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# Assessment of variable speed pumps in water distribution systems considering water leakage and transient operations

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## ABSTRACT

In this study, the potential economic and hydraulic benefits of utilizing variable speed pumps (VSPs) in water supply systems are reported. A simple water distribution network simulation is carried out by EPANET and Bentley HAMMER models to examine variable speed operation. It was found that using VSPs could control and improve performance of the water distribution systems. Where the potential energy cost savings realized by installing variable speed drives is a significant value (about 20%), in addition the leakage reduces by 21% compared to constant speed pumps. Also, this approach can improve and control undesired and damaged surge pressures and water leakage resulting from the abnormal operation conditions accompanied by the fixed speed pumping.

**Key words** | distribution systems, energy efficiency, leakage, pumps, transients, variable frequency drives

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## INTRODUCTION

Water distribution networks (WDNs) represent one of the largest infrastructure assets of an industrial society (van Dijk *et al.* 2008), with energy costs for pumping being a significant part of the operational cost of water distribution systems worldwide (Lopez-Ibanez *et al.* 2008; Bene *et al.* 2010; Giustolisi *et al.* 2013; Johns *et al.* 2014; Menke *et al.* 2016).

Using constant speed pumps for operating water supply systems produces a situation where pressure may be significantly higher than required and could exceed specifications. Meeting pressure requirements also may require operating valves in a throttled condition. Gibbs *et al.* (2010) identified near optimal solutions for the operation of a real water distribution system (WDS) (Woronora) in Sydney, Australia, including both pump scheduling and disinfectant dosing, by application of optimization algorithms (genetic algorithms, GA). They found that significant energy cost savings of up to 30% can be made by scheduling the pumping in the system. Morley & Tricarico (2016) presented a methodological solution for the expansion and operation optimization problems, and this solution is solved by means of a population-based algorithm incorporating heuristics. This model successfully minimized both infrastructure and operational costs and system-wide leakages.

Equipping of pumps with variable frequency drives (VFDs) improves the pump system reliability and operating efficiency, accompanied by energy and costs savings (Wood & Lingireddy 1995). Kale *et al.* (2017) provided a basic understanding of VFD terms and its operation. Using VFDs, sometimes called adjustable-frequency drives, adjustable-speed drives or variable speed drives (VSDs) vary the rotational speed by changing supply frequency. VFD produces a variable voltage directly proportional to the frequency, which produces a constant magnetic flux in the motor. The motor speed will vary according to the applied frequency generated by the VFD and, as a result, its components such as fans, pumps, and compressors, behave differently as their speed changes (Blair 2017). Sarbu &

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Valea (2015) investigated the energy efficiency of flow control methods (bypass lines, throttling valves and/or pump speed adjustments) in district heating stations. They pointed out that nearly 20–50% of total pumping energy could be saved by using the variable-speed controllers. Variable speed pumps (VSPs) can effectively and efficiently control the operation of the water pumping systems. The use of fixed speed pumps (FSPs) in these systems is quite difficult and can result in pumps operating at low efficiencies and undesirable pressures occurring at different locations and at certain times of the day. Ant colony optimization algorithm was used by Hashemi *et al.* (2014). Their results showed that using (VSP) in an optimized pump scheduling could lead to greater savings (about 10%) in pumping energy costs compared with the single-speed pump. A study (Samoty 1989) based on the mean duty cycle for the pumps indicated that it may be possible to decrease the annual energy consumption around 47%, through the use of VSPs, accompanied by considerable cost savings. By changing the control of variable speed network pumps from the constant pressure control to the proportional pressure control, about 12.2% of the annually consumed electrical energy may be saved in water supply systems (Pilscikovs & Dzelzitis 2013).

It may be noted that most of the research in this area has been limited to FSP operation. The present study focuses on the operation of water distribution systems with VSPs. In addition, the difference between VSPs and FSPs effect on leakage and transients behavior associated with starting/stopping valves are examined using EPANET and Bentley HAMMER simulations. It is worth noting that, in the remainder of the paper, VFDs or VSDs will refer to the VSPs.

## Energy saving in WDNs by VSPs

The electrical energy used to pump water is a significant portion of the total operational costs in WDSs, $E$ (kWh), and is given as:

$$E = \frac{\gamma Q t H_p}{\eta_w} \tag{1}$$

where $\gamma$ (N/m$^3$) is the specific weight of the fluid, $Q$ (m$^3$s$^{-1}$) is the flow rate delivered, $H_p$ (m) is the pump head, $t$ (h) is the operating time, and $\eta_w$ is the wire to water efficiency.

The pump head $H_{P1}$ is the sum of the static head, minor losses through the system, and the friction losses (dynamic head loss) in suction and delivery pipes of a pump $P_1$. If a different pump $P_2$ is used to lift a smaller discharge ($Q_2 < Q_1$) through the same pipeline diameter, the friction losses are reduced and therefore the new generated head $H_{P2}$ will be smaller than $H_{P1}$. Thus, the energy used by the new pump $P_2$ will be lower than the energy consumed by $P_1$ due to the smaller flow rate and head.

Water demand variations in a system can further shift the actual pump operating point from that expected. These variations in demand can be handled by using a storage facility in combination with a FSP or by using a VFD, which may be a more appropriate approach as its speed varies to match system consumer demands. Figure 1 shows that the use of a variable (adjustable) speed drive modifies the pump speed from $N_1$ to $N_2$ ($N_2 < N_1$) to meet demand duties, so the operating point $A_1$ moves to a new point $A_2$. According to affinity laws there is a substantial reduction in absorbed power accompanying the reduction in pump head and flow rate, the grey area (bcdefg) in Figure 1 can be seen as energy saved by installing variable speed control. Also, energy consumption can be minimized by arranging the run times during the non-peak demand energy cost periods.

The combined pump–motor–variable speed drive efficiency is called wire to water efficiency, and can be represented by Equation (2), where $\eta_{VFD}$, $\eta_{mot}$ and $\eta_{pump}$ are the VFD, motor and pump efficiencies, respectively. If

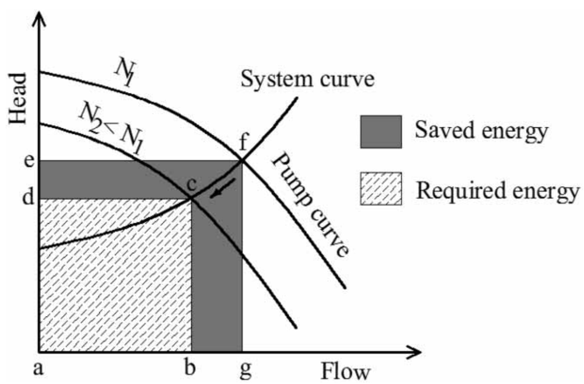


**Figure 1** | Energy saved by using variable speed pumps (grey area).

there is no VFD in the system, i.e. single speed pumps, then $\eta_{VFD}$ is equal to 1.0.

$$\eta_w = \eta_{pump} * \eta_{\text{mot}} * \eta_{\text{VFD}} \tag{2}$$

## Effects of speed variation on pump operation

The basic formulas that govern pump operation at different rotational speeds are usually derived together with those that govern pump operation with different impeller diameters, by the use of similar relations and are called affinity laws (Georgescu *et al.* 2014):

$$\left(\frac{Q_1}{Q_2}\right) = \left(\frac{N_1}{N_2}\right)\left(\frac{D_1}{D_2}\right)^3 \tag{3}$$

$$\left(\frac{H_{p1}}{H_{p2}}\right) = \left(\frac{N_1}{N_2}\right)^2\left(\frac{D_1}{D_2}\right)^2 \tag{4}$$

$$\left(\frac{P_1}{P_2}\right) = \left(\frac{N_1}{N_2}\right)^3\left(\frac{D_1}{D_2}\right)^5 \tag{5}$$

where $Q$ represents the pump flow rate, $H_p$ is the pump head, $P$ is the absorbed power, $N$ is the rotation speed of the impeller and $D$ is the impeller external diameter. It is clear from the squared and cubic expressions of head and power that a small change in speed leads to major changes in these parameters.

The relationship between two different rotational speeds and the corresponding efficiencies (Sarbu & Borza 1998; Georgescu *et al.* 2014) can be obtained in the following form:

$$\eta_2 = 1-(1-\eta_1)*\left(\frac{\mathrm{N}_1}{\mathrm{N}_2}\right)^{0.1} \tag{6}$$

Thus, the changes in efficiency for large pumps can be neglected if the variations in rotational speed are less than 33% of the original pump speed value (Sarbu & Borza 1998). It is well known that the intersection of the system characteristic curve with the pump operating curve (*Q-H* curve) gives the operating point. For systems with only friction loss, reducing pump speed shifts the duty point on the system curve to another node, but these operating nodes have the same efficiency (Figure 2). This means that there is a reduction in power absorbed as a result of the decreased discharge and head. On the other hand, for systems with high static head in relation to friction head, the operating point on the reduced speed curves has an efficiency lower than that at the original speed. There are some problems for systems with considerable static head. A small reduction in speed could move the pump operating point into a region close to shutoff head, where the pump should not be operated continuously, as it could be damaged if it runs for extended periods of time. Decreasing the pump speed cannot generate a sufficient head to pump a liquid through the system, as the flow rate and pump efficiency drop to zero (Figure 2). Operation of pumps at zero flow rate not only wastes energy, but also causes a high temperature rise within the pump and creates a potential for overheating the fluid (through the friction) and must therefore be avoided. However, the area of the usefulness of variable speed pump systems can be improved by making sure that the entire system components (VFD, motor, and pump) have higher efficiency at the working points.

## Leakage in water distribution systems

Water losses comprise various components including physical losses (leaks), illegitimate use, un-metered use and under-registration of water meters. De Marchis *et al.* (2016)

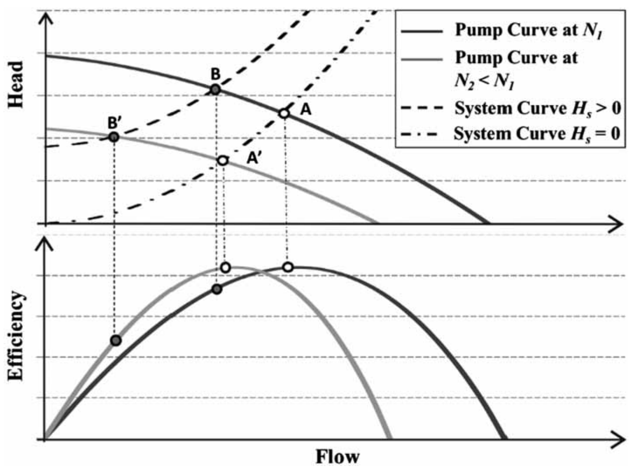


**Figure 2** | Operating points and efficiencies with varying speeds in systems with and without static head (adapted from Marchi *et al.* 2012).

investigated the leak size and pipe rigidity on discharge and the pressure head, by carrying out an experimental campaign on a polyethylene looped WDN. Their results confirmed that the effect of pipe material rigidity depends on the leak area and on the water head upstream of the leak. According to Mora-Rodriguez *et al.* (2014) leak rates do not depend only on pressure, but also can vary depending on type of soil, traffic loading, water quality, specifications and construction quality, materials, infrastructure age, operation practices and maintenance. By using finite element analysis, the relation between pressure head and leakage dimension in pipes with longitudinal, spiral and circumferential cracks is investigated (Cassa & van Zyl 2013). Also, leakages can appear as a result of cross-section crack, crushing and longitudinal cracks. Many of the problems that occur in water supply networks are directly related to operating pressures. For instance, at low pressures, customers find it difficult to meet their demands, besides there is a possibility of cavitation or pollutants intrusion (water quality deterioration). On the other hand, high pressures lead to the probability of system failure, increasing leakage rates and pumping costs. Consequently, one of the system management objectives is to maintain the pressure at all parts of the network within the recommended levels.

The work by Kirmeyer & LeChevallier (2001) stated that leakage rates in water systems range up to 32%. It was found that the orifice equation gives a very good estimation of the unsteady leak rate history for normal leak openings (van Zyl & Malde 2017; Franchini & Lanza 2014), as shown below:

$$q = Cp^n \tag{7}$$

where $q$ is leakage flow rate, $C$ is the discharge coefficient, $p$ is the fluid pressure differential over the orifice and $n$ is the pressure exponent and it is dimensionless and equals 0.5 for sprinklers and nozzles. Fortunately, leak losses can be reduced by means of pressure control such as pressure reducing valves, regulating valves and VSPs.

## CASE STUDY

An example is given in this study in order to illustrate some of the major benefits of assessing VSPs in the WDNs. The case study (Figure 3), and its data can be found in Marchi *et al.* (2012). It consists of an elevated storage tank, an altitude valve (just upstream of the tank) that is activated when the elevated tank fills and a fixed head reservoir, from which a pump supplies water to the remainder of the system. By replacing FSP by a VSP, the resulting hydraulic grade line (dashed line, Figure 3) will have a milder slope than at nominal speed (continuous line) as the pump flow rate is at the minimum necessary limit therefore reducing pipe friction head losses. It is assumed that the pump speed can be reduced to 80% of the initial speed during the minimum demand hours (e.g. during the night), while still providing the necessary quantity of water to users with adequate pressure. To run the transient analysis, model hydraulic data is needed. In our case study, the system material is ductile iron with 1325 m/s pressure wave speed. In order to achieve reasonable precision, transient conditions are simulated with 0.1 second time steps.

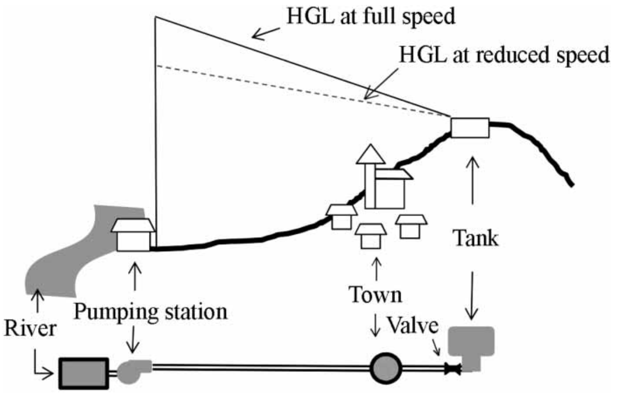


**Figure 3** | Case study layout and its EPANET representation (modified from Marchi *et al.* 2012).

## RESULTS AND DISCUSSION

### Effect of VSPs on energy and associated cost and water losses by leakage

EPANET's hydraulic model (Rossman 2000) is used to perform hydraulic analysis for a distribution system (lower part of Figure 3). EPANET computes junctions head and links flow rate. In addition, the pump characteristics at different relative speeds can be computed in accordance with the affinity laws. At full speed the input pump power is 86.85 kW (flow = 65.27 $Ls^{-1}$, head = 110.59 m and pump efficiency = 81.48%). The model results at the varied speed (80%) show that pump power = 45.44 kW (flow, head and efficiency are 54.94 $Ls^{-1}$, 69.60 m and 82.50%, respectively). However, there is a real need for motor and adjustable frequency drive efficiencies to calculate an accurate value of the total consumed power. The motor efficiency depends upon its type, speed, load and size and it is assumed to be 95%. The efficiency of the VFD is related to its type, size and speed reduction. Data from the Industrial Technologies Program (2012) are used, and a VFD efficiency of 97% will be assumed. Therefore, the total power at the lower speed is 49.01 kW, as shown by Equation (8) ($Q = 54.94$ $Ls^{-1}$, $H =$ 69.60 m, $\eta_{pump} = 0.83$, $\eta_{mot} = 0.95$ and $\eta_{VFD} = 0.97$). This value is about half (53%) of the power absorbed at the original speed, i.e. 91.96 kW ($Q = 65.27$ $Ls^{-1}$, $H = 110.59$ m, $\eta_{pump} = 0.81$, $\eta_{mot} = 0.95$ and $\eta_{VFD} = 1.0$):

$$P(kW) = \frac{\gamma(N/m^3)*Q(m^3/s)*H(m)}{1000*\eta_{pump}*\eta_{mot}*\eta_{VFD}} \tag{8}$$

A cost analysis is carried out using a constant electricity cost of 9 cents per kWh and assuming that in normal operations the FSP is switched on for 16 hours per day, the pump operation consumes a daily cost of $132. On the other hand, we also assume that pumping by VSP, at the relative speed of 80%, is being carried out 24 hours daily to meet the network requirements. The energy cost by using VSP, for the same power cost data, computes a daily cost of $106, which corresponds to an annual saving of $9,490. This represents an energy saving of about 20%.

Another advantage of using VFDs is reducing the leakage rate by lowering the existing pressures. With the EPANET program it is possible to simulate leaks within a pipe network. This is carried out by introducing an emitter in a node (Covelli *et al.* 2016). Emitters are instruments that can be used to model flow rate through fire hydrants/sprinklers that discharge water to the atmosphere. The outflow rate through an emitter depends on pressure at a given junction and is calculated by the orifice equation, Equation (7) (Rossman 2000).

The effect of variable speed pumping on leakage can be estimated by introducing leak elements into the network model. It is assumed that a leakage is applied to the EPANET example (Figure 3), and the loss is concentrated in one point (just after the pump) with an emitter coefficient = 1.35 $L/s/m^{0.5}$.

The model results, at full nominal speed, show that pump power is 100.3 kW (flow = 77.62 $Ls^{-1}$, head = 103.92 m, motor efficiency = 95% and pump efficiency = 83.08%) and leakage rate is equal to 34.4% of the average daily demand (13.76/40) with 103.92 m pressure head at leakage node. At the reduced speed the input power is 54.0 kW ($Q = 64.43$ $Ls^{-1}$, $H = 65.43$ m, $\eta_{pump} = 82.85\%$, $\eta_{mot} = 0.95$ and $\eta_{VFD} = 0.97$) with leakage rate representing 27.3% of the daily demand (10.92/40) and 65.43 m pressure head. It is noticed that the computed pumping energy costs are slightly increased when leakage is considered, by 9.7 and 10.2% for fixed and VSPs, respectively. Using variable speed pumping, a decrease in predicted leakage flow of 21% is calculated. The volume of water lost by leakage is about 246 $m^3$ per day which, at a retail cost of $0.8 per one cubic meter, represents a savings of $71,832 per year. These values report successful outcomes with VSPs.

## Effect of VSPs on transient pressures and water losses by leakage

A hydraulic transient is a flow condition where the velocity and pressure change rapidly with time. The occurrence of transients in water supply systems can introduce large pressure forces and rapid fluid accelerations into WDSs. Therefore, it is very important to simulate VSPs effect on water hammer pressures to determine whether dangerous pressures develop or not. Bently HAMMER software (2003), which can export and import EPANET files, is employed to study the transient analysis of the previous example. Bentley HAMMER V8*i* uses the Method of Characteristics to solve governing equations and unsteady pipe flow.

To show the effect of VSPs on the transient pressures, our case study is examined due to sudden closure of the altitude valve (Figure 3). Figures 4 and 5 show typical variation of head with time at a selected node (upstream of the valve) and the transient pressure heads produced as a result of the instantaneous valve closing for constant speed pump operation. By comparing these graphs with that for VSPs (Figures 6 and 7), it is evident that maximum transient

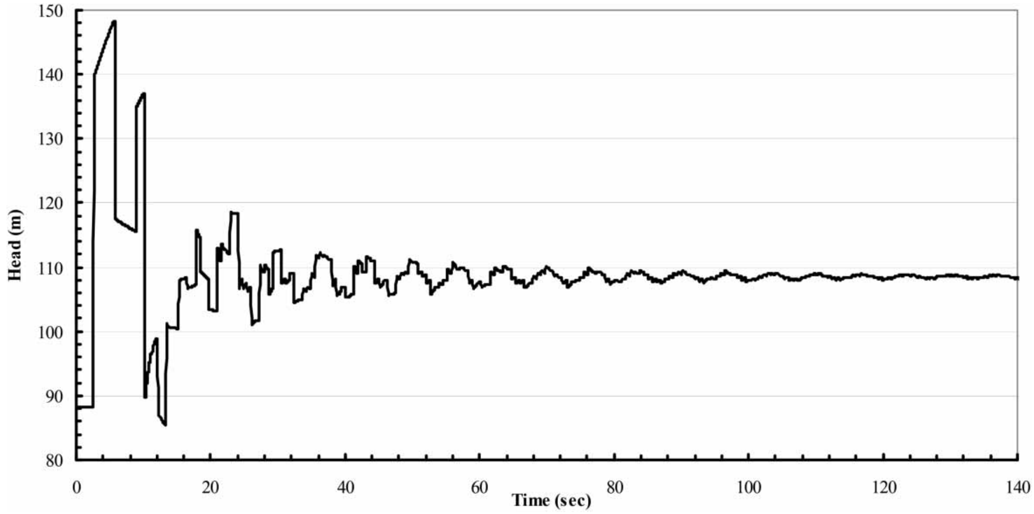


**Figure 4** | Pressure head variation with time at a selected node (upstream of the valve) for FSP operation.

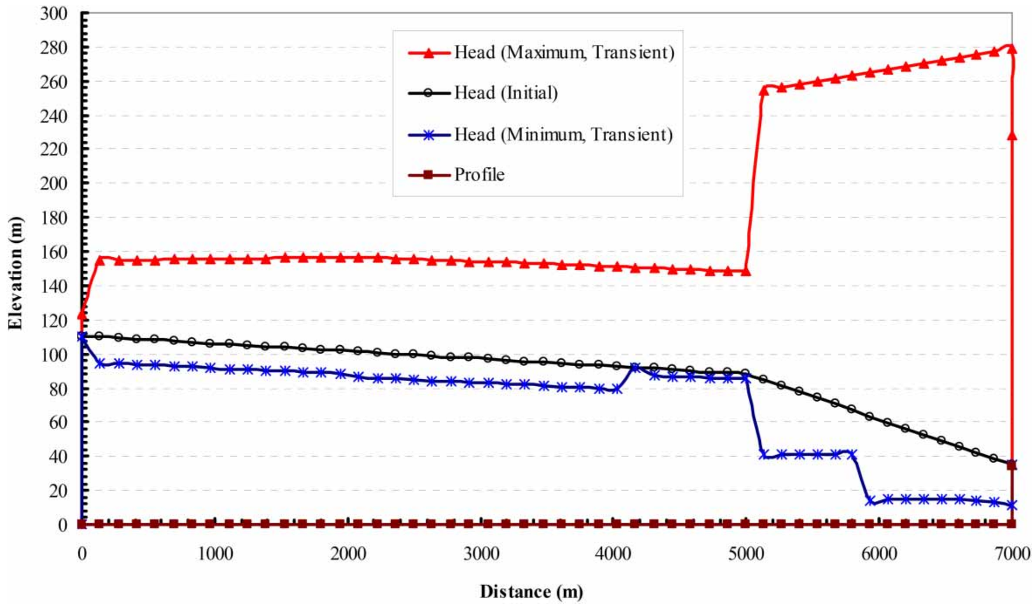


**Figure 5** | Transient pressure heads enveloped due to valve sudden closure and using FSPs.

head associated with VSPs are effectively minimized by approximately 40% (from 279.2 to 167.2 m), while the minimum transient head improves by 36% (from 11.7 to 16.0 m). These transients, in general, may produce severe pressure surges (positive or negative) which can damage the distribution systems and the pumps. Also, a reduction in pump speed to 80% of its initial value decreases the pressure fluctuations at the selected node by 30 m (from 62.9 to 32.8 m). It should be noted that the magnitude of the transient pressures can also be reduced by opening/closing the valves or pumps slowly, using soft-stop/start of pumps or adding some surge protection devices such as closed or open surge tank or pressure relief valves. However, some of these methods may be more expensive.

The calculations are then repeated considering leakage effects, and the results for both constant speed and variable

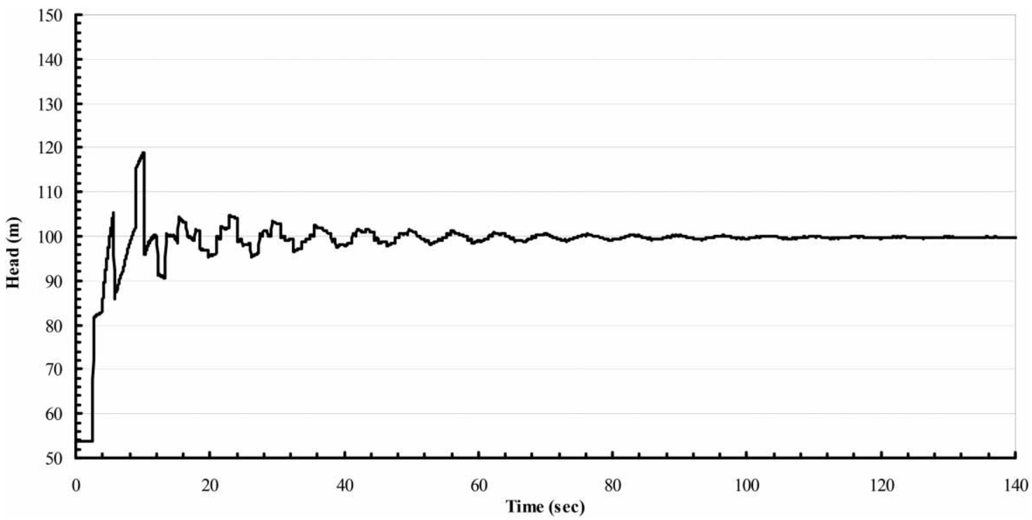


**Figure 6** | Pressure head variation with time at a selected node (upstream the valve) for VSP operation.

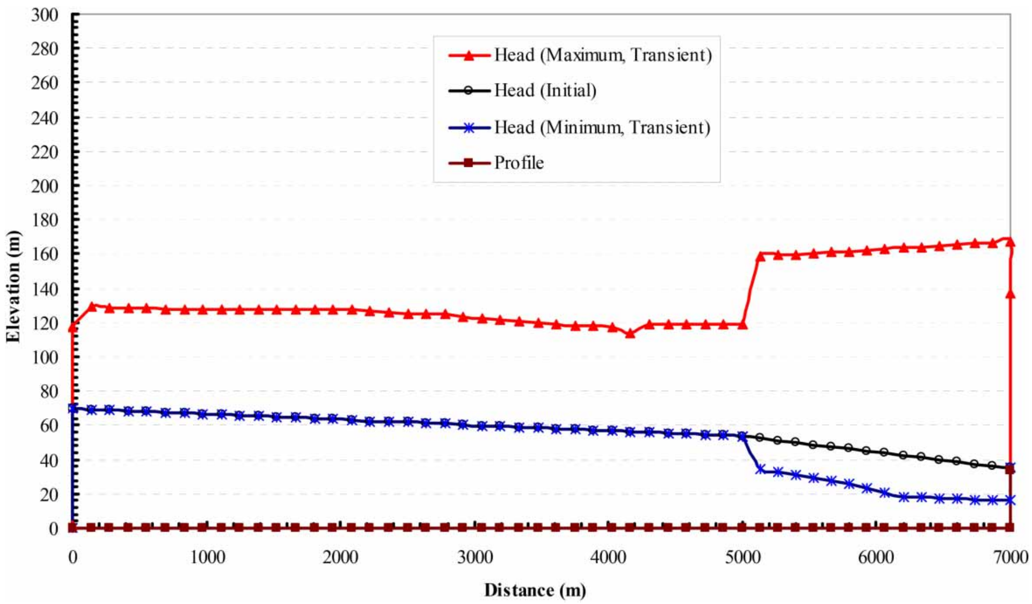


**Figure 7** | Transient pressure heads enveloped due to valve sudden closure and using VSPs.

speed operations are presented in Figures 8 and 9. It can be demonstrated that the maximum transient pressure associated with VSPs is reduced by about 42% (from 263 to 153 m), whereas the minimum head increases by 46% (from 9.5 to 13.9 m). In addition to the minimized pressures, of course, water losses by leakage can be limited.

Figure 10 presents the variation in leakage volume at using FSPs and VSPs. Normally, as the internal pressure fluctuates, the leakage rate changes. From the figure, an average reduction of 11.6% in total leakage volume is achieved by reducing the speed. The reduction in leakage is maximum (21%) at the start of the transient simulation and reaches the minimum value of 2.2% at the end of the simulation. Due to the reduced leakage, financial savings in both water treatment and pumping costs are achieved.

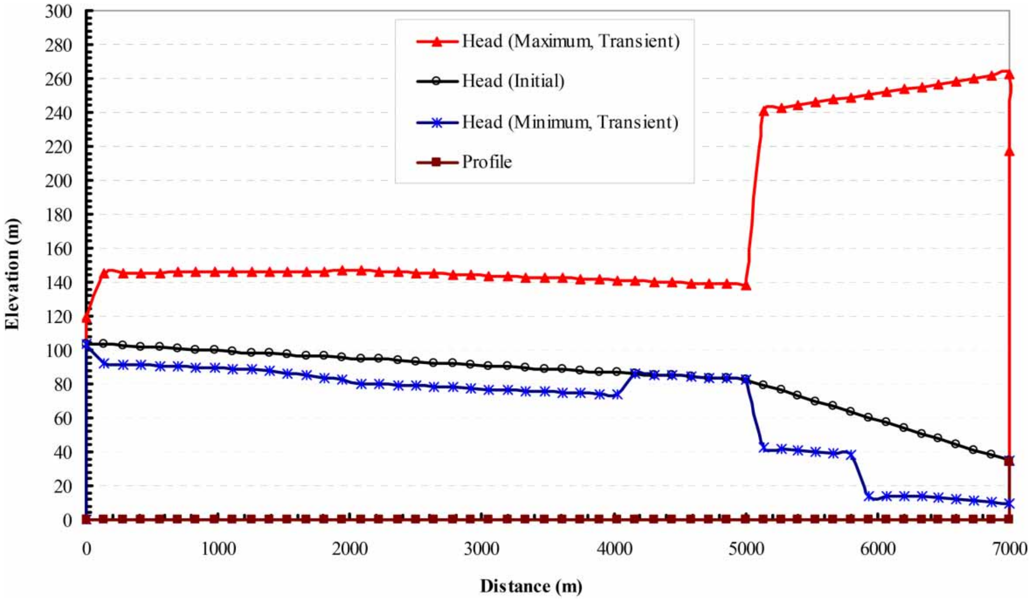


**Figure 8** | Transient pressure heads enveloped due to valve sudden closure at using FSPs and leakage is considered.

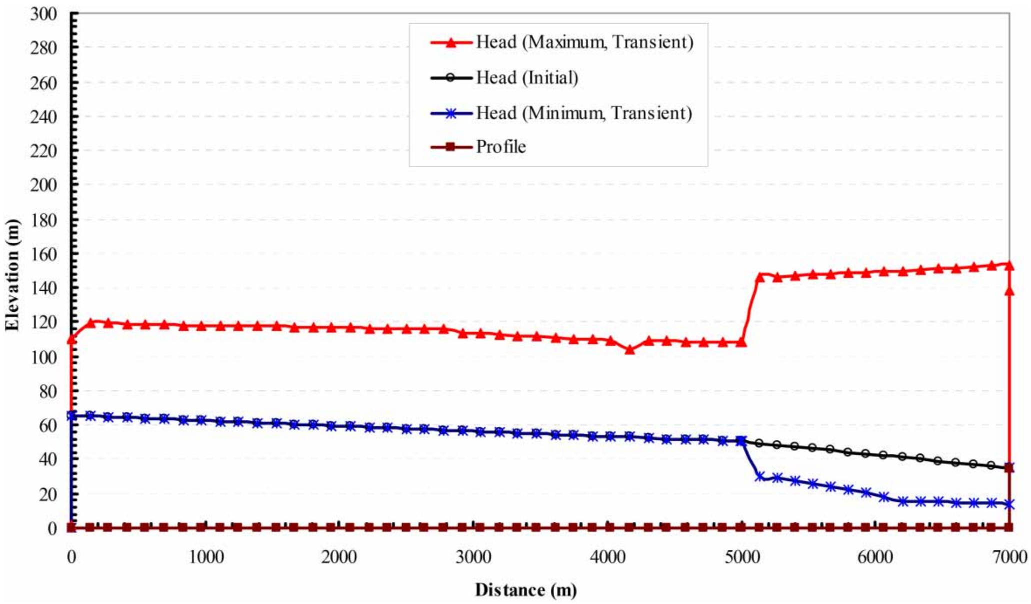


**Figure 9** | Transient pressure heads enveloped due to valve sudden closure at using VSPs and leakage is considered.

It must be noted that the magnitude of leakage reduction accomplished from installation of the VFDs and the corresponding financial savings will obviously differ from other networks, depending on the case study, losses and their distributions, initial pressures, etc. Despite the simplifications of the studied hydraulic system, the obtained results are a powerful indication of the hydraulic and economic benefits achievable from variable speed operation. In fact the VFD speed varies during the day to achieve the operating objectives. For instance, during the peak consumption hours the pump might be run at full speed or slightly higher values (relative speed $\geq 1.0$) according to storage tank size and

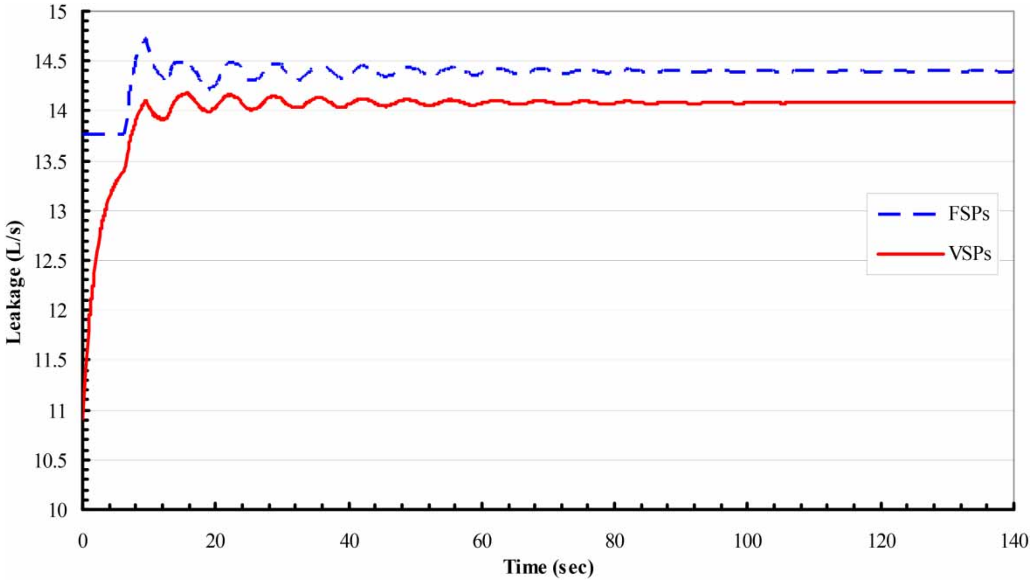


**Figure 10** | Variations of total leakage from the network with time and valve sudden closure.

the actual demand pattern, leading to an increase in pump energy consumption. It must be realized that VFDs are not considered the appropriate technique for all pumping systems. However, in some pumping applications, the capital expenditure cost is relatively high. In addition, if the pump speed is reduced there may be high settling rates of solids in the pump or the system causing serious problems: increasing friction losses, energy wastage and blockage in the system. Therefore, life cycle cost analysis is required for comparing different alternatives so that the most efficient solution can be assigned.

## CONCLUSIONS

Using VSPs for operating pressurized water distribution systems provide many potential benefits. Our case study results highlight the fact that greater operational flexibility of water supply networks can be obtained by fitting VFDs on the pumps, where energy consumption and power costs are saved by about 20%. In addition the leakage reduces by approximately 21%, but the exact amounts saved are specific to a given system and its operation. Also, the potentially damaging extra transient pressures and water losses by leakage resulting from the sudden shutdown of valves and associated to the fixed-speed pumping may be effectively minimized and alleviated by using variable-speed pumping.

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