Integration of Water Transmission and Distribution Systems via Bypassing Storage Reservoirs

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Abstract— Direct connection between the water transmission and the water distribution systems is implemented in United Arab Emirates “UAE” to avail from the residual pressure energy available in transmission lines. The connection is accomplished via bypassing a number of reservoirs and pumping stations in a small transmission system in Al Ain City of UAE. The system has a major transmission pumping station that hosts four fixed-speed pumps, a main 1200mm line, storage reservoirs and boosting pumps besides few other connection pipes. The study objective is achieved by conducting a comprehensive transient analysis to evaluate the potential of pressure rises associated with various operating scenarios. The savings in energy cost associated with the proposed bypass setting are estimated at about $850,000 per year. Such savings are found to be available after a payback period of one year and one month to cover the capital cost of the needed bypasses and pressure relief valves.

Index Term— United Arab Emirates, Water distribution system, transmission, bypass, transient.

I. INTRODUCTION
Desalinated water has become the main source of freshwater in the U.A.E. In the last decade, consecutive expansion projects of desalination plants of different types (such as Multi Stage Flash (MSF), Multi Effect Distillation (MED) & Reverse Osmosis (R.O) have been successfully executed to cope with the increasing demands for high water quality as a result of social growth and industrial and agricultural activities. The low selling cost (close to zero) of desalinated water in the Emirate of Abu Dhabi has encouraged the people to use the costly and high quality desalinated water, in cleaning, gardening, irrigation, car wash and other general water uses that may tolerate lower water quality. Because of that, the water consumption per capita (115 gallon/person/day) in Abu Dhabi is considered to be one of the highest in the world.

To promote freshwater sustainability in Abu Dhabi Emirate, the local government has defined a number of strategic plans to supply water to all regions that are threatened by water shortage. In order to reduce the load on existing water supply schemes (water from Taweerah and Umm Alnnar), new alternatives for Al Ain region (Showaihat and AlFujairah-Al Ain Water Projects) were commissioned and put in operation few years back. Fujairah Water Scheme aims to deliver water from AlFujairah to Al Ain via a twin-1600 mm transmission pipelines (see Figure 1). The pipe system is designed to include strategic water storage tanks and to serve as an emergency water back-up system to Al Ain and Abu Dhabi. Moreover, a large volume of this high quality-water will be mixed with brackish ground water and used for farm irrigation to preserve the natural underground water storage. Considerable volumes of desalinated water are already used in aquifer recharge pilot studies.

To supply water to areas distant to desalinated water production facilities in the coastal areas, long transmission pipelines reaching distances as long as 300 km have been constructed with booster water pumping stations along these pipelines. Long distance water transmission pipelines and boosting pumping stations have contributed significantly to the high cost in terms of capital and operation expenditures of water production. Further expansions on water production, transmission and distribution are planned to cater to the forecasted supply until year 2020.

The main objective of this study is to minimize the water conveyance cost by reducing the pumping time, pumping flow rate, spare parts requirements, maintenance frequency, manpower and future expansion projects. This goal is accomplished by utilizing the available pressure energy in the transmission pipelines before it is lost within the storage tanks (energy dissipation). It is aimed to achieve such objective while considering potential transient problems that may arise during operations due to the direct connection of the transmission and the downstream distribution systems (Al Maamary, 2007).

II. SYSTEM DESCRIPTION
The system in the considered study is composed of a large 2 x 3 km Water Reception Station that receives water from two huge desalinated water sources, i.e., Fujairah and Taweerah. Fujairah is located on the eastern coast of UAE on the Arabian Sea some 250 km from Al Ain. Taweerah is located on the western coast of UAE on the Arabian Gulf some 160 km from Al Ain. The case study of this thesis targets the largest of the pumping groups, i.e., Markhania Group to utilize the available pressure energy at water consumption nodes to directly supply water to distribution networks without the need for booster stations. It is located at elevation of 253 m and comprised four variable speed pumps (that receive water from the common four water reservoirs in AARS), three pressurized surge vessels, a single 1200 mm ductile iron pipeline, flow control valves, check valves, air valves and shut-off valves. The first tap off connection (node) to the outlet of this group is Dahma Pumping Station some 3.6 km from AARS at elevation of 278 m above sea level. The second tap off connection (node) to the outlet of this group is Markhania (Maqam) Pumping Station some 12.1 km from AARS at elevation of
The third tap off connection (node) to the outlet of this group is Zakher Pumping Station some 20.7 km from AARS at elevation of 250 m above sea level. The fourth tap off connection (node) to the outlet of this group is Al Wagan Node some 21.2 km from AARS at elevation of 250 m above sea level. The intake water source is 800 mm dia from AARS through a main 1400 mm transmission pipeline. The station is composed of a boundary wall (1900 m x 800 m), four concrete water reservoirs with 5 MIG (22730 m³) capacity and 80 m x 60 m x 6 m-dimensions, four pumping groups contained inside pumping house (146 m x 27 m x 8 m) dimensions and four outlet pipelines (1200 mm D.I to Dahma, Markhania, Zakher and AlWagan, 900 mm DI to Hili, 900 mm D.I to Khabisi and 900 mm D.I to Sarouj). The station also houses a chlorination building for chlorine disinfection. Chlorine is injected at the inflow mains to the station as well as at the outlet mains. Fujairah Desalination Plant has recently become the main water source to Al Ain water reception complex (AARS), through twin 1400 mm transmission pipelines. Taweelah Desalination Plant is the second main water source to AARS through twin 1200 mm transmission pipelines. Al Ain reservoirs inlet mains have separate circuits to be supplied either from Taweelah, Fujairah or from both. The reservoirs outlet mains are arranged to feed the same pump house.

Markhania Pump Group is composed of four transmission pumps, three on duty and one on standby arranged in parallel to supply the water to Markhania, Dahma, Zakher and Al Wagan. These transmission pumps are centrifugal type driven by electrical motors. Between the electrical motors and the pumps hydraulic coupling type variable speed drives are installed to perform steep speed regulation. All pumps and drivers are housed in the pump house and described as follows:

- Pump Design Capacity: 3938 m³/h
- Pump Differential Head: 47 m
- Pump Rated Power: 558 KW
- Motor Rated Power: 980 KW

The anti-surge equipment in AARS includes the following:

- Surge tank on the incoming main suction header to Markhania pump group at AARS. Each surge tank is provided on the incoming main to the pump house (pump house main suction header) with a nominal capacity of 37.5 m³.
- A set of surge vessels on the water pipeline to Markhania is composed of 3 units that are arranged in parallel at the pumps’ outlet 1200 mm ductile iron transmission pipeline. Each surge vessel has a nominal capacity of 73.55 m³.

The pipe pressure rating varies relative to the pipe location as follows: 25 bars for the inlet pipe work to reservoirs, 10 bars for suction pipe work from reservoirs to pumps, and 16 bars for delivery pipe work from transmission/distribution pumps.

**AARS Water Outflow**

Four transmission outlet pipelines are installed in AARS to supply water to:

- Dahma, Markhania, Zakher, and Alwagen via.1200 mm pipeline.
- Sarouj and Military via.900 mm pipeline.
- Khabisi and Powerhouse via.900 mm pipeline.
- Hili and Zoo via.900 mm pipeline.

**Total Water Outflows from AARS to Markhania Group** is explained below:

**At Dahma Node:**

The incoming water source is 800 mm dia from AARS at 2.5 bars that is feeding a 5 MG water reservoir. The outlet of the reservoir feeds 8 distribution pumps that in turn feed two distribution networks.

- Distribution to AADC – D1 is 600 mm dia. at 2.3 bars.
- Distribution to AADC – D2 is 600 mm dia. at 2.3 bars.

**At Markhania (Maqam) Node:**

The incoming water source is 1000 mm dia from AARS at 4.4 bars that is feeding 3 x 5 MG water reservoirs. The outlet of these reservoirs feeds 8 distribution pumps that in turn feed two distribution networks.

- Distribution to AADC – D1 is 600 mm dia. at 2.3 bars.
- Distribution to AADC – D2 is 600 mm dia. at 2.3 bars.

**At Zakher Node:**

The incoming water source is 800 mm dia from AARS at 3 bars that is feeding 5 MG water reservoir. The outlet of the reservoir feeds 8 distribution pumps that in turn feed two distribution networks.

- Distribution to AADC – D1 is 600 mm dia. at 2.3 bars.
- Distribution to AADC – D2 is 600 mm dia. at 2.3 bars.

**At Al Wagan Node:**

It is a pipe extension from the main 800 mm D.I pipeline to Zakher. The size of this extension is 800 mm D.I that is fitted with flow control valve, flow meter, and isolation valves.

**Hydraulic Performance of the Existing System**

This section describes the main hydraulic conditions prevailing in the four supply zones and then variation during a typical operating day. Such conditions are obtained from 24-hour EPS using InfoWater Model (MWH Software Inc., 2004) and verified against the actual field conditions. The presented conditions include pressure head, hydraulic head, total flow, head loss and velocity in the main 1200 mm line. Figure 3 shows the pressure head conditions of the existing system.

**Transient Conditions of the Existing System**

Hybrid flow-level control valves (FCV/LCV) are installed upstream the existing tanks to control the incoming flow rates and tank levels at the same time. Transient conditions may develop as a result of the operation mode of these valves and potentially affect the upstream transmission system. Even though the tanks will likely dampen the pressure waves in the short pipe downstream those valves, they won't have any impact on the main transmission system. This is verified by transient analyses conducted by InfoSurge Software (MWH Software Inc. b, 2004).
III. BYPASS PROPOSAL

As stated earlier, due to the availability of the incoming flow and pressure requirements from AARS to the demand nodes (Dahma, Maqam and Zakher), it is proposed to bypass the reservoirs and booster pumps. The proposed bypasses are extensions of the existing branched-pipelines to be connected to the consumers without being let into tanks or further boosted by pumps. Bypass sizes are identical to the size of pipes feeding each zone. Therefore, bypasses of Dahma, Maqam, Zakher, are 800 mm D.I, 1000 mm D.I, and 800 mm D.I; respectively. Figure 4 shows the proposed bypasses on the 1200 mm pipeline. Such sizes accommodate the given water supply and the corresponding pressure heads available in the current system (Figure 4). This has been verified using EPS as explained earlier.

Figure 5 shows that the head loss/600 m at peak flow rate of Dahma is 1.68 m from 6:00 to 11:30 hrs, the head loss/km at peak flow rate of Maqam is 1.1 m from 1300 to 1800 hrs, the head loss/km at peak flow rate of Zakher is 1.7 m and the head loss/km at Al Wagen is constant at 0.4 m.

Figure 6 shows that the velocity peak in the Dahma pipe branch is 2.1 m/s from 600 to 1130 hrs, and the velocity peak in Maqam pipe branch is 1.35 m/s from 1300 to 1800 hrs. The head loss in Al Wagen pipeline is constant at 0.7 m/s.

As it is apparent from the above simulations that the proposed sizes of all bypasses are satisfying their objectives. Velocities are not violated that are all below the maximum allowable by pipe manufacturers (≈ 4 m/sec), head losses are fine as they don’t exceed 1.75 m/branch length (m) at maximum flow rates. The available pressure at all nodes is moderately higher than the distribution requirements but still within the desirable distribution limits. Next section evaluates the bypass proposals with respect to transient conditions generated during normal and abnormal operations.

IV. TRANSIENT SIMULATION SCENARIOS AND RESULTS

The results discussed in this section are obtained from two modes of operation; Normal Operation Mode and Abnormal Operation Mode. The normal operation mode considers the transient events possibly developed during typical operating conditions while the abnormal operation mode considers the transient events associated with rare and unplanned conditions.

The opening and closing of the flow control valve at each node has its own hydraulic implication and effect on the system. Normally the transients associated with valve opening are less severe than the ones associated with valve closures. The opening of flow control valve at each node is associated with increased supply. Regardless of how fast the valve opening is, the head rise in the system should not exceed the pipeline rated pressure. The sudden drop in pressure though may cause vacuum in the system if it doesn’t have sufficient surge protective devices such as air valves and surge vessels. In addition, the water flow rates may exceed the erosion velocity and may cause damage to the pipelines internal linings which may be followed by corrosion.

The peak water supply in the considered system starts daily, at 6 AM until 6 PM which corresponds to 3 pump operation at AARS to feed the tap off connections which in turn feed the customers of Al Ain Distribution Company (AADC). The normal water supply starts, daily, at 5 AM until 6 AM and 6 PM until 9 PM which corresponds to 2 pump operation at AARS. The low water supply starts daily, at 9 PM until 5 AM which corresponds to 1 pump operation at AARS. Figure 7 shows the operating pumps at different water supply periods.

There are seven daily water supply changes on the system; four of which are major changes. During the valve opening and closing to accommodate normal water supply changes (increase or decrease), the condition is described by “Normal Operation”. The abnormal operation is encountered during the sudden valve opening and closing due to poor operation, pipe ruptures, power failures, gate valve sudden drop and improper design of fast-operating flow control valves.

Normal Operating Conditions

This section discusses the change of water supply at different nodes associated with either gradual or sudden partial flow control valve closures or openings to reach the desired water flow rates according to the distribution daily programs at different nodes in the system.

Scenarios of Gradual Valve Closure

The water supply reduction is associated with gradual or sudden partial flow control valve closures. Figure 7 shows that a typical day involves seven instants of flow reductions described as follows:

- **R1:** Minor flow reduction at 09:00 AM due to drop in water supply requirements at Zakher and Maqam (Markhania) nodes.
- **R2:** Major flow reduction at 11:30 AM due to drop in water supply requirements at Dahma node.
- **R3:** Major flow reduction at 04:30 PM due to supply drop at Zakher node.
- **R4:** Major flow reduction at 5:00 PM due to supply drop at Dahma and Zakher nodes.
- **R5:** Major flow reduction at 6:00 PM due to water supply drop at Maqam node.
- **R6:** Major flow reduction at 9:00 PM due to supply drop at Maqam and Zakher nodes.
- **R7:** Minor flow reduction at 10:00 PM due to supply drop at Maqam node.

Each of the above reduction cases involves a rise of the hydraulic head at the source of supply reduction and other points in the entire system particularly the nodes at the low elevation (Maqam, Zakher and Al Wagen). The rise of the hydraulic head is associated with a recovery time after which the system gets back to its equilibrium condition as the effect of increased head on the system diminishes. Both, the increased head and the recovery time are affected by the period of valve closures. A sample result of such impact is depicted in Figure 8 that shows the change of head with time for the cases of flow reduction at Dahma node at 11:30 AM considering a sudden valve closure. The closure time was set in the simulation model, in this case, at one second to
avoid numerical instability. The recovery time is estimated from Figure 8 as 1321-599 = 722 seconds. The system head after the recovery time is higher than its original value before the valve closure occurrence due to water supply reduction at Dahma node that occurs simultaneously with the valve closure.

Four major reduction cases; R2, R3, R5 and R6 were simulated and the simulated head and recovery time are plotted versus closure times for each case. All flow reduction simulations were carried out for 11 hours (39600 seconds) starting at 11:20 AM to 10:20 PM. This means the zero time for these simulations represents 11:20 AM in Figure 7.

Figure 9 shows the maximum nodal head and system head recovery times versus valve closure times at Dahma PS. The considered valve closure times are: 1, 30, 60, 90, 120, and 150 seconds. The simulated system head recovery times are: 722, 478, 233, 180, 127 and 75 respectively. Such results indicate that it is acceptable and safe for Dahma PS valve to close in at least 60 seconds which is sufficient time for the system head (pressure) to settle back within the acceptable range of pipe and fittings pressure ratings. Although the pipeline itself can stand the transients resulted from 1 sec and 30 sec valve closures, the recovery time for the system head is long enough to cause major instability. This may cause the bolts to get loose, the gaskets to get ruptured, the spigots/sockets to get disconnected and hence water leaks may develop. Therefore, it is unsafe for Dahma valve to close in less than 60 seconds. Similarly, maximum nodal heads and system head recovery times were plotted versus valve closure times for flow reductions applied at Zakher PS (@ 04:30 PM), at Maqam (@ 6.0 PM), and at Dahma and Zakher (@ 09:00 PM), respectively. Similar results and observations found with Dahma case are noticed here. These results are summarized in Table 1 indicating that an overall system control valve safe closing time during water supply reduction is in the range of 90 to 150 seconds for all nodes.

**Scenarios of Gradual Valve Opening**

The water supply increase is associated with gradual, sudden, partial or complete flow control valve openings to reach the desired water flow rates described as per the distribution daily programs at different nodes in the system (Figure 7). The daily valve opening periods in Dahma, Maqam and Zakher starts early morning at 5 AM until 1 PM. This period is always associated with the peak water supply to the system nodes. Specifically, five cases of increased flows occur during the day as follows:

- 11: Increased flow at 05:00 AM due to increased water supply to Maqam and Zakher.
- 12: Increased flow at 06:00 AM due to increased supply to Dahma.
- 13: Increased flow at 06:30 AM due to increased supply to Zakher.
- 14: Increased flow at 07:00 AM due to increased supply to Maqam.
- 15: Increased flow at 01:00 PM due to increased supply to Maqam.

The above cases were all simulated considering the worst scenarios of valve opening in which the valve opening was set at 1 second. The results (not shown here) indicated the pump shut-off heads and the pipe rating pressure are never reached. The vacuum in the system is taken care of by air-pressurized surge vessels at the discharge of the pumps of AARS and adequately sized air valves at high elevations. The water supply/demands are instantaneously changed with the valve opening because the distribution system in this study is defined by a pipe branch taken from the transmission system to fill customers’ domestic tanks that are closed by float valves when they are full. This type of distribution system is not a pressurized network right to the customers’ tabs; it is composed of domestic tanks that hold water just enough for one day consumption.

**Abnormal Operating Conditions**

In this section, sudden complete flow control valve closures at different nodes and pump trips at AARS during peak water supply are simulated to represent the most severe conditions for the system analysis. Even though rare; these conditions can result in undesirable impacts on the proposed bypass setting that implies specific remediation measures.

**Scenarios of Sudden Complete Valve Closures**

The sudden complete flow control valve closures at different nodes during peak supplies are considered. The valve closures in these cases are assumed to happen abruptly in the model setup (one second).

**Complete valve closure at Dahma**
The flow control valve installed at Dahma bypass is suddenly closed during the peak supply in the period of 6:00 AM to 11:30 AM when the flow reaches 1050 L/s. Figure 10 shows the simulated heads at four nodes representing the four supply zones. The simulation started at 6:00 AM and ended at 6:00 PM. The closure was set at 07:45 AM that corresponds to 6300 seconds in Figure 7. It is noticed that the maximum system head reaches 120 m at Wagan Node while the minimum system head reaches -10 m (cavitation) at Dahma Node itself. The existing surge protective devices (air valves and surge vessels) can not cope up with such severe transient conditions.

**Complete valve closure at Maqam**
The flow control valve installed at Maqam bypass is suddenly closed during peak demand in the period of 1:00 PM to 6:00 PM when the flow reaches 1025 L/s. Figure 11 shows the simulated heads at four nodes representing the four demand zones. The simulation started at 1:00 PM and ended at 5:00 PM. The closure was set at 4:00 PM that corresponds to 10833 seconds in Figure 7. It is noticed that the maximum hydraulic head reaches 197 m at Maqam Node itself while the minimum system head reaches -10 m at four nodes (J-39: Maqam, J-43: Zakher, J-45: Wagan, and J-49: Dahma). The transient conditions are very severe in this case that exceed the pipeline design ratings for both aspects (high and low system heads).

**Sudden complete valve closure at Zakher**
The flow control valve installed at Zakher bypass is suddenly closed during
peak supply in the period of 1:00 PM to 6:00 PM when the flow reaches 740 L/s. Figure 12 shows the simulated heads at four nodes representing the four supply zones. The simulation started at 6:00 AM and ended at 6:00 PM. The closure was set at 07:45 AM that corresponds to 6300 seconds in Figure 7. It is noticed that the maximum hydraulic head reaches 196 m at Maqam Node itself while the minimum system head reaches -10 m at four nodes (J-39: Maqam, J-43: Zakher, J-45: Wagan and J-49: Dahma). The transient conditions are very severe here similar to the previous case of Maqam.

Discussion of the above simulation results

The classified pressure rating of the pipes is reached and even exceeded during fast or sudden complete closure of control valves especially at nodes of low elevations like Maqam and Zakher. Although the pipeline itself can withstand 20% higher pressure than its rating to account for major transient events, the bolts normally get loose, gaskets get ruptured, spigots/sockets get disconnected and hence leaks may develop. As a summary, the above simulation results and table 2 have shown how serious is the effect of fast/sudden valve closures of control valves at different demand nodes. Hence, to cater for sudden valves closures during high demands at the lowest nodes of the system (Maqam, Zakher and Wagen), pressure relief valves at the pipe branches of all nodes are examined. The goal is to maintain the system head (pressure) within safe limit for the system fittings not to be damaged and the water supply to customers not to be interrupted. More discussion on the use of pressure relief valves is presented in Section 5.4 after discussing the pump trip scenarios.

The distribution systems are designed to withstand the same pressure rating similar to the transmission system and they have their own surge protective devices as well. However, the distribution systems need to be further checked through new surge simulations to confirm the adequacy of their design. There is a concern though about the non-pressurized distribution systems associated with the backflow (reverse flow) which can bring contamination from the surrounding into the system.

Scenarios of Pump Trips

Al Ain Water Reception Station (AARS) is the main source of water supply to the four nodes considered in the current study. For the available four medium size pumps, the number of pumps in operation depends on the hourly nodal water supply changes in 24-hour cycle. A maximum of three pumps can be in operation during peak hours. The fourth one is on stand bye. Specifically, three cases of pump operation scenarios occur during the day, as the following:

- One-pump operation from 9:00 PM to 5:00 AM (the next day).
- Two-pump operation from 5:00 AM to 6:00 AM and at 6:00 PM to 9:00 PM on daily basis.
- Three-pump operation at 6:00 AM to 6:00 PM on daily basis.

This section discusses the impacts of trip of one and two pumps upon the system performance in the presence of the proposed bypass.

Trip of one pump
The current set of scenarios simulates the trip of one pump (sudden trip) and leaving two pumps in operation. One pump trip was set at time 6300 sec (07:45 AM) to capture the extreme peak conditions. Figure 13 shows the pressure profile for Dahma Node (J49), Maqam Node (J39), Zakher Node (J43) and Wagan Node (J45). It is clearly observed that the available pressure at all nodes drops about 13 Meters below the normal operation conditions. This causes system instability and some transient surge but all stayed above the cavitation pressure in the whole system. The minimum pressure is found to be 7 m above zero indicating the adequacy of the existing surge protective devices (SPD) installed in the system.

Figure 14 shows the available discharge pressure of two pumps at AARS when 1 pump trips out of 3 pump operation at 6300 seconds. The discharge pressure decreases to a minimum of 42 m and stays steady (slightly erratic) all the way until the end of the period. The shape of the graph for downstream pressures mimics almost the pressure changes in the upstream pressures.

Figure 15 shows the water flows, at the discharge side, of two pumps at AARS during the trip of transmission pump #1 at AARS at time 6300 seconds (07:45 AM). The flow of pump #1 dropped to zero while the flow of pumps #2 & #3 increased instantaneously from 983 L/s to 1350 L/s each; in order to equally share the partial compensation of the water shortage of 983 L/s lost due to the trip of one pump. In this case, pump #2 and #3 flow rates increase by 367 L/s. There is a difference of 249 L/s between the supplied quantity and the flow rates of the two pumps that can't be compensated by the two pumps in operation. So for the model to continue through the full period of simulation, although the supply quantity is not met, an external flow equivalent to 249 L/s is assumed hypothetically to get into the system from surge vessels and air valves. The surge devices normally supply water into the system during rapid drops in head to avoid sub-atmospheric pressures and water column separation. This alleviates both low and high pressures in the system.

Figure 16 shows the available inlet pressure of one surge vessel and one air valve at pumps’ main discharge 1200 mm pipeline. The inlet pressure to the surge vessel is supposed to be slightly less than the available discharge pressure of the pumps at AARS and follow the same erratic trend after a one pump trip. The inlet pressure to the air valve is supposed to be equivalent to the lowest system pressure (21 m) at the discharge of the pumps at the highest elevation point (EL=285 Meters in Figure 2). During the case of a one pump trip out of three pump operation (peak water supply) the inlet pressure head decreases to a minimum of zero and stays at this value for 2 hours then increases slightly to 18 m, after wards the inlet pressure to the air valve approaches 30 m.

Figure 17 shows the external water inflow/outflow through air valves (-70 / +70 L/s). In this scenario, +35/-110 L/s of water are drawn off / into each individual surge vessel to damp the surge waves resulted from the trip. Figure 18 shows the external compressed air volume to pressurize the surge vessels (35 m³ in normal operation). About 46 m³ of compressed air are drawn into each individual surge vessel to damp the surge waves resulted...
from one pump trip and continued steady (slightly erratic) until the end. About 65 m³ of atmospheric air are drawn through each air valve into 1200 mm pipeline.

Trip of Two Pumps

Trip of two pumps (sudden trip) and leaving one pump only in operation was simulated. Two pump trip was set at time 6300 sec (07:45 AM), similar to the one pump trip scenario, to capture the extreme conditions of peak flow. It was observed that the available pressure at all nodes drops about 14 m below normal operation. This causes system instability with some transient events but all stayed above the cavitation pressure in the entire 1200 mm transmission system. The minimum pressure is 5 m above cavitation indicating the adequacy of the existing surge protective devices (SPD) installed in the system.

The suction pressure available at the remaining pump at AARS gradually started to drop from 7.9 m until reaching 5.5 m and after that it increases to 6 m. The suction pressure is slightly erratic with less peaks (better stability) during two pump trip than in the case of a one pump trip. The explanation for this phenomenon is that during the two-pump trip; only one pump jumps to full speed (full flow) which results in less transient events opposite to the case of a one pump trip.

The available discharge pressure for the remaining operating pump at AARS is initially at 60 m, drops to 35 m and stays at this pressure value until the end of this cycle. This indicates that the only operating pump is forced to supply its maximum flow and operate at its lowest head (35 m) regardless of the downstream variable water supply.

For the flow at the discharge side of the operating pump at AARS, it goes up immediately from 983 L/s to 1700 L/s; in order to, helplessly, cater for some of the water shortage as flow rate jumps to 1700 L/s along the remaining time of this cycle. This is associated with drop in the inlet pressures for the Surge Vessel from 55 m to 29 m and for the Air Valve from 22 m to -2 m. The surge tanks, surge vessels and air valves compensate the shortage in water supply into the system during rapid drops in head to avoid sub-atmospheric pressures and water column separation. This alleviates both low and high pressures in the system.

For the external water inflow/outflow of the surge vessels and air valves, erratic flows (-900 to + 300 L/s) of high pressure have been getting out of the air valves to release the high pressure off the system during water hammering and surge waves resulted from the two-pump trip. Flow through air valve becomes steady at 480 L/s from 25200 seconds (1 PM) until 37800 seconds (4:30 PM). As a conclusion the transient events are maximized at locations where air valves are installed. This may be related to the 2-phase flow regimes (air mixed with water or air pockets) in atmospheric condition. For the surge vessel, a flow of + 90 L/s gets into the vessel and a flow of 150 L/s gets out of it to the system. Transient events at surge vessels are minimized and system condition is stable due to having clear single phase flow. Under pressurized conditions, air works as a blanket on the top of water surface to damp transient wave inside the vessel; in turn water transfers dampen the effect to the system and hence minimize transients. Normally, air doesn’t intrude into the system through surge vessels. If air intrudes into the system through surge vessels, the surge vessels become like big air valves that can cause severe damage to the water facilities.

During the two-pump trip, continuous and gradually increasing atmospheric air volumes (up to 17000 m³) are drawn into each individual air valve to prevent absolute vacuum pressure inside the pipelines. An average air volume of 10000 m³ is drawn through each air valve into the 1200 mm pipeline. Table 3 summarizes the main results reported with one-pump and two-pump trips.

V. PROPOSED REMEDIATION MEASURES

Critical transient conditions are found to relate to flow control valves used to manage and regulate the flow to different zones. The immediate pulse of the pressure rise is first sensed at the source branch. The pressure wave then quickly travels with the speed of sound to the rest of the system. The best remediation action is to dampen the pressure wave at source where it initially starts. Some of the remediation measures include installing either surge vessels or pressure relief valves. Surge vessels are larger, needs support of external pressurized air system, needs frequent maintenance and they are more expensive. Also, municipal restriction on their installation in the city that is part of region beautification. They are therefore common downstream the pump station in which major pressure drop may occur. The arbitrary choice is installing pressure relief valves on all four branches as they are simple, smaller in size, normally contained or hidden in valve chambers, easy to install, easy in maintenance and less expensive.

The principle of PRV in InfoSurge Model considers a typical surge device that is defined as node junction similar to other surge devices such as surge vessels and air valves with the following requirements: Inflow resistance \( R_i \) = head loss across the valve / flow rate². \( R \) is inversely proportional to the size of the PRV. A higher \( R \) value produces smaller sizes of PRVs and vice versa. Initially, \( R \) is assumed = 1 which is resulted in PRV that can't hold the set 100 m pressure in the system (upstream of PRV). After several trial and errors when \( R = 0.5 \) is used, the set system pressure of 100 m is achieved. Hence,

- \( R = 0.5 \) is used to predict the correct PRV size.
- Head loss = upstream pressure – down stream pressure
- Upstream pressure = 100 m which is the set pressure of the system.
- Downstream pressure = 0 which is the atmospheric pressure.
- Head loss =100 m – 0 = 100 m = 328.1 ft (ignoring minor losses across the valve).
- Solve the equation of \( R \) (in fps system) to obtain the flow rate through the PRV:
  \[ R = \frac{Q^2}{Q^2} = \frac{0.5 \times 328.1}{25.62} = 0.7253 \ m^3/s. \]
- Maximum Recommended Velocity across the valve = \( V_{max} \) (of lined pipes) = 7.0 m/sec
- By rule of thumb, A (area of valve) = \( Q/V_{valve} = (0.7253 \ m^3/sec)/7 \ m/sec) = 0.1036 \ m²
- Then \( D = 363.31 \ mm \approx 400 \ mm \) (standard size)
In conclusion, four pressure relief valves with a size of 400 mm are proposed to maintain the system head (pressure) within safe limits and to be installed on the Dahma branch of 800 mm, Maqam branch of 1000 mm, Zakher branch of 800 mm, and Wagan branch of 800 mm. Carrying out a new set of simulations for the critical transient scenarios determined earlier (sudden complete closure of control valves) in the presence of considered PRVs, all resolved pressures were found within the classified pressure rating of the pipes (16 bars for delivery pipe work from transmission pumps). Table 4 summarizes these results showing how useful are the pressure relief valves in minimizing the adverse effect of fast or sudden valve closures of control valves at different water demand nodes on the pipelines. The impacts of proposed PRVs are summarized as follows:
- Drop of maximum pressure due to sudden closure of valves from 120 m to 89 m in Dahma, 197 m to 90 m in Maqam, and 196 m to 91 m in Zakher.
- Rise of associated minimum pressure from – 10 m to 20 m at all four nodes.

VI. COST ESTIMATES
In order to show the merit of the proposed bypass, a cost analysis is conducted to compare the expenditures of existing system and those expected when the bypass is in place. The expenditures include installation costs of pipes, valves and fittings, and the operational energy cost. The cost also considers the labor and maintenance cost associated with the current pump operation. The cost calculation is also needed in this study to determine the payback period and the profit gain afterwards. The cost estimations are based on the following:
- The proposed bypass setting is based on cost of pipes, valves, fittings, and construction as outlined in Table 5.
- Electrical cables, instrumentations and control systems are estimated at about 15% of pipe materials, valves and fittings cost.
- Contingency fees is added (normally 20% of the total capital cost for contingency such as variation orders).
- The energy cost estimation is based on actual charges of $0.0411 per KWH for the bypassed booster stations i.e Dahma, Maqam, and Zakher and 85% pump efficiency is assumed as an average value that corresponds to the best efficiency point on pump curves.
- The operation and maintenance (O&M) cost estimation is based on annual cost of man hours from Transco Personnel Policy and spare parts are from Transco stores.

Table 5 summarizes the estimates of different types of capital costs with total project cost of $923,967. Annual operating costs include energy use, operation and maintenance, and spare parts estimated as 191,355, 616,500, and 40,000; respectively. This yields a total annual running cost of $ 847,355. Thus, the Project Pay Back Period is estimated as 1.09 years (about 1 year and 1 month). After this period, it is anticipated to save $ 847,355 per year indicating a feasible and highly profitable proposal.

VII. CONCLUSIONS
This paper presented a feasibility study to utilize the valuable pressure energy from Markhania Pump Group in AlAin Reception Pumping Station in AlAin of United Arab Emirates. This has been done via implementing the following tasks:
- Actual operating and design data have been collected for AARS’ pumps, the main water transmission pipelines 1200 mm D.I, the associated installations, and the varying water supply of final destination points (supply nodes) at each consumption branch.
- Scenarios of potential transient effects on the proposed bypass system have been determined and classified to normal and abnormal operating conditions.
- The gathered data were used to setup two hydraulic models (InfoWater and InfoSurge Software) for each considered scenario.
- The available pressures in each scenario have been determined at different consumption branches and at the water demand nodes.
- Various new regulating flow and pressure control valves (and required surge protection devices such as pressure relief valves) have been incorporated at different points for evaluation purposes.
- The best settings of valve installations have been selected in association with identified operating conditions for different demand scenarios.
- The system hydraulic performance and potential of transient conditions caused by the new proposal under different flow scenarios have been studied. This has been done by conducting transient simulations using a specialized software that handles the hydraulic transients in pipenetworks. Such simulations have allowed to evaluate the existing surge vessels’ size and water source pumps’ operating schemes, confirmed their suitability for the new mode of operation and helped in providing recommendations for possible modification if needed.
- The capital and operational costs associated with potential modifications have been estimated.
- The findings and recommendations are presented and can be utilized as a conceptual basic design scheme (feasibility study) for further detailed engineering development and implementation.

The main findings of the study are summarized as follows:
- Normal operating conditions haven’t shown major problems for the system rating pressure
- Safe closure time of 120 seconds was found adequate for all FCVs.
- Sudden closure of valves produced unsafe pressures and required some remediation measures.
- Four PRVs were sized and proposed to be installed on the proposed bypasses.
- The elimination of the operating by-passed booster pumping stations has reflected positively into savings of spare parts requisition, maintenance, man-hours (operating hours) and number of shift staff working for the Operation & Maintenance of the booster Pumping stations.
Providing un-interrupted water supply right from the water transmission mains directly to the consumers via the proposed by-pass system was found possible.

The stagnant time of the high quality water in the storage tanks will be eliminated and will eventually improve the quality of drinking water delivered to consumers.

The water reservoirs and booster pumps that are available in booster stations can still be maintained, water circulated and frequently operated to be kept for use during upstream facility planned shutdowns and emergencies.

Upon implementing the proposal in this study, the project pay back was found to be around one year and one month and is highly profitable by saving of $847,355/year.

REFERENCES

Table I
Summary of valve safe closure time (sec), head recovery time and nodal head

<table>
<thead>
<tr>
<th>Location of valve closure</th>
<th>Minimum Safe valve closure time (sec)</th>
<th>Head recovery time (sec)</th>
<th>Maximum Nodal Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahma</td>
<td>60</td>
<td>200</td>
<td>47</td>
</tr>
<tr>
<td>Zakher</td>
<td>90</td>
<td>253</td>
<td>40</td>
</tr>
<tr>
<td>Maqam</td>
<td>90</td>
<td>247</td>
<td>53</td>
</tr>
<tr>
<td>Dahma &amp; Zakher</td>
<td>90</td>
<td>280</td>
<td>55</td>
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</table>

Table II
Summary of maximum and minimum heads (m) in the absence of pressure relief valves (PRV)

<table>
<thead>
<tr>
<th>Location of sudden valve closure</th>
<th>Maximum head (m)</th>
<th>Maximum head location</th>
<th>Minimum head (m)</th>
<th>Minimum head location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahma</td>
<td>120</td>
<td>Al Wagen</td>
<td>-10</td>
<td>Dahma</td>
</tr>
<tr>
<td>Maqam</td>
<td>197</td>
<td>Maqam</td>
<td>-10</td>
<td>All nodes</td>
</tr>
<tr>
<td>Zakher</td>
<td>196</td>
<td>Zakher</td>
<td>-10</td>
<td>All nodes</td>
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</table>

Table III
Summary of various parameters as a result of pump tripping

<table>
<thead>
<tr>
<th>Number of tripping pumps</th>
<th>Maximum head drop (m)</th>
<th>Minimum nodal head (m)</th>
<th>Minimum nodal head location</th>
<th>Minimum head at highest elevation point (m)</th>
<th>Volume of compressed air into surge vessels (m$^3$)</th>
<th>Volume of atmospheric air into the 1200 mm pipeline (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>7</td>
<td>Dahma</td>
<td>0</td>
<td>138</td>
<td>195</td>
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<tr>
<td>2</td>
<td>14</td>
<td>5</td>
<td>Dahma</td>
<td>-2</td>
<td>-</td>
<td>30000</td>
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Table IV
Summary of maximum head (m), minimum head (m) with PRV installed

<table>
<thead>
<tr>
<th>Location of sudden valve closure</th>
<th>Maximum head (m)</th>
<th>Maximum head location</th>
<th>Minimum head (m)</th>
<th>Minimum head location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahma</td>
<td>89</td>
<td>Al Wagen</td>
<td>20</td>
<td>All nodes</td>
</tr>
<tr>
<td>Maqam</td>
<td>90</td>
<td>Maqam</td>
<td>20</td>
<td>All nodes</td>
</tr>
<tr>
<td>Zakher</td>
<td>91</td>
<td>Zakher</td>
<td>20</td>
<td>All nodes</td>
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</table>
Table V
Project Capital Costs

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Piping</th>
<th>Valves/fittings</th>
<th>Instrumentation &amp; Control</th>
<th>Contingency Cost</th>
<th>Total Project Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)</td>
<td>261,100</td>
<td>408,441</td>
<td>669,541</td>
<td>100,431</td>
<td>769,972</td>
</tr>
</tbody>
</table>

15% of piping/fittings cost (based on TRANSCO/UAE approach of cost estimates)
20% of piping/fittings/instrumentation cost (based on TRANSCO/UAE approach of cost estimates)

Fig. 1. Layouts of Al Ain major water supplies and distributions

Fig. 2. Elevation view of considered system (Markhania Pumping Group)

Fig. 3. Pressure head (m) for the four supply nodes (Dahma node J-49, Maqam node J-39, Zakher node J-43 and Al Wagen node J-45)
Fig. 4. The proposed bypasses on the 1200 mm pipeline

Fig. 5. Headloss / length (m) for proposed bypass of Dahma, Maqam, Zakher and Al Wagen

Fig. 6. Velocity profile for the proposed bypass of Dahma, Maqam, Zakher and Al Wagen
Fig. 7. Hourly supply changes, associated operating pumps, and considered transient scenarios
Fig. 8. Nodal maximum head versus time for the sudden valve closure at Dahma

Fig. 9. Effect of valve closure times at Dahma PS on max nodal head and system head recovery times

Fig. 10. Hydraulic head versus time at different nodes for the case of valve closure at Dahma Node (J-39: Maqam, J-43: Zakher, J-45: Wagan, and J-49: Dahma)
Fig. 11. Hydraulic head at different nodes versus time during Maqam node valve closure (J-39: Maqam, J-43: Zakher, J-45: Wagan and J-49: Dahma)

Fig. 12. Hydraulic head at different nodes versus time during Zakher node valve closure (J-39: Maqam, J-43: Zakher, J-45: Wagan and J-49: Dahma)

Fig. 13. Nodal pressures for 1 pump trip scenario (J-39: Maqam, J-43: Zakher, J-45: Wagan and J-49: Dahma)

Fig. 14. Downstream pump pressures (m) at AARS for a one pump trip scenario
Fig. 15. Flows (L/s) at the discharge sides of the pumps at AARS for a one-pump trip scenario

Fig. 16. Inlet pressure of one surge vessel (SPD) and one air valve (AV) for one-pump trip scenario

Fig. 17. External water inflow/outflow of the surge vessels for a one-pump trip scenario

Fig. 18. External compressed air volume to pressurize the surge vessels and external atmospheric air volume to get into the system through air valves for a one-pump trip scenario