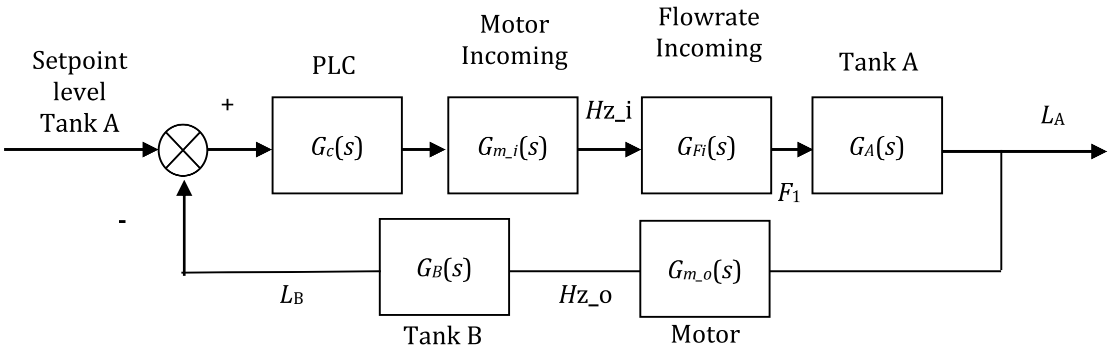


Fig. 8 - Block diagram of the laboratory-scaled system

3.2 Mathematical Modelling Results

The WDS laboratory set-up is run with an interval time of one second for one hour, and the trending of the variables are shown in Fig. 6 and Fig. 7 in the previous section. To obtain the mathematical model of the system, the data in excel are then inserted in MATLAB and PEM is utilized, to find the relationship between level of Tank A and the incoming motor speed i.e. L_A vs H_{zi}. Since the level sensor produces electrical noise, a band-pass filter is used to eliminate the apparent electrical noise, which is due to the cable connection in the system set-up. The mathematical model order estimation is given in Table 2 for the filtered (with band-pass filter) and unfiltered data. Values obtained for mean square error (MSE) and the best fits for model order 2 until 10 is presented.

From Table 2, all model orders are found to be stable. It can be observed that PEM yields a good set of mathematical models which can now be utilized for the control algorithm (next phase). For the unfiltered data, the best order is taken as the 10th order with best fits of 93.69 and MSE of 3.74. Meanwhile, for the filtered data, the best mathematical model is the 6th model order, with a percentage best fit of 99.99983 with its MSE of 0.00000000388. It can be observed that from Table 2, all the filtered model order yields goof best fits (~100%) and very low MSE. Although the unfiltered data yield bigger MSE and smaller best fits, the mathematical model order obtained is bigger than 80%, i.e. can be used for the control phase.

Table 2 - Mathematical model using PEM

Order	MSE Unfiltered	% Best Fits Unfiltered	MSE Filtered	% Best Fits Filtered
2	4.08	93.39	3.70×10^{-4}	99.94869
3	3.87	93.56	1.75×10^{-6}	99.99647
4	3.92	93.52	5.20×10^{-8}	99.99939
5	3.80	93.61	7.57×10^{-9}	99.99977
6	3.80	93.61	3.88×10^{-9}	99.99983
7	3.85	93.57	9.14×10^{-9}	99.99975
8	3.75	93.65	2.82×10^{-8}	99.99955
9	3.74	93.66	4.56×10^{-8}	99.99943
10	3.74	93.69	1.38×10^{-7}	99.99901

The plot of the estimated 10^{th} order unfiltered data and the 6^{th} order model filtered data in time domain are given in Fig. 9 and Fig. 10 respectively. It can be observed that PEM is able to model the system well to give a stable model with best fits of bigger than 90%.

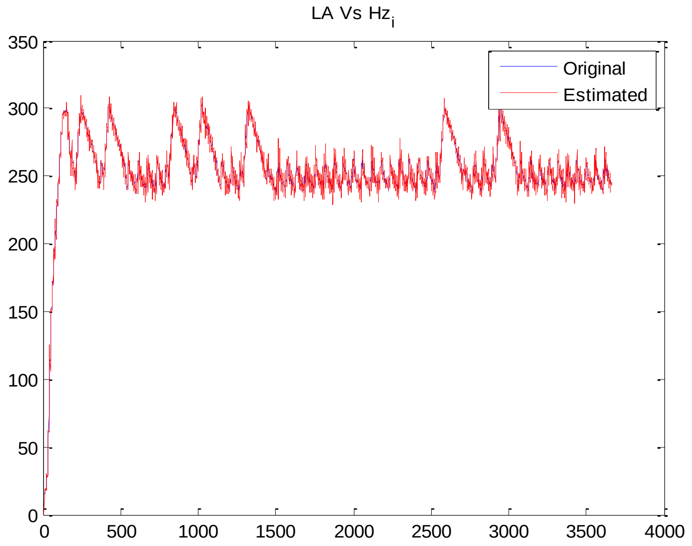


Fig. 9 - A 10th order model of the unfiltered data

The transfer function of the 10th order model of the unfiltered data obtained in discreet time is

$$\frac{L_A}{Hz\_i} = \frac{0.03975z^{-1} - 0.05873z^{-2} + 0.04762z^{-3} + 0.02081z^{-4} + 0.00762z^{-5} + 0.002652z^{-6} + 0.01382z^{-7} + 0.00296z^{-8} - 0.02008z^{-9} + 0.01286z^{-10}}{1 - 2.211z^{-1} + 1.624z^{-2} - 0.5078z^{-3} + 0.3537z^{-4} - 0.4159z^{-5} + 0.5206z^{-6} + 0.3235z^{-7} + 0.944z^{-8} + 1.528z^{-9} + 0.6215z^{-10}}$$

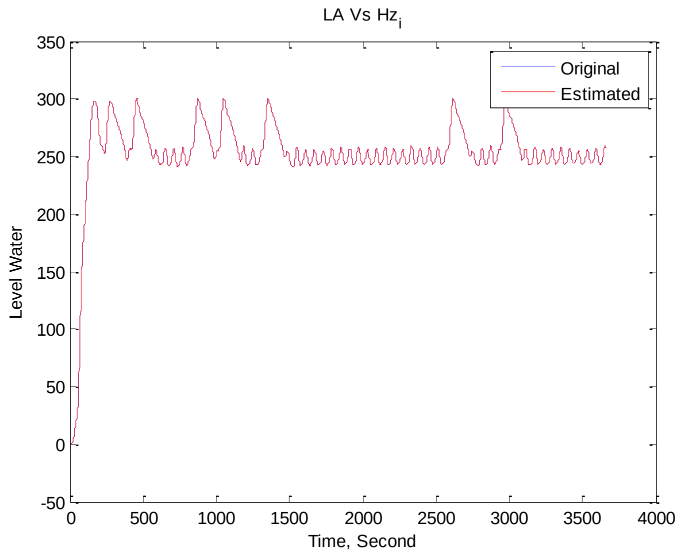


Fig. 10 - A 6th order model of the filtered data

Meanwhile, the transfer function of the 6th order model of the filtered data obtained in discreet time is

$$\frac{L_A}{Hz\_i} = \frac{4.26\times10^{-7}z^{-1} - 6.74\times10^{-8}z^{-2} - 1.18\times10^{-6}z^{-3} + 2.75\times10^{-6}z^{-4} - 2.37\times10^{-6}z^{-5} + 1.04\times10^{-6}z^{-6}}{1 - 5.89z^{-1} + 14.5z^{-2} - 19.11z^{-3} + 14.22z^{-4} - 5.66z^{-5} + 0.94z^{-6}}$$

The attainment of the mathematical model makes application of controllers an imminent application. The laboratory-scaled system is envisioned to be applied with a complete remote monitoring and control SCADA system for the purpose of a more efficient system through predictive maintenance practices [15].

4. Conclusion

In this research, a laboratory set-up, which represents a real water distribution system in the water utility industry, has been successfully fabricated and modelled using PEM in MATLAB. The laboratory set-up is automatically run using PLC Omron, equipped with a SCADA for control and monitoring purposes, from a master workstation. From the results obtained, a mathematical model of a 6th order is chosen to be the best mathematical model for the system for Tank A level as the output and the incoming motor speed as the input (L_A vs H_{zi}), as it yields a best fit of 99.99% and a MSE value of 0.00000000388. From the mathematical model obtained, has proved that a real water distribution system in the water industry can be mathematically modelled when sufficient data from the existing sensors can be retrieved. The model can now be utilized in the next phase of the research, i.e., developing an optimized control algorithm in maintaining the level of the reservoir tanks.

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