A FRAMEWORK FOR MODELING AND CONTROL OF WASTEWATER PUMPING STATIONS

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ABSTRACT:

In waste water pumping stations, centrifugal pumps driven by induction motors are used to transport the effluent collected from residential and commercial buildings to the treatment plants. Due to the varying nature of collected effluent rate, means of pump flow control should be applied. Recently, there is an engineering debate on either recommending frequency converters control or on-and-off control using soft starter technology. While there are obvious reward and cost of utilizing either approach, the lack of a simulation model makes the selection decision a matter of poor agreement. This is likely to happen in developing areas where abnormal running conditions such as power failure, excess flows, and lack of spare parts are frequently encountered. In this paper, a method for modeling wastewater pumping stations using the component oriented modeling language Modelica is presented. The model provides a valuable simulation tool to validate and judge on the different control schemes of these stations. This approach is applied successfully on a real pumping station located at the northern part of Gaza. The derived model facilitates tuning the control parameters and allows better understanding of the system dynamics.

Keywords: Water system modeling; simulation; automation; Modelica.

1. INTRODUCTION

It is normal to employ two separate sewer systems to convey stormwater runoff and wastewater from domestic and industrial sources, respectively, in separate pipe networks toward a receiving body and to a treatment plant. For the areas characterized by short rainfall season and relatively small stormwater runoff quantities, a combined sewer system which conveys all flows towards a treatment plant in a single network is likely to be implemented. The collection network of wastewater in the Gaza Strip is divided into zones in which gravity force is sufficient to direct the effluent to a pumping station which is responsible to boost the effluent to a treatment plant or to another pumping station located along the way to a treatment plant. Major streets and city centers are served by dedicated networks for stormwater runoff while refugee camps and poor areas relay on the sewage network to discharge surface flooding during rainy winters. Although such events are infrequent and lasts for short duration, resulting flows by far exceeds the capacity of the sewage system which is already overloaded and deteriorated. There are a total of 4 wastewater treatment plants and about 23 pumping stations in the Gaza strip. Each wastewater pumping station comprises a screen section and a pump section as illustrated in Figure 1.

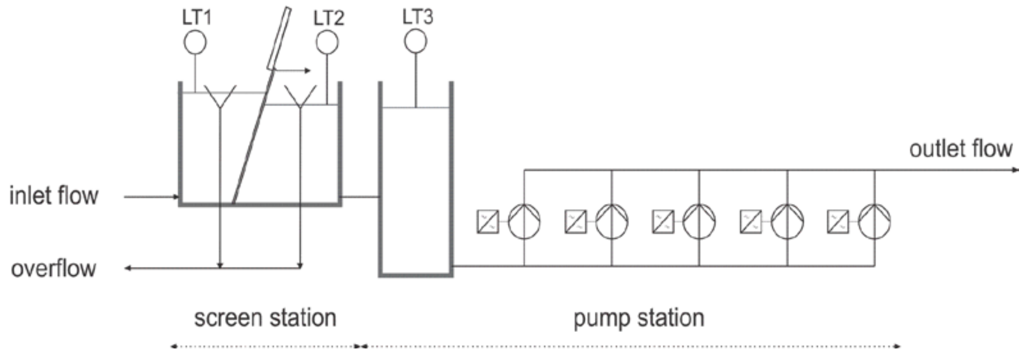


Figure 1: Process flow diagram of a typical wastewater pumping station

The screen separates coarse material out of wastewater. The coarse material is loaded into a conveyor system. The rack screen and the conveyor start at a signal due to a difference in levels of the level transmitters (LT1) and (LT2) located in front of and behind the screen respectively. They run during a preset time to leave at pause position. If the outtake of the screen fails to compensate the intake, wastewater starts to accumulate in the screen chamber and eventually reaches an overflow exit located at a specific level in the screen section. The resulting overflow may either be directed to an emergency overflow bond where it is recharged to the pumping station once pumping resources become adequate again, or it is directed to the sea. In rare worse cases, the overflow is directed to the stormwater collection network. Frequent overflows in the recent years as a result of excess rainfalls, frequent electric power cuts, inadequate control, or limited treatment capacity have raised a serious alert of environment pollution [1]. The pumping section has a suction chamber, whose capacity is about few hundreds of cubic meters, and a number of parallel centrifugal pumps which are driven by induction motors. The number of pumps ranges from 3 to 5 with power between 54 to 315 kW depending on the plant capacity. An efficient control scheme is necessary to match the incoming flow rate with the ongoing pumping rate. It is a common practice to use *frequency converters* to adjust the speed of pumps so that to keep the level in the suction chamber at a preset value. This insures balance between *instantaneous* inlet and outlet flows. However, this approach may not be optimal from energy and depreciation cost point of view. Alternatively, one may use *soft starters* and employ on/off control of the pumps in a cyclic manner to equalize the *average* outlet flow with the instantaneous inlet flow. This approach, however, should adjust the on and off periods not only respecting the maximum and minimum allowable levels in the suction chamber, but also the hidden cost associated with the number of pump restarts which definitely has a maximum permissible value per unit time and has an influence on depreciation. A derivation of a quantitative performance measure is needed to judge on the superiority of either approach. Analytical minimization of a practical performance measure that reflects energy and depreciation cost is likely to be unsolvable problem for such a complex system. Lack of models and simulation tools results in a burden on engineers who have to rely on their engineering sense and experimental experience to judge on their selected approach. Moreover, they usually spend long time on tuning the settings of their approach on real implemented systems to suit the flow patterns, machine data, and plant dimensions. This may lead to unexpected delays and painful costs. In [2], easily manageable component-oriented models were derived and applied to the modeling and simulation of a real wastewater pumping system. A test flow pattern and a specific control scheme were assumed to demonstrate and validate the derived model. The work presented here continues the project by presenting a model for the inlet flow, formulating a practical performance measure for running the station, and comparing simulation results of two controllers based on frequency converters and soft starters respectively. A summary of previous work is presented in Section 2. The inlet flow pattern will be modeled in Section 3 and the performance measures will be formulated in Section 4. The simulation results of two control schemes (cyclic on/off control and variable speed control) will be presented in Section 5; moreover, an application-specific for an additional PID controller is developed. Finally, in Section 6, concluding remarks will be given.

2. PREVIOUS WORK

The northern part of Gaza strip has been served by Beit Lahia wastewater treatment plant (BLWWTP) since 1976. The system was designed as a secondary treatment plant with a capacity of 5,000 m^3/day and to serve a population of 50,000 in the municipality of Jabalia. The treated effluent was simply let out into the sand dunes at the western side of the plant. In the first few years of operation, this practice did not cause problems because the effluent quality was good and the sandy soil was able to handle the volume of effluent through natural infiltration. During the past few years, the situation escalated. Many communities were provided with sewerage networks and were connected to the BLWWTP. Consequently, the volume of wastewater inflow to the plant (currently estimated about 25,000 m^3/day) has exceeded the plant's treatment capacity by far. The combination of increasing volumes of generated wastewater and insufficient treatment capacity at the BLWWTP has led to a deterioration of the effluent quality. The great volumes of poorly treated wastewater have led to clogging effects in the neighboring sand dune areas. The ongoing decrease of the infiltration capacity of the flooded areas and the increasing wastewater volumes have resulted in the formation of enduring ponds and finally a lake [3]. In order to prevent human and ecological disaster in the densely populated Beit Lahia area, the Palestinian Water Authority conducted a "Northern Gaza Emergency Sewage Treatment" (NGEST) project [4]. It targets to drain the existing effluent lake and convey its partly treated effluent to the new wastewater treatment plant site (WWTP). At the present phase of the project, about 10,000 m^3 of partially treated wastewater are daily infiltrated near the BLWWTP while about 15,000 m^3 are daily pumped through the new terminal pumping station (NTPS) to the new wastewater treatment plant (WWTP). Once the construction of a new treatment plant is completed, the pumping rate is expected to reach 35,000 m^3 per day during the high season of summer [5]. The transmission pipe has 7.6 km length, 80 cm diameter, and 26 m static head.

At the present phase, the ponds of the BLWWTP serve as a buffer for the wastewater before being pumped via the NTPS to the new treatment plant. This buffering stage will not be available by the completion of the project as BLWWTP will be removed and incoming wastewater is planned to be transmitted directly to the new treatment plant. Only one small size pond will be left for collecting emergency overflows at the pumping station. As a result, the real challenge of the control problem is not the present phase where a fixed daily amount of wastewater needed to be transported. In the final phase, the pump station must handle the instantaneous variation of the wastewater flow. Accidental overflow will result in an additional re-pumping cost and undesired environmental consequences. Therefore, an estimate of the daily diurnal flow pattern is necessary to examine the plant controller under daily variation of wastewater flow.

3. INLET FLOW MODEL FOR THE NTPS

Various approaches with various degrees of sophistication are in use for modeling flow in sewer systems. The average flow (q_{av}) is usually estimated based on the average water consumption per capita (w_{av}) as follows:

$$q_{av} = k w_{av} P \quad (1)$$

where k is the return factor (wastewater flow divided by water consumption ≅ 0.8), and P is the population served by the sewage system. At present, the population of the area under study is about 260,000 with 90% having access to the sewage network while the rest uses septic tanks. The average daily consumption of water for domestic use in the Palestinian community is about 134 liters per day [6, 7]. This results in a daily average flow of about 25,000 m^3/day.

Another approach based on relating wastewater production to the use of individual domestic appliances has been used in the literature [8]. It is useful not only in estimating average flow, but also in modeling daily diurnal flow pattern. In this approach, a survey for domestic appliances and their single use generated wastewater quantity is done. Moreover, a questionnaire about the frequency of use per capita per day and the timing likelihood is collected. The average results of a survey and a questionnaire done to 30 households (average occupancy: 7.2) living in the northern Gaza are summarized in Table 1 and Figure 2.

Table 1: Wastewater generation fractions in the northern Gaza

sn	Activity	Letter/use	use/ capita /day		l/ capita /day		Average l/ c /day	Average (%)
			winter	summer	winter	summer		
1	Toilet flushing	8.75	4.04	4.41	35.40	38.62	37.01	32.61
2	Showering	26.64	0.57	1.29	15.20	34.28	24.74	21.80
3	Bathing	48.78	0.05	0.18	2.59	8.89	5.74	5.06
4	Faucets use	1.74	12.03	15.15	20.97	26.41	23.69	20.88
5	Dishwashing	21.97	0.47	0.51	10.41	11.23	10.82	9.54
6	Cloths washing	68.15	0.12	0.15	7.91	10.38	9.14	8.06
7	Others	38.24	0.04	0.08	1.42	3.23	2.33	2.05
	Total				93.92	133.03	113.47	100.00

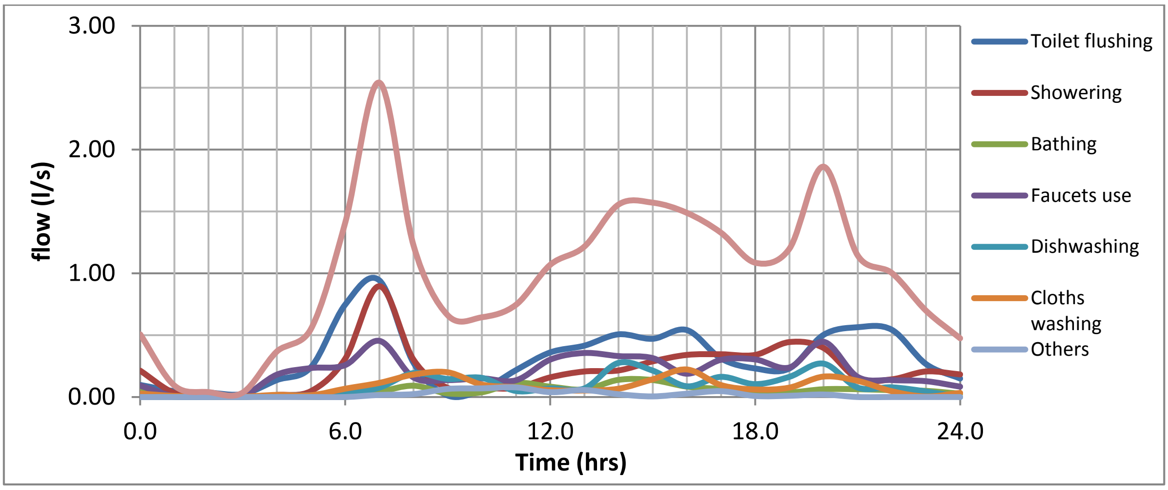


Figure 2: Normalized daily diurnal flow pattern and its components.

In general, an initial increase in appliance usage is observed at around 4:00 clock when prayers start to wake up for the Fajer prayer. This continues to build toward the morning peak (254%) around 07:00, then subsides to a low point (66%) at 09:00. At that time usage tended to increase to another lower peak (157%) at about 14:00 and another higher minimum point (114%) around 18:00. There is a third peak (186%) at about 20:00 while most activities had fallen off by 01:00.

4. PERFORMANCE MEASURES

A practical performance measure of a wastewater pumping station control system should reflect the following two components:

- **Depreciation cost:** This cost is highly affected by choosing frequency converters to drive and speed-control the motors or decide on cyclic on-off control of the pumps. As pumping stations are characterized by high power motors, direct-on-line or star-delta starting is not proper for switching these motors while soft starters facilitate a continuous and surge-free increase in torque with the opportunity for a selectable reduction in starting current. Another feature of the soft starters is the soft stop function, which is very useful in significantly reducing water hammering compared to star-delta starter and direct-on-line starter. Since soft starters are much cheaper than frequency converters, they are seen as an attractive alternative to them despite the need of cyclic switching to regulate the flow. However, high rate of pump restarts causes faster depreciation in the drivers, pumps, and other hydraulic components. Moreover, due to heat dissipation, soft starters have a limit for the maximum number of starts per hour. This maximum limit is dependent on several different factors such as the starting current, ambient temperature, starting and stopping time. In most practical cases, this number is less than 10. Therefore, the use of cyclic control via soft starters technology in wastewater pumping stations is feasible in case of suction chambers which are large enough to buffer inlet flows so as to keep the pumps' number of starts within practical limits. Moreover, attention should be taken while adjusting the preset starting and stopping levels of wastewater in the suction chamber. It is our aim through simulations to investigate the possibility of adopting cyclic control for the NTPS given the flow pattern predicted in the previous section and demonstrate the effect of careful tuning of the preset switching levels on minimizing the number of starts.

- **Energy efficiency:** Soft starters and frequency converters have different power efficiency characteristics. In case of soft starters, the motor voltage is modified by phase angle control of the sinusoidal half wave by means of thyristors. After the start up time (T_{start}) has timed out, the thyristors are fully conductive and are usually bypassed by the so called bypass contactor as illustrated in Figure 3. This helps eliminating the heat losses on the thyristors and replacing them by the considerably lower contact resistance of the mechanical switching device. The bypass contactor is switched back off leaving the connection control to the thyristors prior to the soft stop period (T_{stop}).

Mains voltage

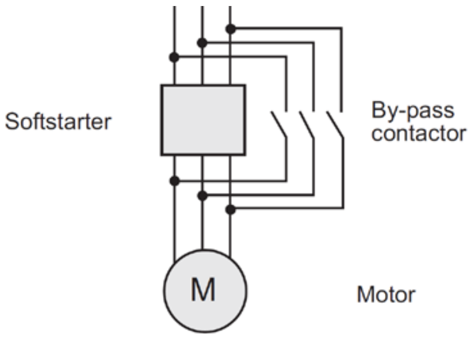


Figure 3. Bypass contactor use to minimize losses.

The voltage drop across a conducting thyristor is about 1.3 volts and this generates semiconductor losses in a soft starter equals $3 \times I_{start} \times 1.3\ \text{V} \times T_{start}$ at start up and equals $3 \times I_{stop} \times 1.3\ \text{V} \times T_{stop}$ at shutting time, where I_{start} and I_{stop} are the average starting and the average stopping currents respectively [9]. Typical heat power dissipation for a commercial soft starter suitable for the 315 kW pumps of the NTPS is about 8 kW during start up, 2 kW during shut down, and 0.2 kW during continues run (mainly due to cooling fans). Therefore, the daily energy loss due to a soft starter is approximated by:

$$E_{ss} = N \times \left(8\ \text{kW} \times T_{start} + 2\ \text{kW} \times T_{stop}\right) + 0.2\ \text{kW} \times T \qquad [\text{k Joule}] \qquad (2)$$

where N is the number of restarts per day and T is the total running period during the day. On the other hand, frequency converters use insulated gate bipolar transistors (IGBTs) to implement a switched-mode DC voltage with sinusoidal-weighted pulse width modulation (PWM). So, they are designed with sufficient cooling capability and their power efficiency is about 97%. The heat power dissipation of the 315 kW frequency converters installed at the NTPS is 8.1 kW at their rated output power [10]. Since the converter output power is proportional to pump power and the pump power is proportional to the liquid flow which is assumed to be proportional to the speed of the pump, then the converter loss is proportional to the speed. Consequently, the following equation is used in the simulations to estimate the daily energy loss due to a frequency converter:

$$E_{fc} = 8.1\text{ kW} \times \frac{1}{s_r}\int_0^{86400s} s(t)dt \qquad [\text{k Joule}] \tag{3}$$

where $s(t)$ and s_r are the instantaneous speed and the rated speed of the driven pump respectively, and 86400 is the number of seconds in a day.

5. SIMULATION RESULTS

The top level model of the NTPS is built in Dymola as illustrated in Figure 4 using the system components derived by Abdelati et al. [2, 11]. The screen controller triggers the screen discharge signal when the wastewater level in front of the screen exceeds the level behind the screen by a preset level (in the range of 10 to 20 cm). For the control of pumps, two different control scenarios will be specified and simulated; the first one is based on frequency converters while the other is based on soft starters. The simulation will be for the one daily diurnal flow pattern with an average of 35,000 m^3 in summer and 23,000 m^3 in winter. This allows investigating the plant operation after the completion of the second phase of the NGEST project. In this control problem, the control variable is the wastewater level (L) in the suction chamber and it is desired to keep it much below the overflow level (390 cm). The suction chamber is 230 cm below the screening station. Therefore, levels between 230 cm and 390 cm should not be reached except in case of emergency situations such as power failure or unexpected high stormwater flood. In practice, the level should be kept also above a minimum low level of about 100 cm to protect pumps from dry operation. As a result, the active equalization volume corresponds to the allowable or preferred level's domain interval [100, 230] cm.

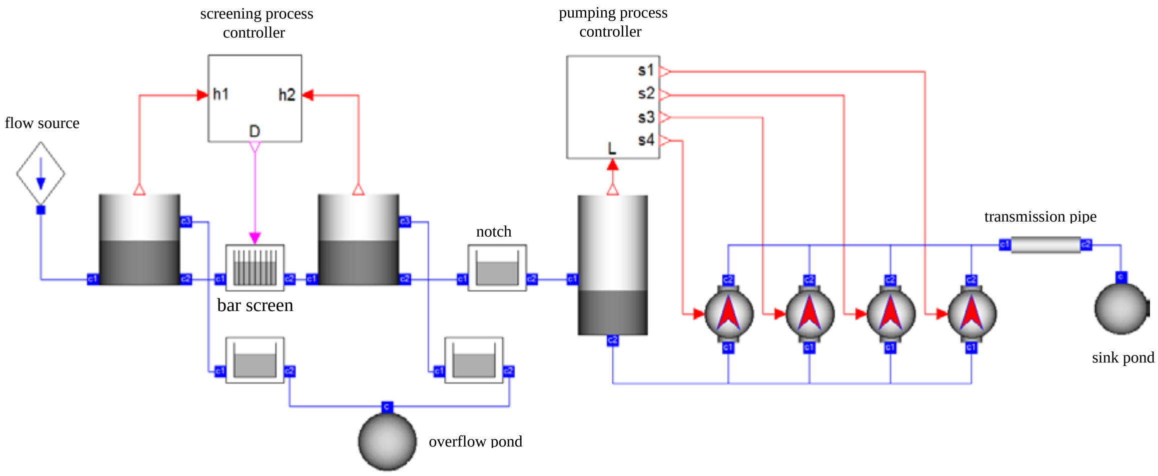


Figure 4: The top level model of the NTPS.

Cyclic on/off control: In this method, the first pump in operation starts at level L_h^1. If the inlet flow is less than the flow capacity of a single pump, the level in the suction chamber decreases until it reaches a preset level L_l^1 (less than L_h^1) when the pump is switched off. On the other hand, if the inlet flow exceeds a single pump capacity, then the level increases and exceeds the start level of the first pump. The second pump starts operation at level L_h^2 (greater than L_h^1). If the inlet flow is less than the capacity of two pumps, the level decreases until it reaches a preset level L_l^2 $(L_l^1 < L_l^2 < L_h^2)$ when the pump is switched off. The same logic of operation is extended for the third and forth pumps. It is expected from the simulation tool to help in setting the start/stop levels of the pumps in a way to optimize the performance measures. To this end, simulation of one summer day is done. The threshold levels L_l^1 and L_h^4 are set to 100 cm and 230 cm respectively corresponding to the end points of the allowable level interval. The other preset levels are adjusted according to these endpoints as follows:

$$L_l^2 = L_l^1 + \Delta L\ ,\ L_l^3 = L_l^2 + \Delta L,\ L_l^4 = L_l^3 + \Delta L \qquad (4)$$
$$L_h^3 = L_h^4 - \Delta L\ ,\ L_h^2 = L_h^3 - \Delta L,\ L_h^1 = L_h^2 - \Delta L$$

where ΔL is allowed to vary from 0 to its consistent maximum value (= 130 cm / 3 = 43.33 cm). The resultant number of starts of all pumps during one day is shown in Figure 5.

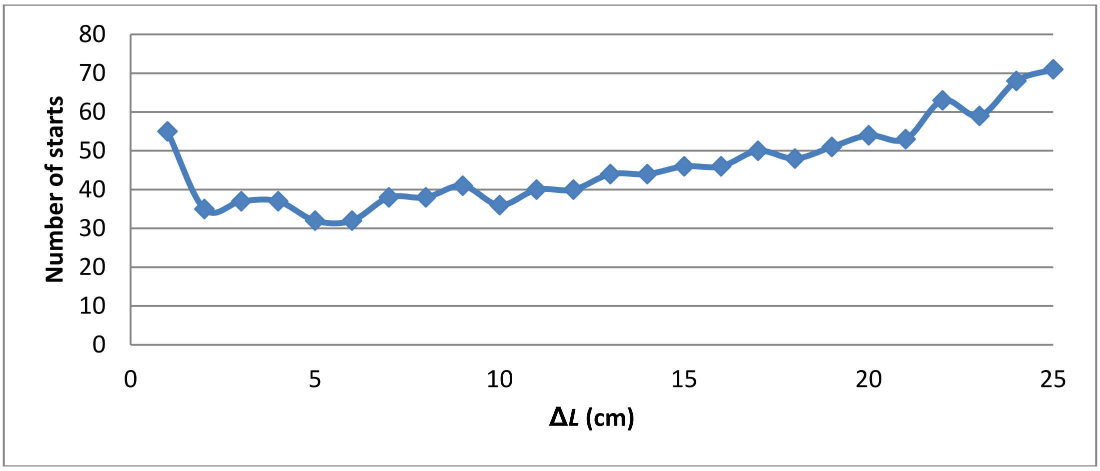


Figure 5. Variation of number of starts of pumps with respect to ΔL

The best operating range for ΔL is between 5 and 6 cm, corresponding to 32 restarts. For higher values, the effective buffering volume decreases resulting in an increase of the number of starts. For smaller values, on the other hand, the number of starts increases due to the effect of the delay in the feedback loop. For example, when a pump is commanded to start, it should be given some time to see its influence on the outlet flow and the level signal before making another decision on starting an additional pump. The little oscillation in the number of starts is due to the variation in the flow pattern. For the given flow pattern, one may sacrifice with a little increase in the number of starts for the benefit in reducing the maximum number of concurrent running pumps. For example, setting $\Delta L = 6.5$ cm instead of 5.5 cm results in an additional increase of 6 in the daily number of starts but limits the number of required pumps to 3 instead of 4. This point may be significant when the plant runs using a limited power standby generator.

The same experiment is repeated for different average flows. Insignificant variability of the optimum incremental threshold ΔL was obtained. The minimum daily power loss due to soft starters is found to be 6.24 kWh and 4.41 kWh during summer and winter respectively corresponding to $\Delta L = 5.5$ cm.

Variable speed control: It is similar to the previous approach except the additional flexibility in changing the speed of pumps. This allows adjusting the outlet flow to meet the inlet flow, keeping a preset value of the level (L_r) in the suction chamber. However, this should not be the objective in this control problem. It is desired here to minimize power losses due to frequency converters while keeping the level within the allowable domain. To this end, the following constraints should be fulfilled while assigning speeds to the individual pumps:

- When a single pump is in operation, its minimum allowable speed is 33% of its full capacity speed. This limit is specified by designers of the hydraulic system due to the non-zero static head of the transmission pipe.
- When there are n pumps in operation $(n > 1)$, they should share the load equally and their minimum allowable speed is $(n-1)/n$ of full capacity speed. If a group capacity less than the minimum allowable capacity is required, one pump must be removed from the group of running pumps. In other words, one pump is switched off when its assigned load can be carried by the other running (active) pumps.

As a result of this policy, if pump $i \in \mathrm{C}$ where C is the group of active pumps, then its speed s_i should respect the condition:

$$\begin{array}{ll} 33\% \leq s_i \leq 100\% & \text{if } N = 1 \\ 50\% \leq s_i \leq 100\% & \text{if } N = 2 \\ 67\% \leq s_i \leq 100\% & \text{if } N = 3 \\ 75\% \leq s_i \leq 100\% & \text{if } N = 4 \end{array} \qquad (5)$$

where N is the cardinality of C.

By engineering sense, the reference level should be 165 cm which is the midpoint of the level interval [100, 230] cm. Moreover, the role of adding a pump to the group of active pumps or removing one from it should be done according to the best hysteresis thresholds found in previous cyclic on/off control scenario. An additional PID controller should be employed to calculate the required pumping capacity according to the error signal $(L - L_r)$ and split it equally between the active pumps. The load share of each pump has a maximum saturation value of 100% and a minimum saturation value equals either zero or one of the limits specified in formula 5. This implies the possibility of adopting two criteria in removing a pump from the set C :

a) Removing one pump immediately when the required capacity reaches a value that can be carried by the remaining other members.
b) Sustaining on the minimum allowable speed until reaching the stop level of the pump.

Criterion (a) is expected to yield a smother flow, while criterion (b) is expected to decrease the number of restarts. The block diagram of the controller is illustrated in

Figure 6 and the simulation tool is expected to help deciding on which method to adopt in the load distributor module and help tuning the PID module.

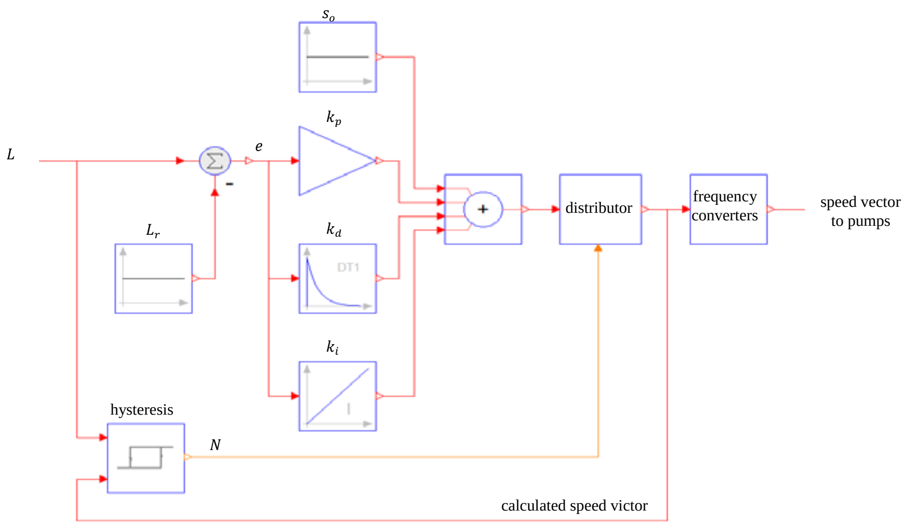


Figure 6. Block diagram of the PID-based variable speed controller

Finding the exact combination of P, I and D gains and the speed offset s_o that will deliver the most stable response of the PID module by trial and error is frustrating while Ziegler Nichols technique is found to be unhelpful. A tuning rule for this type of application is developed in this paper aiming to minimize the power loss of frequency converters by giving attention to the number of starts more than the error signal itself.

On the long average sense, half of the installed pumps are able to transmit the average inlet flow and keep the error signal e close to zero. Therefore, s_o is set to 200%. When there is a positive error of $L_h^4 - L_r = 0.65$ m all pumps should operate. Therefore, the proportional term should generate an increase of 200% speed. As a result, the proportional gain k_p is set to 200/0.65 = 307.7. This also insures a decrease of 200% at level L_l^1 at which the aggregate pumping capacity should be zero. Moreover, the calculated aggregate pumping capacity at other starting and stopping levels is beyond the saturation values.

The mismatch between inlet and outlet mass flow rates is related to the derivative of the error signal as follows:

$$\Delta q = q_{in} - q_{out} = A\rho\frac{dL}{dt} = A\rho\frac{de(t)}{dt} \qquad (6)$$

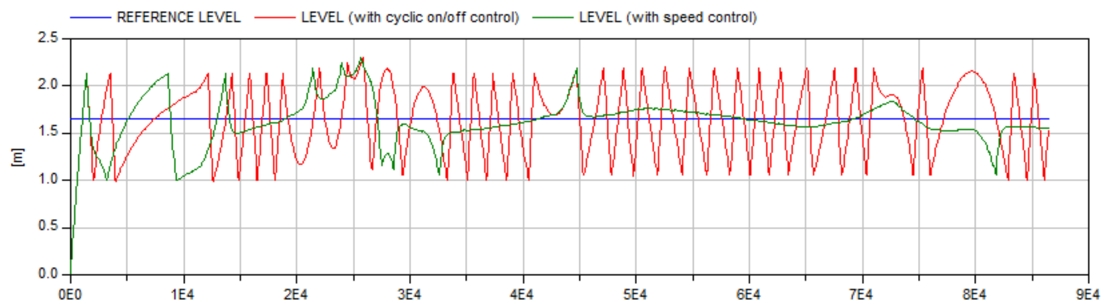
where A is the cross sectional area of the suction chamber and ρ is the wastewater density. Measured as a percentage of pump nominal operating point capacity (q_{nop}), this mismatch flow is equivalent to

$$\Delta q = A\rho\frac{de(t)}{dt} \times \frac{100}{q_{nop}} = 35417\frac{de(t)}{dt} \qquad (7)$$

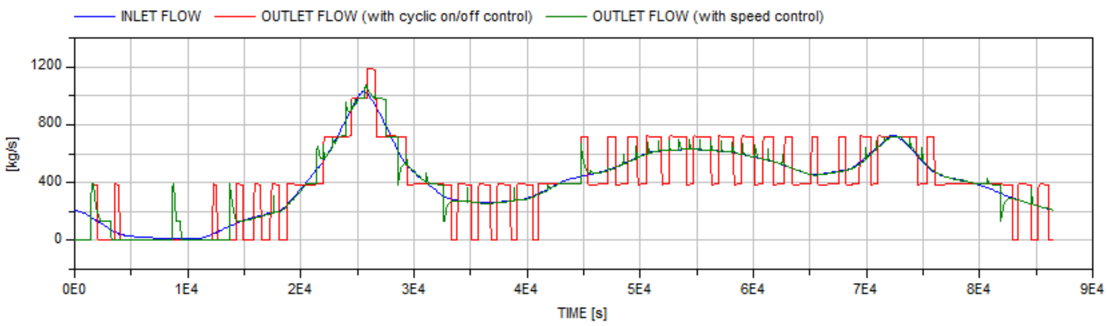
where the specific parameters of the plant are $A = 125\ \mathrm{m}^2$, $\rho = 1020\ \mathrm{kg/m^3}$and $q_{nop} = 360\ \mathrm{kg/s}$. In order to eliminate this mismatch the derivative gain should be set to 35417.

Using simulations, it is found that there is no apparent significant improvement to the use of the integral component. The PD components are sufficient to keep the error signal within the preferable domain of L. A value of k_i greater than 0.1 is found to degrade the controller performance by increasing the number of restarts. Thus, a value of 0.05 for k_i is set. Moreover, Adopting criterion (a) for removing a pump from the set $\mathcal{C}$ has shown negligible improvement on the flow disturbance, while criterion (b) decreased the daily aggregate number of starts from 9 to 7. The minimum daily power loss due to frequency converters is found to be 210.46 kWh and 134.64 kWh during summer and winter respectively.

In order to better visualize the variation of the level and flow signals under the addressed control schemes, these signals are depicted over one day in Figures 7a and 7b respectively. As expected, both controllers keep the level within the preferred range while speed controller insures smother outlet flow.



(a)



(b)

Figure 7. Level and flow variation under soft starters-based and frequency converters-based controllers

6. COMMENTS AND CONCLOUSIONS

This paper addresses the control methodologies used in wastewater pumping stations. It is an extension of the work done in [2] and [11] where an easily manageable model for a wastewater pumping station was developed based on the Modelica programming language. The present study focuses on extracting a model for the daily flow pattern and investigating the performance of cyclic on/off control and variable frequency control of a real system at the Northern Gaza (NTPS). The performance measures are the power loss in motors' drivers and their number of restarts, which have an impact on maintenance cost. Simulations have shown that the cyclic control is possible for the NTPS as it yields an acceptable number of restarts (which is much less than the maximum value specified by commercial soft starters manufacturers, 10 starts per hour per pump). Moreover, losses of soft starters are found to be only about 3% of frequency converters' losses. On the other hand, the daily number of starts using frequency converters is about 20% of its corresponding value using soft starters.

In a future work we plan to develop a model for stormwater flow and investigate the performance of the developed controllers. Although rainfall is a rare event in Gaza, the risk of surface flooding is high under these circumstances.

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